Book of Abstracts

Welcome to the 5th edition of the International Conference Advances in Magnetics (AIM2025), which will be held in Bressanone (Bolzano), Italy, on February 9-12, 2025, in a setting of historic South Tyrolean buildings and beautiful Alpine peaks.
Previous AIM conferences took place in Bormio (2016), La Thuile (2018), online (2021), and Moena (2023).
AIM will be a forum for presentation and discussion of the most recent advancements in all the fields of Magnetism, involving theory, numerical modeling, experiments and applications.
The event is open to experts and scientists with different backgrounds (engineers, physicists, mathematicians, material scientists, chemists, biologists, etc) to present, discuss, exchange ideas, methods and results.

The 3-day event will include plenary presentations, invited and contributed talks organized in multi-sessions, and poster sessions.
We would like to cordially invite you to contribute to the success of AIM2025, proposing special sessions, submitting abstracts to the different technical categories, and finally attending the conference in the beautiful South-Tyrol of Italy.

We look forward to meeting you in Bressanone!

Vito and Silvia (AIM2025 Chairs)

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Technical Sessions

Additive Manifacturing of Magnetic Materials
(*Chairs: Victorino Franco, Paola Tiberto*)

Altermagnets
(Chairs: Mario Carpentieri, Johan Mentink)

Antiferro- and Ferri-magnetic Spintronics
(Chairs: Alberto Brambilla, Romain Lebrun)

Artificial Intelligence, Machine Learning and Soft-Computing for Magnetism
(Chairs: Antonino Laudani, Alexander Kovacs)

Magnetic Materials for Energy Applications
(Chairs: Franca Albertini, Spomenka Kobe)

Magnetic Measurements
(Chairs: Bernardo Tellini, Cindi Dennis)

Magnetic Nanoparticles and Biomedical Applications
(Chairs: Marco Coisson, Makis Angelakeris)

Magnetism for Neuromorphic and Unconventional Computing
(Chairs: Giovanni Finocchio, Jean Anne Incorvia)

Non-Destructive Testing
(Chairs: Stefano Laureti, Qiuji Yi)

Numerical Modeling and Micromagnetics
(Chairs: Massimiliano d'Aquino, Riccardo Hertel)

Skyrmions and Magnetic Textures
(Chairs: Andrea Meo,Christina Psaroudaki)

Spin Waves and Magnonics
(Chairs: Giovanni Carlotti,Katrin Schulteiss)

Spin-Orbit Torque and Spin-Currents
(Chairs:Cristian Rinaldi,Jagoda Slawinska)

Special Sessions

Artificial Spin Ice Physics and Applications
(Chairs: Nicolas Rougemaille, Daniel Lacour)

Controlling Dzyaloshinskii-Moriya Interaction
(Chairs: Michaela Kuepferling, Marco Madami)

Curvilinear and 3D Magnetism
(Chairs: Denys Makarov, Gaspare Varvaro, Claire Donnelly, Simone Finizio)

Magnetic Levitation and Bearings and Electrical Machine Modeling
(Chairs: Antonino Musolino, Claudia Simonelli, Nicolò Gori)

Magnetic Wireless Power Transfer: Innovations in Materials, Control Algorithms and Modelling
(Chairs: Alicia Triviño Cabrera, Fabio Corti)

Opportunities and Challenges in Spintronics Technology
(Chairs: Davi Rodrigues, Giovanni Finocchio)

Sensing and Harvesting Devices Employing Multi-Functional Materials
(Chairs: Ciro Visone, Simone Fabbrici)

2025 IEEE Conference on Advances in Magnetics (IEEE AIM 2025) - Bressanone, Italy - 9-12 February 2025

PROGRAM

Sunday, Feb 9

Start	End	Forum Bressanone	room Prishna		room Regensburg		room Mantova		room Tirol	
15:30	16:15	Registration								
16:15	16:30	Opening	Welcome and Introduction		-		-			
16:30	17:30	Tutorial	**J. Sinova** *(Chair: A. Kimel)*		-		-			
17:30	17:45	Multisession	Numerical Modeling and Micromagnetics *(M. d'Aquino)*	**Schrefl**	Magnetism for Neurom. and Unconv. Computing *(O. Gomonay)*	Rodrigues	Magnetic Wireless Power Transfer *(A. Triviño Cabrera)*	**Musumeci - Solimene**		
17:45	18:00					Riminucci				
18:00	18:15			**Kim**		**Khymyn**		**Cardelli - Bertolini**		
18:15	18:30									
18:30	18:45			Hertel		Ebels		Cohen		
18:45	19:45	Welcome Reception								

Monday, Feb 10

Start	End	Forum Bressanone	room Prishna		room Regensburg		room Mantova		room Tirol	
08:45	09:00	Multisession	Magnetism for Neurom. and Unconv. Computing *(R. Khymyn)*	**Fukami**	Spin-Orbit Torque and Spin-Currents *(C. Rinaldi)*	**Avci**	Magnetic Measurements *(B. Tellini)*	Zaiets	Artificial Spin Ice Physics and Applications *(N. Rougemaille)*	**Nisoli**
09:00	09:15							Koplak		
09:15	09:30			**Åkerman**		**Johansson**		Raghu		Pirota
09:30	09:45							**Tiberto**		Berchialla
09:45	10:00					Laterza				Cecchi
10:00	10:45	Plenary	**H. Yang** *(Chair: R. Tomasello)*		-		-		-	
10:45	11:05	Coffee break								
11:05	11:20	Multisession	Altermagnets *(M. Carpentieri)*	**Kimel**	Numerical Modeling and Micromagnetics *(R. Hertel)*	Vallobra	Magnetic Materials for Energy Applications *(F. Casoli)*	Barrera	Skyrmions and Magnetic Textures *(A. Meo)*	Slezak
11:20	11:35					Breth		Varvaro		Walker
11:35	11:50			**Smejkal**		Malagò		Pecheux		Jiang
11:50	12:05					d'Aquino		Pradhan		**Barker**
12:05	12:20			**Song**		**Buda-Prejbeanu**		**Caron**		
12:20	12:35									**Aqeel**
12:35	12:50			Grzybowski				Lalitha R.		
12:50	13:05			Wegrove				Sharma H.		
13:05	15:00	Posters I and Lunch *(A. Aqeel, P. Malagò, C. Simonelli)*								
15:00	15:15	Multisession	Magnetic Materials for Energy Applications *(L. Caron)*	Law	Curvilinear and 3D Magnetism *(D. Makarov)*	**Jacobsen**	Magnetic Nanoparticles and Biomedical Applications *(M. Angelakeris)*	**Frandsen**	Spin Waves and Magnonics & Antiferro- and Ferri-magnetic Spintronics *(D. Petti)*	Bonetti
15:15	15:30			Vinai						Cocconcelli
15:30	15:45			Gai H.		**Sevim**		Wiekhorst		Vitali
15:45	16:00			Klinar				Jaufenthaler		Mantion
16:00	16:15			Fournée		Pylypovskyi		Bugase		Mertelj
16:15	16:30			**Jenuš Belec**		Kiselev		Shubbak		Ma S.
16:30	16:45					Fesenko		**Laurenzana**		Zhang B.
16:45	17:00					Wojewoda				
17:00	17:20	Coffee break								
17:20	17:35	Multisession	Spin Waves and Magnonics *(K. Schultheiss)*	**Petti**	Magnetic Measurements *(E. Darwin)*	Josteinssos	Sensing and Harvesting Devices *(D. Davino)*	**Waske**	Artificial Spin Ice Physics and Applications *(D. Lacour)*	**Ladak**
17:35	17:50					Solimene				
17:50	18:05			**Korber**		**Weickert**		Meo		Levartoski
18:05	18:20							Das		Branford
18:20	18:35			Van Dijken		**Nlebedim**		Cugini		**Tierno**
18:35	18:50									

Tuesday, Feb 11

Start	End	Forum Bressanone	room Prishna		room Regensburg		room Mantova		room Tirol	
08:45	09:00	Multisession	Opportunities and Challenges in Spintronic Technology *(G. Finocchio)*	**Jué**	Spin-Orbit Torque and Spin-Currents *(C. Avci)*	**Gambardella**	AI, Machine Learning and Soft Computing for Magnetism *(A. Laudani)*	**Kulesh**	Additive Manifacturing of Magnetic Materials *(P. Tiberto)*	Faba
09:00	09:15									**Salazar**
09:15	09:30			Fagiani		Miranda De Paula		Schaffer		
09:30	09:45			**Nembach**		Skowronski		Vishina		Franco
09:45	10:00					Perna		Garzon		
10:00	10:45	Plenary	**P. Pirro** *(Chair: S. Van Dijken)*		-		-		-	
10:45	11:05	Coffee break								
11:05	11:20	Multisession	Spin Waves and Magnonics *(G. Carlotti)*	Schultheiss	Curvilinear and 3D Magnetism *(C. Donnelly)*	**Dunin-Borkowski**	Magnetic Materials for Energy Applications *(G. Vinai)*	Petelin	Antiferro- and Ferri-magnetic Spintronics *(S. Mantion)*	**Bergenti**
11:20	11:35			Brevis				Tomc		
11:35	11:50			Lopes Seeger		**Hierro Rodriguez**		Almanza		Koliushenkov
11:50	12:05			Soares				Casadei		Offi
12:05	12:20			Salama		Bezsmertna		Poskovic		Prusik
12:20	12:35			**Bossini**		Butcher		Moreno Ramírez		Sato
12:35	12:50					Abert		Duan		Wang H.
12:50	13:05					Rybakov				
13:05	15:00	Posters II and Lunch *(S. Finizio, E. Garzon, Q. Yi)*								
15:00	15:15	Multisession	Antiferro- and Ferri-magnetic Spintronics *(A. Brambilla)*	**Fusil**	Controlling Dzyaloshinskii-Moriya Interaction *(M. Kuepferling)*	Di Pietro	Sensing and Harvesting Devices *(S. Fabbrici)*	Gacnik	Magnetic Levitation and Bearings and Electrical Machine Modeling *(A. Musolino)*	**Díez Jiménez**
15:15	15:30					Vedmedenko		Lopes A. C.		
15:30	15:45			Lehmann		**Lavrijsen**		Lumetti		**Chen**
15:45	16:00			Kozioł-Rachwał				**Davino**		
16:00	16:15			Finizio		**Pizzini**				Pilat
16:15	16:30			Lopez Dominguez				**Chesnel**		Gori
16:30	16:45			Janus		Gandini				Simonelli
16:45	17:00			Ge		Ajejas				
17:00	17:20	Coffee break								
17:20	17:35	Multisession	Opportunities and Challenges in Spintronic Technology *(D. Rodrigues)*	**Kent**	Controlling Dzyaloshinskii-Moriya Interaction *(M. Madami)*	Holt	Non-Destructive Testing *(S. Laureti)*	**Ricci**		
17:35	17:50					Kuswik				
17:50	18:05			**Slavin**		**Carlotti**		**Hughes**		
18:05	18:20									
18:20	18:35			Finocchio		**Marrows**		Gontarz		
18:35	18:50			Bessarab						
20:00		Social Dinner								

Wednesday, Feb 12

Start	End	Forum Bressanone	room Prishna		room Regensburg		room Mantova		room Tirol
08:45	09:00	Multisession	Skyrmions and Magnetic Textures *(C. Psaroudaki)*	**Boulle**	Magnetic Nanoparticles and Biomedical Applications *(M. Coïsson)*	Albertini	Magnetic Wireless Power Transfer *(F. Corti)*	Bertolini	
09:00	09:15					Iglesias		Khatu	
09:15	09:30			Panzeri		Angelakeris		Triviño Cabrera	
09:30	09:45			Tomasello		**Gobbo**		**Delgado**	
09:45	10:00			Qiu					
10:00	10:45	Plenary	**N. Dempsey** *(Chair: F. Albertini)*		-		-		
10:45	11:05	Coffee break							
11:05	11:20	Multisession	AI, Machine Learning and Soft Computing for Magnetism *(A. Kovacs)*	**Sanvito**	Curvilinear and 3D Magnetism *(G. Varvaro)*	Augustin	Magnetic Materials for Energy Applic. & Additive Manifacturing *(V. Franco)*	Gimaev	
11:20	11:35					Morales Fernández		Hasan	
11:35	11:50			Coïsson		**Gubbiotti**		**Scheibel**	
11:50	12:05			Pathak					
12:05	12:20			Pollok		**Gomonoy**		**Brück**	
12:20	12:35			Delin					
12:35	12:50					Meda		Löwa	
12:50	13:20	Closing	Acknowledgements and Awards						

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2025 IEEE Conference on Advances in Magnetics (IEEE AIM 2025)

Bressanone, Italy - 9-12 February 2025

PROGRAM

SUNDAY, FEBRUARY 9th, 2025

15:30	Registration	Forum Bressanone Foyer I
16:15	Opening - Welcome and Introduction **Vito Puliafito** and **Silvia Tacchi**, General Chairs of AIM2025	Room Prishna
	TUTORIAL - Chair: **Alexey Kimel**, Radboud University (The Netherlands)	Room Prishna
16:30	**Jairo Sinova**, Johannes Gutenberg University of Mainz (Germany), INVITED *Unconventional magnetism in spintronics: the emergence of altermagnetism and its new variants*	
	SESSION - Numerical Modeling and Micromagnetics Chair: **Massimiliano d'Aquino**, Università degli Studi di Napoli Federico II (Italy)	Room Prishna
17:30	**Thomas Schrefl**, University for Continuing Education Krems (Austria), INVITED *Extending length scales of micromagnetic simulations*	
18:00	**Joo-Von Kim**, CNRS/Univ. Paris-Saclay (France), INVITED *Mode filtering and projection in micromagnetics for studying magnon population dynamics*	
18:30	**Riccardo Hertel**, Université de Strasbourg, CNRS (France) *Micromagnetic modeling with tetmag: an open-source finite-element software with GPU acceleration*	
	SESSION - Magnetism for Neuromorphic and Unconventional Computing Chair: **Olena Gomonay**, Johannes Gutenberg University of Mainz (Germany)	Room Regensburg
17:30	**Davi Rodrigues**, Politecnico of Bari (Italy) *Advancing Neural Network Performance through Magnetic Tunnel Junctions implementations*	
17:45	**Alberto Riminucci**, CNR-ISMN Bologna (Italy) *Glassy synaptic time dynamics in molecular La0.7Sr0.3MnO3/Gaq3/AlOx/Co spintronic crossbar devices*	
18:00	**Roman Khymyn**, University of Gothenburg (Sweden), INVITED *Paving the way towards high-performance spin-wave Ising machines*	
18:30	**Ursula Ebels**, SPINTEC, Université Grenoble Alpes (France) *Towards a programmable Ising Machine using a network of coupled vortex spin-torque nano-oscillators*	
	SESSION - Magnetic Wireless Power Transfer: Innovations in Materials, Control Algorithms and Modelling Chair: **Alicia Triviño Cabrera**, University of Málaga (Spain)	Room Mantova
17:30	**Salvatore Musumeci - Luigi Solimene**, Politecnico di Torino (Italy), INVITED *Power Regulation in Inductive Wireless Power Transfer Systems Using a Controlled Variable Inductor*	
18:00	**Ermanno Cardelli - Vittorio Bertolini,** University of Perugia (Italy), INVITED *Modelling of Eddy Current Losses in Ferrite Cores*	
18:30	**Opal Cohen**, Israel Institute of Technology (Israel) *Design and modelling of higher bending modes in a magnetoelectric device*	
18:45	Welcome Reception	Foyer I

MONDAY, FEBRUARY 10th, 2025

SESSION - Magnetism for Neuromorphic and Unconventional Computing — Room Prishna
Chair: **Roman Khymyn**, University of Gothenburg (Sweden)

08:45 **Shunsuke Fukami**, Tohoku University (Japan), INVITED
Engineering stochastic magnetic tunnel junction for probabilistic computing

09:15 **Johan Åkerman**, Gothenburg University (Sweden), Tohoku University (Japan), INVITED
Mutual synchronization of thousands of spin Hall nano-oscillators

SESSION - Spin-Orbit Torque and Spin-Currents — Room Regensburg
Chair: **Christian Rinaldi**, Politecnico di Milano (Italy)

08:45 **Can Onur Avci**, Institute of Materials Science of Barcelona (Spain), INVITED
Spin and orbital torques in Cu-based ferromagnetic heterostructures

09:15 **Annika Johansson**, Max Planck Institute of Microstructure Physics (Germany), INVITED
Spin, orbital, and magnetotransport in oxide interfaces

09:45 **Simone Laterza**, Elettra Sincrotrone Trieste (Italy)
Ultrafast spin dynamics across metal/semiconductor interfaces: all-optical injection of spin currents in silicon

SESSION - Magnetic Measurements — Room Mantova
Chair: **Bernardo Tellini**, University of Pisa (Italy)

08:45 **Oleksandr Zaiets**, IFW Dresden, TU Dresden (Germany)
Determination of Magnetic Symmetries by Convergent Beam Electron Diffraction

09:00 **Oksana Koplak**, Università degli Studi di Milano-Bicocca (Italy)
Tuned deposition parameters for control the magnetic properties of SmCo thick films

09:15 **Athira Raghu**, UGC-DAE Consortium For Scientific Research Mumbai Centre (India)
Investigating Physical Properties in Tb2Ni1-xCoxMnO6 Double Perovskites

09:30 **Paola Tiberto**, INRiM Torino (Italy), INVITED
Magnetic Characterisation at the Nanoscale: Challenges and Reliability

SESSION - Artificial Spin Ice Physics and Applications — Room Tirol
Chair: **Nicolas Rougemaille**, CNRS - Institut Néel (France)

08:45 **Cristiano Nisoli**, Los Alamos National Laboratory (USA), INVITED
Architecting emergence in nanomagnets: artificial spin ice

09:15 **Kleber Roberto Pirota**, State University of Campinas (Brazil)
Impacts of multipolar corrections, boundary conditions and cutoff radius on the ground state of artificial kagome spin ice

09:30 **Luca Berchialla**, ETH Zurich - Paul Scherrer Institute (Switzerland)
Controlling phase transitions and magnetic order in a ruby artificial spin ice

09:45 **Breno Cecchi**, State University of Campinas (Brazil)
Effective interaction strengthening and absence of spin fragmentation in connected artificial kagome ice

PLENARY - Chair: **Riccardo Tomasello**, Politecnico di bari (Italy) — Room Prishna

10:00 **Hyunsoo Yang**, National University of Singapore (Singapore), INVITED
Spin-based non-volatile memories, unconventional computing, and energy harvesting

10:45 Coffee break — Foyer I

SESSION - Altermagnets — Room Prishna
Chair: **Mario Carpentieri**, Politecnico di Bari (Italy)

11:05 **Alexey Kimel**, Radboud University (The Netherlands), INVITED
Ultrafast antiferromagnetism – terra incognita beyond the conventional approximations

11:35 **Libor Smejkal**, Max Planck Institute for the Physics of Complex Systems, Dresden (Germany), INVITED
Spin group theory of unconventional magnetism:altermagnets and beyond

12:05 **Cheng Song**, Tsinghua University (China), INVITED
Manipulation of the altermagnetic order via crystal symmetry

12:35 **Michał Grzybowski**, University of Warsaw (Poland)
Wurtzite MnSe as an altermagnetic candidate

12:50 **Jean-Eric Wegrowe**, Ecole Polytechnique, CNRS (France)
Power efficiency of Hall-currents in NiFe, GdCo and Si3Mn5 altermagnet: a comparative study

SESSION - Numerical Modeling and Micromagnetics — Room Regensburg
Chair: **Riccardo Hertel**, Université de Strasbourg, CNRS (France)

11:05 **Pierre Vallobra**, Beihang University (China)
Generation of topological spin textures using light-induced radially polarized magnetic field

11:20 **Leoni Breth**, University for Continuing Education Krems (Austria)
Reduced order micromagnetics of permanent magnets

11:35 **Perla Malagò**, Silicon Austria Labs (Austria)
Magnetic MEMS micromirror with closed-loop control

11:50 **Massimiliano d'Aquino**, Università degli Studi di Napoli Federico II (Italy)
Micromagnetic simulation of inertial magnetization dynamics in ferromagnets

12:05 **Liliana Buda-Prejbeanu**, Spintec (France), INVITED
Dynamics of coupled layers in magnetic tunnel junctions

SESSION - Magnetic Materials for Energy Applications — Room Mantova
Chair: **Francesca Casoli**, CNR - IMEM Parma (Italy)

11:05 **Gabriele Barrera**, INRiM Torino (Italy)
Opto-mechanical control over FeGa magnetic properties via liquid crystalline networks

11:20 **Gaspare Varvaro**, CNR - ISM Roma (Italy)
Facile and fast synthesis of highly ordered L10-FeNi nanoparticles from cyano/nitrosyl-metal complexes

11:35 **Alexis Pecheux**, Université Paris-Saclay, CNRS (France)
Study of the laser-induced modulated Antiferromagnetic-Ferromagnetic phase transition in a magnetocaloric FeRh Film

11:50 **Gajanan Pradhan**, INRiM Torino (Italy)
Electric Field Control of Magnetization in FeGa microstructures on PMN-PT

12:05 **Luana Caron**, Bielefeld University (Germany), INVITED
The magneto- and baro-caloric properties of Hf0.84Ta0.16Fe2

12:35 **Nivedita Lalitha Raveendran**, Israel Institute of Technology (Israel)
Effect of porosity on the magnetic and magnetostrictive properties of Galfenol sputtered on porous silicon

12:20 **Hemanita Sharma**, University of Trieste, CNR IOM Trieste (Italy)
Temperature controlled magnetic modifications in Ni/KNbO3 artificial multiferroic heterostructures

SESSION - Skyrmions and Magnetic Textures — Room Tirol
Chair: **Andrea Meo**, Politecnico di Bari (Italy)

11:05 **Michał Ślęzak**, AGH University of Krakow (Poland)
From magnetostatics to topology: antiferromagnetic vortex states in NiO-Fe nanostructures

11:20 **Benjamin Walker**, University of Texas at Dallas (USA)
Near-landauer pipelined voltage-propagated skyrmion logic

11:35 **Sheng Jiang**, South China University of Technology (China)
Dynamically stabilized synthetic antiferromagnetic skyrmions

11:50 **Joseph Barker**, University of Leeds (United Kingdom), INVITED
Metadynamics calculations of the effect of thermal spin fluctuations on skyrmion stability

12:20 **Aisha Aqeel**, University of Augsburg (Germany), INVITED
Magnetization dynamics of skyrmion lattice in cubic chiral magnets

13:05 **POSTER I and LUNCH** — Foyer I and II
Chairs: **Aisha Aqeel**, University of Augsburg (Germany), **Perla Malagò**, Silicon Austria Labs (Austria),
Claudia Simonelli, University of Pisa (Italy)

SESSION - Magnetic Materials for Energy Applications — Room Prishna
Chair: **Luana Caron**, Bielefeld University (Germany)

15:00 **Jia Yan Law**, University of Seville (Spain)
Influence of secondary phases on the determination of the order of thermomagnetic phase transitions: model and experiment

15:15 **Giovanni Maria Vinai**, CNR - IOM Trieste (Italy)
Light-induced interfacial oxigen migration in PMN-PT/Fe heterostructures

15:30 **Hang Gai**, University of Technology Delft (The Netherlands)
Room temperature magnetocaloric materials (MnFe) 1.9 (PSi) Fe-rich compounds for heat pump application

15:45 **Katja Klinar**, University of Ljubljana (Slovenia)
From electromagnet to electro-permanent magnet for magnetocaloric heat pumps

16:00 **Vincent Fournée**, Université de Lorraine, CNRS (France)
Structural and magnetocaloric properties in rare-earth free high-entropy alloys

16:15 **Petra Jenuš Belec**, Jožef Stefan Institute-Ljubljana (Slovenia), INVITED
Greener permanent magnets without or with less critical raw materials for electric motor application

SESSION - Curvilinear and 3D Magnetism — Room Regensburg
Chair: **Denys Makarov**, Helmholtz-Zentrum Dresden-Rossendorf (Germany)

15:00 **Sol Jacobsen**, Norwegian University of Science and Technology (Norway), INVITED
Controlling superconductivity with curvilinear magnetism

15:30 **Semih Sevim**, ETH Zurich (Switzerland), INVITED
Magnetically Guided Small-Scale Robots for Biomedical Applications

16:00 **Oleksandr Pylypovskyi**, Helmholtz-Zentrum Dresden-Rossendorf (Germany)
Magnetic textures in curvilinear spin chains of constant torsion

16:15 **Nikolai Kiselev**, Forschungszentrum Jülich (Germany)
Hopfion rings

16:30 **Oksana Chubykalo-Fesenko**, Instituto de Ciencia de Materiales de Madrid (Spain)
Current-induced nucleation, propagation and pinning of Bloch-point domain walls in cylindrical nanowires

16:45 **Ondřej Wojewoda**, Brno University of Technology (Czech Republic)
Modeling of the micro-focused Brillouin light scattering signal

SESSION - Magnetic Nanoparticles and Biomedical Applications — Room Mantova
Chair: **Makis Angelakeris**, University of Thessaloniki (Greece)

15:00 **Cathrine Frandsen**, Technical University of Denmark (Denmark), INVITED
Measuring the heating power and temperature of magnetic nanoparticles

15:30 **Frank Wiekhorst**, Physikalisch-Technische Bundesanstalt (Germany)
The perspectives on using magnetorelaxometry imaging in clinical hyperthermia applications

15:45 **Aaron Jaufenthaler**, University of Innsbruck (Austria)
Developments in human-sized quantitative imaging of magnetic nanoparticles with optically pumped magnetometers

16:00 **Jonas Bugase**, University of Kassel (Germany)
Controlled transport of magnetic cuboidal particles in dynamic potential energy landscapes for lab-on-chip applications

16:15 **Yahya Shubbak**, University of Kassel (Germany)
Magnetophoretic distinction of differently surface-functionalized magnetic microparticles by close-to-surface transport in a quiescent liquid

16:30 **Anna Laurenzana**, University of Florence (Italy), INVITED
Nanoparticle Innovations: Harnessing Magnetic Iron Nanoparticles for Obesity and Hybrid Gold-Iron Nanourchins for Advanced Lung Cancer Therapies

SESSION - Spin Waves and Magnonics & Antiferro- and Ferri-magnetic Spintronics — Room Tirol
Chair: **Daniela Petti**, Politecnico di Milano (Italy)

15:00 **Stefano Bonetti**, Ca' Foscari University of Venice (Italy)
Terahertz charge and spin transport in metallic ferromagnets: The role of crystalline and magnetic order

15:15 **Maria Cocconcelli**, Politecnico di Milano (Italy)
Fully-integrated self-biased magnonic phase-shifter

15:30 **Matteo Vitali**, Politecnico di Milano (Italy)
Three dimensional, nanoscale control of magnetism in crystalline yttrium iron garnet for magnonics

15:45 **Sarah Mantion**, Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay (France)
Unraveling spin-wave dynamics in ferro- and antiferro-magnetic insulators

16:00 **Tomaz Mertelj**, Jozef Stefan Institute (Slovenia)
Anomalous hardening of spin waves in cobalt/molecular-semiconductor heterostructures implying strongly anisotropic spinterface magnetism: a time-resolved MOKE investigation

16:15 **Shuangying Ma**, University of Milan (Italy)
Organic Molecular Adsorption Promotes Exchange Interactions in Antiferromagnetic Transition Metal Oxide

16:30 **Boyu Zhang**, Beihang University (China)
Single-Shot Laser-Induced Switching of an Exchange Biased Antiferromagnet

17:00 Coffee break — Foyer I

SESSION - Spin Waves and Magnonics — Room Prishna
Chair: **Katrin Schultheiss**, Helmholtz-Zentrum Dresden-Rossendorf (Germany)

17:20 **Daniela Petti**, Politecnico di Milano (Italy), INVITED
Controlling and imaging spin waves in 3D

17:50 **Lukas Körber**, Radboud University Nijmegen (The Netherlands), INVITED
Spin waves in curved magnetic shells

18:20 **Sebastiaan van Dijken**, Aalto University (Finland)
Magnonic convolutional neural networks

SESSION - Magnetic Measurements — Room Regensburg
Chair: **Emily Darwin**, Empa (Switzerland)

17:20 **Björn Josteinssos**, QZabre Ltd (Switzerland)
Quantum sensing with NV centers: magnetometry and beyond

17:35 **Luigi Solimene**, Politecnico di Torino (Italy)
Measurement of magnetic losses in soft magnetic materials for power electronics under DC-bias and non-sinusoidal operation

17:50 **Dagmar Franziska Weickert**, Physikalisch - Technische Bundesanstalt (Germany), INVITED
Primary Tesla standards at the German metrology institute PTB

18:20 **Ikenna Nlebedim**, Ames National Laboratory (USA), INVITED
Advances and Challenges in Additive Manufacturing of Permanent Magnets

SESSION -Sensing and Harvesting Devices Employing Multi-Functional Materials — Room Mantova
Chair: **Daniele Davino**, University of Sannio (Italy)

17:20 **Anja Waske**, BAM Berlin (Germany), INVITED
Energy harvesting of waste heat using thermomagnetic materials

17:50 **Andrea Meo**, Politecnico di Bari (Italy)
Coupled magnetic tunnel junctions arrays for sensor applications

18:05	**Proloy Taran Das**, Helmholtz-Zentrum Dresden-Rossendorf (Germany) *High resolution Flexible planar-Hall magnetic field sensors and its applications*
18:20	**Francesco Cugini**, University of Parma (Italy) *A laboratory-scale prototype of thermomagnetic generator for harvesting of waste heat*

	SESSION - Artificial Spin Ice Physics and Applications Chair: **Daniel Lacour**, CNRS – Institut Jean Lamour Nancy, (France)	Room Tirol
17:20	**Sam Ladak**, Cardiff University (United Kingdom), INVITED *3D Artificial spin-ice*	
17:50	**Clodoaldo Irineu Levartoski de Araujo**, Universidade Federal de Viçosa (Brazil) *Strategies for degeneracy and monopole mobility in two-dimensional artificial spin ices*	
18:05	**Will Branford**, Imperial College London (United Kingdom) *Spatially ultra-selective all-optical magnetic switching and vortex writing in nanomagnets*	
18:20	**Pietro Tierno**, University of Barcelona (Spain), INVITED *Topological boundaries and geometric constraints in artificial colloidal ice*	

TUESDAY, FEBRUARY 11th, 2025

	SESSION - Opportunities and Challenges in Spintronics Technology Chair: **Giovanni Finocchio**, University of Messina (Italy)	Room Prishna
08:45	**Emilie Jué**, NIST (USA), INVITED *Superconducting artificial synapses integrated into a self-training neuromorphic architecture*	
09:15	**Federico Fagiani**, Politecnico di Milano (Italy) *Tuning of ferroelectric Rashba semiconductors via alloying for energy-efficient computing devices*	
09:30	**Hans Nembach**, NIST (USA), INVITED *Heisenberg exchange in magnetic thin films*	

	SESSION - Spin-Orbit Torque and Spin-Currents Chair: **Can Onur Avci**, Institute of Materials Science of Barcelona (Spain)	Room Regensburg
08:45	**Pietro Gambardella**, ETH Zurich (Switzerland), INVITED *Spin or orbital? Torques for efficient manipulation of the magnetization*	
09:15	**Ivan Miranda De Paula**, Linnaeus University (Sweden) *Optimal magnetization switching via spin-orbit torque in ferromagnet/topological insulator heterostructures*	
09:30	**Witold Skowronski**, AGH University of Krakow (Poland) *Spin-orbit-torque switching in α-W-based magnetic tunnel junction*	
09:45	**Paolo Perna**, IMDEA Nanoscience (Spain) *Interfaces with Graphene: an amazing playground for SpinOrbitronics*	

	SESSION - Artificial Intelligence, Machine Learning and Soft-Computing for Magnetism Chair: **Antonio Laudani**, University of Catania (Italy)	Room Mantova
08:45	**Nikita Kulesh**, National Institute for Materials Science (Japan), INVITED *Realistic micromagnetic modelling of Nd-Fe-B permanent magnets based on FIB-SEM tomographye*	
09:15	**Sebastian Schaffer**, University of Vienna (Austria) *Constraint Free Physics-Informed Machine Learning for Micromagnetic Energy Minimization*	
09:30	**Alena Vishina**, Uppsala University (Sweden) *Data-Mining Search for Rare-Earth-Free Permanent Magnets Among Predicted Crystal Structures*	
09:45	**Esteban Garzón**, University of Calabria (Italy) *STT-MRAM technology for energy-efficient 2-D and 3-D associative in-data processing architectures*	

	SESSION -Additive Manifacturing of Magnetic Materials Chair: **Paola Tiberto**, INRiM Torino (Italy)	Room Tirol
08:45	**Antonio Faba**, University of Perugia (Italy) *Additively manufactured components for passive stabilization of microsatellites*	
09:00	**Daniel Salazar Jaramillo**, BCMaterials (Spain), INVITED *Additive manufacturing of magnetic shape memory alloys for solid-state refrigeration*	
09:30	**Victorino Franco**, University of Seville (Spain) *The role of the polymer matrix on the manufacturability and properties of soft magnetic filaments for additive manufacturing*	

	PLENARY - Chair: **Sebastiaan van Dijken**, Aalto University (Finland)	Room Prishna
10:00	**Philipp Pirro**, RPTU Kaiserslautern-Landau (Germany), INVITED *Magnonic technologies: from linear delay lines for RF signal processing to nonlinear magnonic neurons*	

10:45	Coffee break	Foyer I

	SESSION - Spin Waves and Magnonics Chair: **Giovanni Carlotti**, University of Perugia (Italy)	Room Prishna
11:05	**Katrin Schultheiss**, Helmholtz-Zentrum Dresden-Rossendorf (Germany) *Floquet magnons in a periodically-driven magnetic vortex*	
11:20	**Felipe Brevis**, Universidad Técnica Federico Santa María (Chile) *The toroidal moment in nanomagnets and its connection with nonreciprocal magnonics*	
11:35	**Rafael Lopes Seeger**, Université Paris-Saclay, CNRS (France) *Vortex gyrotropic mode excited by surface acoustic waves*	
11:50	**Gabriel Soares**, SPEC CEA Paris-Saclay (France) *Mutual nonlinear interactions between parametrically excited spin-wave modes in a YIG microdisk*	
12:05	**Sali Salama**, University Paris Saclay (France) *Nonlinear spin waves processes in a 500nm Bismuth Yttrium Iron Garnet disk*	
12:20	**Davide Bossini**, Konstanz University (Germany), INVITED *Dynamical renormalization of the magnon spectrum via nonlinear coherent spin dynamics*	

	SESSION - Curvilinear and 3D Magnetism Chair: **Claire Donnelly**, Max Planck Inst. for Chemical Physics of Solids Dresden (Germany)	Room Regensburg
11:05	**Rafal Dunin-Borkowski**, Forschungszentrum Jülich GmbH (Germany), INVITED *Progress and challenges in the measurement of three-dimensional magnetization textures using transmission electron microscopy*	
11:35	**Aurelio Hierro-Rodriguez**, Universidad de Oviedo (Spain), INVITED *Controlling Bloch point singularities in magnetic systems*	
12:05	**Olha Bezsmertna**, Helmholtz-Zentrum Dresden-Rossendorf (Germany) *Magnetic solitons in hierarchical 3D magnetic nanoflower shaped architectures*	
12:20	**Tim. A. Butcher**, Max-Born-Institut (Germany) *Three-dimensional magnetic imaging with soft X-ray ptychographic laminography*	
12:35	**Claas Abert**, University of Vienna (Austria) *Energy Landscape and Pinning Fields of Bloch-Point Domain Walls in Curved Nanowires*	
12:50	**Filipp Rybakov**,Uppsala University (Sweden) *Topological magnetic textures with extreme combinatorial diversity*	

	SESSION - Magnetic Materials for Energy Applications Chair: **Giovanni Maria Vinai**, CNR - IOM Trieste (Italy)	Room Mantova
11:05	**Nada Petelin**, University of Ljubljana (Slovenia) *Oscillating Gadolinium Thermal Switch for Efficient Heat Flow Management*	
11:20	**Urban Tomc**, University of Ljubljana (Slovenia) *Cool BatMan project: Digital Microfluidic Magnetocaloric Cooling*	
11:35	**Morgan Almanza**, Université Paris-Saclay-CNRS (France) *A thin and light Gd-based thermomagnetic generator*	
11:50	**Matteo Casadei**, University of Bologna (Italy) *Fe2P-based hard magnetic materials for permanent magnets applications*	
12:05	**Emir Poskovic**, Politecnico di Torino (Italy) *Soft Magnetic Composite materials based on thermal resistant boron nitride layer*	
12:20	**Luis M. Moreno-Ramírez**, Universidad de Sevilla (Spain) *Magnetocaloric effect by micromagnetic simulations based on the Landau–Lifshitz–Bloch equation*	
12:35	**Zhongxia Duan**, Chinese Academy of Sciences, Beijing (China) *Preparation and characterization of MnxZn1-xFe2O4 nanofibers via a water-assisted solvothermal method*	

	SESSION - Antiferro- and Ferri-magnetic Spintronics Chair: **Sarah Mantion**, Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay (France)	Room Tirol
11:05	**Ilaria Bergenti**, CNR ISMN Bologna (Italy), INVITED *Spin dynamics in an exchange biased heterostructure coupled with a C60 molecular layer*	
11:35	**Maksim Koliushenkov** *On the Einstein–de Haas effect in van der Waals microelectromechanical systems*	
11:50	**Francesco Offi**, Università degli Studi Roma Tre (Italy) *Structural, electronic and magnetic properties of Fe3O4/MgCr2O4/Fe3O4 trilayers*	
12:05	**Paulina Prusik**, Helmholtz-Zentrum Dresden-Rossendorf (Germany) *Domain wall properties, surface states and spin-flop transition in Cr2O3*	
12:20	**Yuma Sato**, Tohoku University (Japan) *Thermal stability of epitaxial and polycrystalline Mn3Sn nanoscale single dots*	
12:35	**Huiwen Wang**, Beihang University (China) *Field-like Torque Driven Switching in Rare-earth Transition-metal Alloys*	

13:05	**POSTER II and LUNCH** Chairs: **Simone Finizio**, Paul Scherrer Institut (Switzerland), **Esteban Garzon**, University of Calabria (Italy), **Qiuji Yi**, Northumbria University (UK)	Foyer I and II

	SESSION - Antiferro- and Ferri-magnetic Spintronics Chair: **Alberto Brambilla**, Politecnico di Milano (Italy)	Room Prishna
15:00	**Stephane Fusil**, Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay (France), INVITED *Tailoring spin textures in multiferroic BiFeO3*	
15:30	**Paul Lehmann**, University of Basel (Switzerland) *Nanoscale studies of intrinsic surface magnetism and spin-texture manipulation in a magneto-electric antiferromagnet*	
15:45	**Anna Kozioł-Rachwał**, AGH Univeristy of Krakow (Poland) *Transfer of magnetic anisotropy in epitaxial Co/NiO/Fe trilayers*	
16:00	**Simone Finizio**, Paul Scherrer Institut (Switzerland) *Imaging of multiferroic coupling in freestanding bismuth ferrite films by means of soft X-ray ptychography*	
16:15	**Victor Lopez Dominguez**, Universitat Jaume I (Spain) *Electrically Controlled All-Antiferromagnetic Tunnel Junctions on Silicon with Large Room-Temperature Magnetoresistance*	
16:30	**Weronika Janus**, Institute of Materials Science of Barcelona (Spain) *Efficient two-terminal magnetoresistive reading of ferrimagnetic insulators with perpendicular magnetic anisotropy*	
16:45	**Yuqing Ge**, KTH Royal Institute of Technology (Sweden) *Magnetic phase transition in van der Waals magnet CrCl3 induced by pressure*	

	SESSION - Controlling Dzyaloshinskii-Moriya Interaction Chair: **Michaela Kuepferling**, INRiM Torino (Italy)	Room Regensburg
15:00	**Adriano Di Pietro**, INRiM Torino (Italy) *Domain wall curvature effects on the measurement of the Dzyaloshinskii-Moriya interaction strength in the creep regime*	
15:15	**Elena Vedmedenko**, University of Hamburg (Germany) *Recent progress in studies of interlayer Dzyaloshinskii-Moriya interactions*	
15:30	**Renaud Lavrijsen**, Eindhoven University of Technology (The Netherlands), INVITED *Controlling and tuning the interfacial Dzyaloshinskii-Moriya interaction: Chiral domain walls, Skyrmions and Merons*	
16:00	**Stefania Pizzini**, CNRS, Institut Néel, Grenoble (France), INVITED *Measurement of Dzyaloshinskii-Moriya interaction and its modification by magneto-ionic effects*	
16:30	**Giovanni Gandini**, Politecnico di Milano (Italy) *Ferroelectric control of the magnetic properties in the layered multiferroic Co/Hf0.5Zr0.5O2*	
16:45	**Fernando Ajejas**, IMDEA nanociencia (Spain) *Amplitude modulation and sign inversion of the Dzyaloshinskii-Moriya interaction by work function engineering in Co based metallic multilayers*	

	SESSION - Sensing and Harvesting Devices Employing Multi-Functional Materials Chair: **Simone Fabbrici**, CNR - IMEM Parma (Italy)	Room Mantova
15:00	**Darja Gacnik**, University of Ljubljana (Slovenia) *Magneto-Thermoelectrics in Cryogenic, Room, and High-Temperature Regimes: Material and Device Innovations*	
15:15	**Ana Caterina Lopes**, University of Basque Country (Spain) *Self-bias magnetoelastic resonance sensors with improved mass sensitivity performance: The effect of nanocrystallization induction by annealing*	
15:30	**Stefano Lumetti**, Silicon Austria Labs GmbH (Austria) *Tracking the 3D motion of a sub-mm magnet for tactile sensing applications: development of a hybrid platform combining a graphene-based Hall sensor with AMR sensor arrays*	
15:45	**Daniele Davino**, University of Sannio (Italy), INVITED *Piezo-resistive behaviour of magnetically controlled multifunctional polymeric composite foams*	
16:15	**Karine Chesnel**, Brigham Young University (USA), INVITED *Dynamics of magnetic fluctuation in magnetite nanoparticles probed via coherent X-rays*	

	SESSION - Magnetic Levitation and Bearings and Electrical Machine Modeling Chair: **Antonino Musolino**, University of Pisa (Italy)	Room Tirol
15:00	**Efrén Díez Jiménez**, Universidad de Alcalá (Spain), INVITED *Magnetic Bearings for Space Cryogenic Applications*	
15:30	**Hao Chen**, China University of Mining and Technology (China), INVITED *Thermal management study of switched reluctance drive motor and power converter for electric heavy-duty trucks*	
16:00	**Adam Pilat**, AGH University of Krakow (Poland) *Study on 3 pole radial Active Magnetic Bearing virtual prototype*	
16:15	**Nicolò Gori**, University of Pisa (Italy) *Design of an axial rotary transformer for wound rotor synchronous machines excitation winding feeding*	
16:30	**Claudia Simonelli**, University of Pisa (Italy) *Equivalent Network modelling of an Axial Flux Air-Core Compulsator*	

17:00	Coffee break	Foyer I

	SESSION - Opportunities and Challenges in Spintronic Technology Chair: **Davi Rodrigues**, Politecnico di Bari (Italy)	Room Prishna
17:20	**Andrew Kent**, New York University (USA), INVITED *Solving Combinatorial Optimization Problems and Generating Random Numbers with Stochastic Magnetic Tunnel Junctions*	
17:50	**Andrei Slavin**, Oakland University (USA), INVITED *Nonreciprocity of hybridized surface acoustic/spin waves in a magnetic multilayer containing layers with non-collinear magnetizations*	
18:20	**Giovanni Finocchio**, University of Messina (Italy) *Nonlinear amplification of microwave signals in spin-torque oscillators*	
18:35	**Pavel Bessarab**, Linnaeus University (Sweden) *Energy-efficient control of magnetic states*	

	SESSION - Controlling Dzyaloshinskii-Moriya Interaction Chair: **Marco Madami**, University of Perugia (Italy)	Room Regensburg
17:20	**Sam Holt**, Max Planck Institute for the Structure and Dynamics of Matter Hamburg (Germany) *Computational studies of novel Dzyaloshinsky-Moriya interactions*	
17:35	**Piotr Kuswik**, Institute of Molecular Physics, Polish Academy of Sciences (Poland) *Tailoring magnetic anisotropy and Dzyaloshinskii-Moriya interaction in a ferromagnetic layer by contact with antiferromagnetic NiO*	
17:50	**Giovanni Carlotti**, University of Perugia (Italy), INVITED *Measuring the Dzyaloshinskii-Moriya interaction and the METROSPIN project*	
18:20	**Christopher Marrows**, University of Leeds (UK), INVITED *Spin textures in synthetic antiferromagnetic multilayers*	

	SESSION - Non-Destructive Testing Chair: **Stefano Laureti**, University of Calabria (Italy)	Room Mantova
17:20	**Marco Ricci**, University of Calabria (Italy), INVITED *Ultrasonic nondestructive evaluation of lithium-ion cells*	
17:50	**Robert Hughes**, University of Bristol (UK), INVITED *Modes and Fields in Multimodal Resonant Inductor Arrays*	
18:20	**Szymon Gontarz**, Warsaw University of Technology (Poland) *Analysis of magnetic-mechanical symptoms occurring near the plastic area in order to estimate material effort*	

20:00	Social Dinner - "Brix01" Bressanone

WEDNESDAY, FEBRUARY 12th, 2025

SESSION - Skyrmions and Magnetic Textures — Room Prishna
Chair: **Christina Psaroudaki**, Ecole Normale Supérieure in Paris (France)

08:45 **Olivier Boulle**, SPINTEC Grenoble (France), INVITED
Manipulation of magnetic skyrmions for memory and logic applications

09:15 **Matteo Panzeri**, Politecnico di Milano (Italy)
Magnetic nanopatterning of skyrmion lattices via direct laser writing

09:30 **Riccardo Tomasello**, Politecnico di Bari (Italy)
Topological spin-torque diode effect in skyrmion-based magnetic tunnel junctions

09:45 **Xianggang Qiu**, Institute of Physics, Chinese Academy of Sciences (China)
Visualization of skyrmion-superconducting vortex pairs in a chiral magnet-superconductor heterostructure

SESSION - Magnetic Nanoparticles and Biomedical Applications — Room Regensburg
Chair: **Marco Coïsson**, INRiM Torino (Italy)

08:45 **Franca Albertini**, CNR - IMEM Parma (Italy)
Magnetic Shape-Memory Heuslers Turn to Bio

09:00 **Òscar Iglesias**, Universitat de Barcelona (Spain)
Understanding magnetic hyperthermia performance within the Brezovich criterion: beyond the uniaxial anisotropy description

09:15 **Makis Angelakeris**, Aristotle University Thessaloniki (Greece)
Magnetic nanoparticle formulations for early diagnosis of Alzheimer's disease

09:30 **Oliviero Gobbo**, Trinity College Dublin (Ireland), INVITED
Magnetic nanoparticles and magneto-mechanical effects: A novel approach to preventing adiposopathy

SESSION - Magnetic Wireless Power Transfer: Innovations in Materials, Control Algorithms and Modelling — Room Mantova
Chair: **Fabio Corti**, University of Firenze (Italy)

08:45 **Vittorio Bertolini**, University of Perugia (Italy)
Robust Component Optimization for Multi-Transmitter Wireless Power Transfer Systems

09:00 **Nupur Ninad Khatu**, Ca' Foscari University of Venice (Italy)
Transient grating investigation of magneto-elastic coupling dynamics in Co78TbxGd22-x thin films

09:15 **Alicia Triviño Cabrera**, University of Málaga (Spain)
Parasitic capacitance effects in wireless chargers for underwater vehicles

09:30 **Alberto Delgado**, Universidad Politécnica de Madrid (Spain), INVITED
Design of Inductive link for battery charging for future space rover and drones

PLENARY - Chair: **Franca Albertini**, CNR - IMEM Parma (Italy) — Room Prishna

10:00 **Nora Dempsey**, Institut Néel CNRS (France), INVITED
Thin film combinatorial studies of hard magnetic materials

10:45 Coffee break — Foyer I

SESSION - Artificial Intelligence, Machine Learning and Soft Computing for Magnetism — Room Prishna
Chair: **Alexander Kovacs**, University for Continuing Education Krems (Austria)

11:05 **Stefano Sanvito**, Trinity College Dublin (Ireland), INVITED
The AI toolbox for magnetic materials discovery and design

11:35 **Marco Coïsson**, INRiM Torino (Italy)
Magnetic Particles Imaging: solving the inverse problem with machine learning approaches

11:50 **Swapneel Amit Pathak**, Max Planck Institute for the Structure and Dynamics of Matter Hamburg (Germany)
Clustering magnetisation vector-fields using unsupervised machine learning

12:05 **Stefan Pollok**, Technical University of Denmark (Denmark)
Breaking the O(M×N) scaling in magnetostatic calculations with symmetry-respecting hypernetworks

12:20 **Anna Delin**, KTH Royal Institute of Technology (Sweden)
Magnetism and spin dynamics in low-dimensional materials

SESSION - Curvilinear and 3D Magnetism — Room Regensburg
Chair: **Gaspare Varvaro**, CNR - ISM Roma (Italy)

11:05 **Mathias Augustin**, KTH Royal Institute of Technology (Sweden)
Estimation of exchange parameters in system deformed by a strain-gradient

11:20 **I. Pamela Morales Fernández**, MPI for Chemical Physics of Solids Dresden (Germany), TU Vienna (Austria)
Oscillatory dynamics of strongly coupled magnetic domain walls in three-dimensional chiral nanostructures

11:35 **Gianluca Gubbiotti**, CNR - IOM Perugia (Italy), INVITED
Spin-Wave Edge and Cavity Modes in a Moiré Magnonic Crystals

12:05 **Olena Gomonay**, Johannes Gutenberg University Mainz (Germany), INVITED
Nonchiral topologically protected antiferro-(alter)-magnetic textures stabilized by magnetoelastic interactions

12:35 **Francisco Meda**, INESC Lisboa (Portugal)
Robustness of magnetic skin upon touch assessed with TMR-based magnetic tactile sensors

SESSION - Magnetic Materials for Energy Applications & Additive Manifacturing of Magnetic Materials — Room Mantova
Chair: **Victorino Franco**, University of Seville (Spain)

11:05 **Radel Gimaev**, University of Ljubljana (Slovenia)
Materials for the thermomagnetic energy harvesting technology devices

11:20 **M. Nur Hasan**, Uppsala University (Sweden)
Tuning Magnetic Anisotropy in Fe3Y: An Ab-Initio High-Throughput Study with Transition Metal Doping

11:35 **Franziska Scheibel**, Technical University of Darmstadt (Germany), INVITED
Additive Manufacturing of magneto- and multicaloric materials – from single particle to processed part

12:05 **Ekkes Brück**, TU Delft (The Netherlands), INVITED
Materials for efficient conversion of low temperature waste heat

12:35 **Norbert Löwa**, Physikalisch-Technische Bundesanstalt Berlin (Germany)
Novel system for ultrasound-assisted mixing of photopolymers with nanoparticles for additive manufacturing of magnetic materials

12:50 Closing - Acknowledgements and Awards — Room Prishna
Vito Puliafito and **Silvia Tacchi**, General Chairs of AIM2025

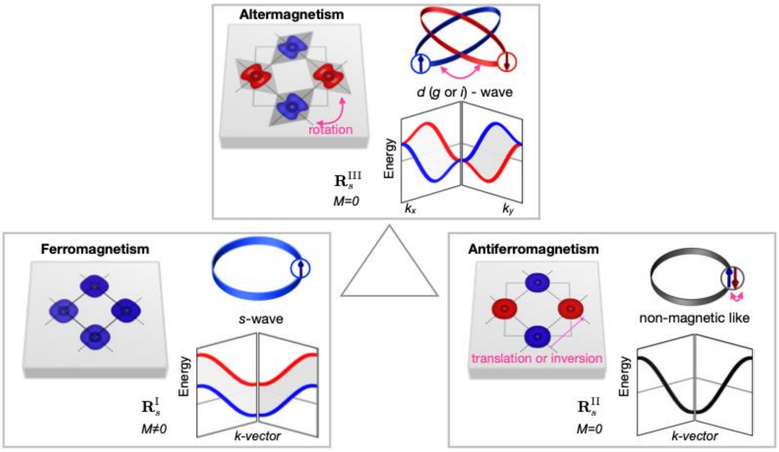
Plenary Talks

Unconventional magnetism in spintronics: the emergence of altermagnetism and its new variants

Jairo Sinova

Johannes Gutenberg University Mainz, Germany

Antiferromagnetic spintronics has been a very active research area of condensed matter in recent years. As we have learned how to manipulate collinear antiferromagnets actively and their emergent topology by means of new types of spin-orbit torques, a key problem remained: the inefficiency of relativistic mechanism. The necessity of relativistic effects to manipulate and detect Néel order arises from the spin degeneracy of collinear antiferromagnets in the non-relativistic limit – or at least it was thought. The discovery of d-wave magnetic order in momentum space motivated a closer look at the symmetry classification of collinear magnetic systems. This has emerged as the third basic collinear magnetic ordered phase of altermagnetism, which goes beyond ferromagnets and antiferromagnets. Altermagnets exhibit an unconventional spin-polarized d/g/i-wave band structure in reciprocal space, originating from the local sublattice anisotropies in direct space. This gives properties unique to altermagnets (e.g., the spin-splitter effect), while also having ferromagnetic (e.g., polarized currents) and antiferromagnetic (e.g., THz spin dynamics and zero net magnetization) characteristics useful for spintronics device functionalities. I will cover the basic introductory view to altermagnetism and its consequences to spintronics as well as new emerging exchange driven phenomena akin to spin-orbit coupling effects, such as p-wave magnetism, emerging from the basic concepts that gave rise to the discovery of altermagnetism.



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[1] Libor Šmejkal, Jairo Sinova and Tomas Jungwirth, Phys. Rev. X **12**, 031042 (2022)
[2] Libor Šmejkal, Jairo Sinova and Tomas Jungwirth, Phys. Rev. X **12**, 040501 (2022)
[3] Zexin Feng, et al, Nature electronics **5**, 735-743 (2022)
[5] Libor Šmejkal, et al, Phys. Rev. X **12**, 011028 (2022)
[6] Rafael González-Hernández, et al, Phys. Rev. Lett. 126, 127701 (2021)
[7] Libor Šmejkal, Rafael González-Hernández, T. Jungwirth and J. Sinova, Sci. Adv. 6, 23 (2020)

Spin-based non-volatile memories, unconventional computing, and energy harvesting

Hyunsoo Yang, Raghav Sharma, Fei Wang, Qu Yang, Yakun Liu

National University of Singapore, Singapore

Spin-based magnetic random-access memory is emerging as a key enabling low-power technologies, which have already spread over markets from embedded memories to the Internet of Things. In addition, spin devices can offer alternative solutions for unconventional computing and energy harvesting. We present an experimental Ising computer based on magnetic tunnel junctions, which successfully solves a 70-city travelling salesman problem (4761-node Ising problem) [1]. We also propose a spintronic artificial neuron based on the heavy metal (HM)/ferromagnet (FM)/antiferromagnet (AFM) [2], which can reset itself due to the exchange bias. Using our proposed neuron, we further implement a restricted Boltzmann machine (RBM) and stochastic integration multilayer perceptron (SI-MLP). By integrating the electrically connected eight spin-torque oscillators (STOs), we demonstrate the battery-free energy-harvesting system by utilizing the wireless RF energy to power electronic devices such as LEDs [3,4].

We present our perspective on spin device applications using emerging materials [6]. Previous proposals for spin-orbit torque (SOT) switching of perpendicular magnetic anisotropy (PMA) require an additional magnetic field or complex structures. Exploiting the out-of-plane spins could be a solution to this challenge [6]. Here we experimentally demonstrate field-free switching of PMA CoFeB at room temperature utilizing out-of-plane spins from $TaIrTe_4$ [7] and $PtTe_2/WTe_2$ [8]. Finally, we discuss magnon-mediated spin torques, which could minimize Joule heating and corresponding energy dissipation [9]. We demonstrate magnon current-driven switching of PMA at room temperature and field-free operation [10].

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Magnonic technologies: from linear delay lines for RF signal processing to nonlinear magnonic neurons

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Coherent spin waves [1] are ideal candidates both for radio-frequency (RF) signal processing and wave-based computing [2] since they offer properties like scalability, reconfigurability via magnetic fields and controllable nonlinear effects. I will give an overview of the concepts and progress of magnonic technology and discuss the various challenges associated with the respective applications using delay lines and magnonic neurons as example.

For RF signal processing, magnon technology offers components like, e.g., filters, time delay units and limiters which are based on magnonic delay lines. Fig. 1a shows a schematic of such a magnonic delay line including the different loss channels. One main challenge is to reduce these losses and to efficiently make use of the tunablity of their working frequencies via magnetic fields. Fig. 1b schematically shows how tunablity can be achieved with low power consumption by using voltage-driven MEMS instead of charge current based methods.

For wave-based computing, nonlinear magnonic effects play an essential role since they are at the core of logic functionalities. I will discuss nonlinear effects that have been used to construct logic elements like the nonlinear shift of the magnon wave vector, foldover effects and magnonic bistabilitites [3], enabling the creation of logic gates and magnonic repeaters [4]. By making magnonic pulses interact, magnonic neuron networks with leaky integrate-and-fire functionalities (Fig 1c)-e)) can be created. Due to the inherent amplification of the signals inside the neurons, this concept can be scaled to large networks of interacting neurons.

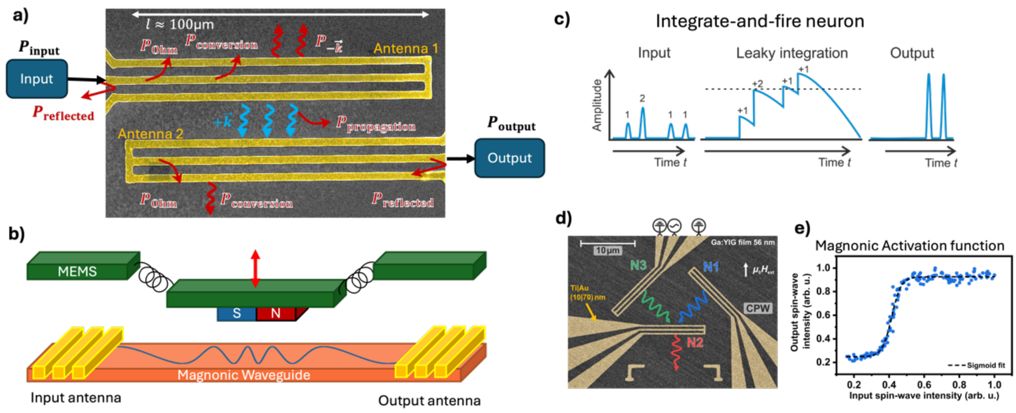

Figure 1 (a) Magnonic delay line and its different loss channels. (b) Sketch of a tunable delay line based on magnets moved by MEMS. Magnonic leaky integrate-and-fire neuron: (c) concept, (d) realization and (e) magnonic activation function

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Thin film combinatorial studies of hard magnetic materials

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Combinatorial studies based on the preparation and characterisation of compositionally graded thin films are being used for the screening and optimization of a range of functional materials [1]. When combined with Machine Learning (ML), such high-throughput film-based studies hold much potential to guide data driven design of new materials [2,3]. In this talk I will present our thin film combinatorial studies of hard magnetic materials. By way of introduction to the high throughput fabrication and characterisation techniques we use, I will begin by presenting a study of compositionally graded Fe-Pt films [4]. I will then present on-going studies of the effect of element substitution and annealing conditions on both structural and magnetic properties of compositionally graded films based on different high anisotropy Rare Earth - Transition Metal phases. I will finish up by briefly outlining the potential of combining high throughput experimentation and ML-driven data analysis for the accelerated development of high-performance magnets with reduced dependence on critical elements [5].

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Additive Manifacturing of Magnetic Materials

Invited

Advances and Challenges in Additive Manufacturing of Permanent Magnets

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This presentation will explore the advances and challenges in the additive manufacturing of both sintered and bonded permanent magnets. It aims to highlight the opportunities for further advancements in the field. Additionally, the presentation will provide insights into how additive manufacturing can uniquely address the material criticality issues associated with rare earth permanent magnets.

The importance of permanent magnets in advancing the clean energy revolution is widely recognized, and they have even been incorporated into the economic plans of several nations. For instance, the United States' Bipartisan Infrastructure Law includes the development of a domestic market for neodymium-based magnets [1]. This focus on permanent magnets arises from their extensive use in consumer, industrial, and national defence applications. However, many countries heavily rely on vulnerable supply chains for rare earth elements, which is concerning given the projected demand for Nd-Fe-B magnets in future applications [2].

To address the criticality of permanent magnet materials, three key principles are applied: source diversification, substitute (alternatives) development, and reuse/remanufacturing/ elemental recovery. Additive manufacturing is one approach to developing substitutes, offering the potential to produce permanent magnets with less waste and fewer critical rare earth elements [3]. Significant global efforts, especially in the USA and Europe, have been made towards the additive manufacturing of both sintered and bonded permanent magnets. Researchers have explored various additive manufacturing processes, including binder jetting, directed energy deposition, extrusion, powder bed fusion, and cold spray methods. Each method presents unique processing challenges that must be addressed to produce magnets comparable to commercially available products. These challenges primarily involve achieving the microstructure and texture necessary for good coercivity, remanence, and demagnetization behavior, all of which contribute to the energy density of the magnets [4].

This presentation will review the advances in the additive manufacturing of both sintered and bonded permanent magnets. It will cover the progress made in overcoming microstructural changes during additive manufacturing and their impacts on the coercivity of the finished magnets. Additionally, it will discuss advancements towards achieving a high degree of alignment, which affects both remanence and squareness of the demagnetization plot. The talk will highlight opportunities for further advancing the field of additive manufacturing of permanent magnets.

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Invited

Additive manufacturing of magnetic shape memory alloys for solid-state refrigeration

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Addressing current societal challenges demands the advancement of innovative, environmentally sustainable technologies and the capability to manufacture complex 3D structures in an economically viable manner. Recent progress in caloric materials, specifically magneto- and elasto-caloric compounds, offers promising avenues for additive manufacturing and positions these materials as key components in the development of next-generation energy-efficient devices. Metamagnetic shape memory alloys have emerged as prime candidates for magnetic refrigeration, attributable to their high magnetic entropy change through the first-order martensitic transformation. Nevertheless, it is critical to acknowledge that their crystalline phase stability diminishes at elevated temperatures exceeding 300 ºC

In this work, we formulated original inks and pastes tailored for cold extrusion printing techniques, enabling the fabrication of intricate 3D structures using high-performance NiMnSn-based magnetocaloric powders. A sustainable matrix composed of hydroxypropyl cellulose and deionized water as a solvent was used. The ink, comprising over 95 wt.% of powder, was carefully optimized to attain ideal viscosity, resulting in the capability to deposit a maximum of 250 layers with the utmost printing resolution (0.5mm wall thickness). The proposed post-processing for the printed structures involves two main steps: (i) specific thermal treatments for densification of the printed structures, eliminating the polymer via calcination, succeeded by sintering to achieve an all-metal structure, and (ii) nickel electrodeposition to protect the printed structure against corrosion. Furthermore, we demonstrate that the magnetocaloric performance of the printed samples is comparable to that of bulk materials prior to processing.

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Invited

Additive Manufacturing of magneto- and multicaloric materials – from single particle to processed part

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Additive manufacturing (AM) transforms the development and application of magnetic materials by providing unprecedented control over geometric and microstructural design, which is critical for optimizing magnetic and functional properties. Magneto- and multicaloric materials like Gd and Ni-Mn-based Heusler alloys are potential materials for alternative eco-friendly refrigeration applications [1]. However, their use for application is often limited by their brittleness and the challenges in shaping and scaling. AM solves these problems by allowing the creation of complex structures that optimize thermal exchange and magnetic responsiveness, overcoming significant challenges in developing high-performance magneto- and multicaloric regenerators. Furthermore, layer-wise processing and directional growth methods, such as laser powder bed fusion (PBF-LB) and direct energy deposition (DED), facilitate the development of textured or columnar grain structures, which significantly enhance the mechanical stability of Ni-Mn-based Heusler alloys. Powder-based AM methods are scalable, which makes them ideal for large-scale applications.

This work demonstrates the ability to tailor functional properties from single particles to fully processed components through precise microstructure and intricate geometric structure design by integrating a range of AM and other powder-based processing techniques, including PBF-LB, DED, spark plasma sintering (SPS), and hot compaction [2,3].

Our findings prove that particle size is the key factor controlling the thermal hysteresis and characteristics of the first-order magnetostructural transition (FOMST) in Ni-Mn-Sn [2]. Using these particles as foundational building blocks in powder-based processes, we can precisely control FOMST characteristics and functional properties through strategic adjustments in processing techniques, process parameters, and particle size distribution. Microstructural design by DED, PBF-LB or SPS will significantly improve the mechanical and cyclic stability of brittle Heusler alloys compared to conventional casting techniques [3].

The work is funded by ERC (Adv. Grant "CoolInnov"), the Deutsche Forschungsgemeinschaft (DFG) CRC/TRR 270 "HoMMage" and 52721505, and LOEWE 3 Project „OptiKal“.

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Additively manufactured components for passive stabilization of microsatellites

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The stabilisation of microsatellites and smaller classes of satellites in orbit can be achieved using a passive magnetic attitude control system. This generally consists of permanent magnets and ferromagnetic bars, designed with specific shapes and sizes to optimise system performance. Many papers present numerical computations and experiments to demonstrates the attitude and performances of different setups. Different kind of alloys and different geometries of that passive elements are compared and discussed [1-2]. Starting from the study and the analysis of this literature, we propose here a different technology to product those passive components, the additive manufacturing. In particular, we present a computational tool to simulate the magnetic behaviour of the elements, when they are rotating in the earth magnetic field at certain altitude, in order to compute the energy dissipation. The computational scheme involves hysteresis phenomena, the eddy currents distribution and the demagnetizing effect. The electric and magnetic properties are identified using samples made by a laser powder bed fusion process. This technology seems to be very promising for the indicated scope due to the capability in the realization of complex geometry and the use of different alloy compositions. Moreover, one of the scope of the paper is to verify if the annealing process of the components, well recommended for other purposes, is still useful also in this application. The figure below shows a passive element with cylindrical shape simulated by a FEM scheme implemented in Comsol Multiphysics©, and using a suitable hysteresis model based on Jiles Atherton approach. The component is simulated during the rotation in the earth magnetic field.

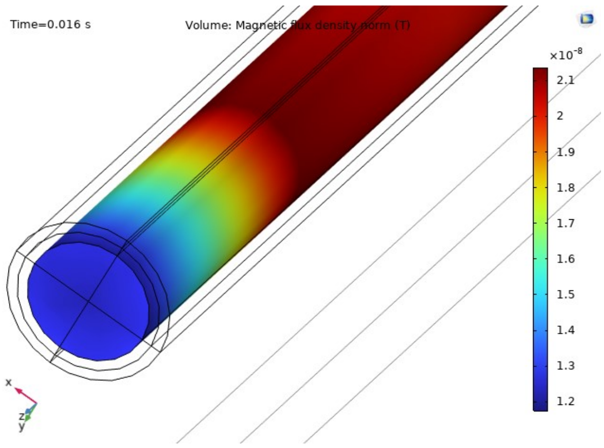

Figure 1: A part of the ferromagnetic cylinder made by additive manufacturing during the magnetization process due to the rotation in the earth magnetic field.

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The role of the polymer matrix on the manufacturability and properties of soft magnetic filaments for additive manufacturing

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Functional parts obtained by Fused Deposition Modelling (FDM) require high quality filaments to be 3D printed. In the case of magnetic functionality, the number of commercial filaments used in FDM is limited, which has led to the need of developing custom-made composite filaments. High homogeneity in the distribution of fillers and predictability of results have been achieved by our recently proposed laboratory scale procedure based on the encapsulation of magnetic fillers in printed capsules and their use as feedstock for a single-screw extruder [1].

In this work, the polymers PLA (polylactic acid), PETG (polyethylene terephthalate glycol-modified) and TPU (thermoplastic polyurethane) have been studied to proof their compatibility with a soft magnetic maraging powder (EOS Maraging). Results have shown that a lower weight percentage of EOS Maraging powder is needed to produce a continuous filament with PLA and TPU. The homogeneity and distribution of powder particles embedded in the polymer has been studied by backscattered electrons in Scanning Electron Microscopy (SEM) (**Error! Reference source not found.** (a)). From the magnetic point of view, a good correlation between nominal filler concentration and experimental magnetization values demonstrates the reproducibility of the procedure, even for different types of polymers (Figure 1 (b)). It was determined that the use of PETG provided the most homogenous and best extruded composite filament to be used in 3D printing.

To improve magnetic softness, a filament with gas atomized Finemet-type alloy powders as fillers and PETG as matrix was fabricated. Due to stress relaxation during the filament fabrication process, the coercivity of the filament is lower than that of the starting alloy powders, enhancing applicability.

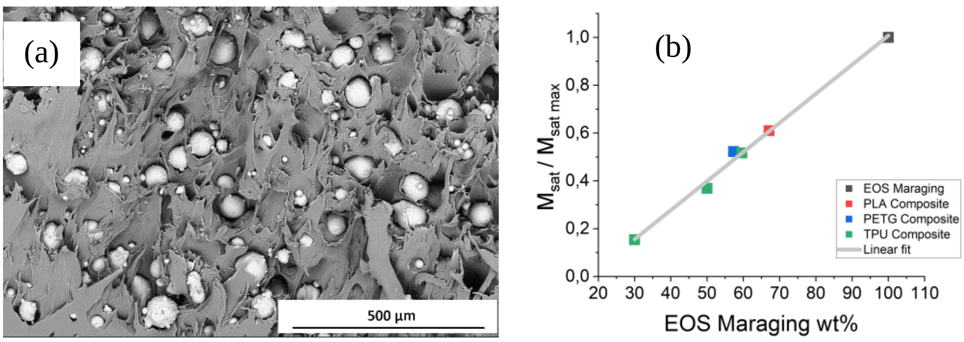

Figure 1. (a) BSE image of PETG + EOS Maraging filament, (b) Plot of the saturation magnetization versus the content of EOS Maraging powder

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Novel system for ultrasound-assisted mixing of photopolymers with nanoparticles for additive manufacturing of magnetic materials

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Additive manufacturing (AM) is characterized by a high degree of design freedom and individualization and thus, ideally suited to produce specimens for biomedical research. A fast and cost-effective AM variant for producing medical specimens is Digital Light Processing (DLP), in which the specimen is created layer by layer from light-curing photopolymer in a vat (vat photopolymerization AM). This process can be used to fabricate parts from a wide range of materials with high detail and precision. In addition, the magnetic properties of the photopolymers can be influenced by incorporating magnetic nanoparticles as an additive [1-2], that are dissolved or dispersed in small quantities into the photopolymer to induce and adjust desired material properties. To obtain medical imaging phantoms with defined concentrations of nanoparticles, we developed a special equipment to mix magnetic nanoparticles with photopolymers, disperse them and then feed them to an additive manufacturing device.

In the automated mixing and homogenization system (see fig. 1) the liquid photopolymer is pumped from a storage tank through a flow cell in which the final homogenization process, based on ultrasound mixing, takes place. The nanoparticles are inserted into the flow cell via an injection system. To ensure the required process stability, this unit is additionally equipped with appropriate monitoring devices (detectors for volume, concentration, temperature).

Figure 1: Continuous Energetic Liquid Agitation System (ConElia). Left: Mixing flow cell. Right: The completed device with mixing, pumping and monitoring parts.

We demonstrate that the implemented mixing process based on ultrasonic high-shear inline homogenization together with in-situ process monitoring and in-situ metrology ensures a defined and reproducible adjustment of the desired material composition This robust approach enables precise control of particle dispersion and homogeneity within the additively manufactured magnetic phantoms. Consequently, the phantoms exhibit defined magnetic properties, which are essential for accurate and reliable magnetic imaging applications and calibrations.

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Altermagnets

Invited

Ultrafast antiferromagnetism – terra incognita beyond the conventional approximations

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Antiferromagnets, in general, and altermagnets, in particular, represent an intriguing playground to search not only for the fastest, but also for the least dissipative mechanism of data processing and storage. Nevertheless, the lack of the net magnetization in thermodynamic equilibrium requires exceedingly high magnetic fields to control antiferromagnetic spins and thus significantly hinders not only application, but even fundamental studies of antiferromagnetism. The idea of this work is to explore how to overcome these fundamental thermodynamic obstacles by pushing antiferromagnets out-of-equilibrium and steering the spins between stable bit states along non-thermodynamic routes.

While magnetism is practically the strongest quantum mechanical phenomenon, modern description of spin dynamics relies on thermodynamics and the corresponding approximations. I will show that ultrashort (sub-100 ps) stimuli push magnetic media into a strongly non-equilibrium state, where the conventional description of magnetic phenomena in terms of equilibrium thermodynamics fail and the experimentally observed ultrafast spin dynamics challenge the current theories. For instance, while the conventionally accepted Curie-Neumann's principle states that "the symmetries of the causes are to be found in the effects" [1], in ultrafast magnetism the principle fails, spin dynamics becomes counter-intuitive and heat can cause magnetization reversal even without any magnetic fields [2].

In my talk, I will discuss recent discoveries of such counter-intuitive spin dynamics in antiferromagnets. While control of spins in antiferromagnets requires increasingly high magnetic fields, rapidly varying magnetic field at THz rates is a game-changer in the field. Picosecond pulses of THz magnetic field with the strength below 1 T can efficiently excite spins in antiferromagnets. Ultrafast stimuli push spin dynamics into nonlinear regime, where new channels of spin-spin [3] and spin-lattice interaction open-up [4,5], the principle of superposition fails, i.e. 1+1>2, [6] and the Néel vector is no longer an adequate approximation [7].

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Invited

Spin group theory of unconventional magnetism: altermagnets and beyond

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Spontaneous symmetry breaking is systematically studied using group theory across various areas of physics, such as high-energy physics, superfluidity, and superconductivity. In this talk, we will demonstrate that spin groups enable the analogous systematic exploration of exchange symmetry breaking in magnetic crystals [1]. This approach has recently led to the discovery of collinear altermagnets[1] and noncollinear p-wave magnets featuring compensated even and odd-partial-wave spin orders[2].

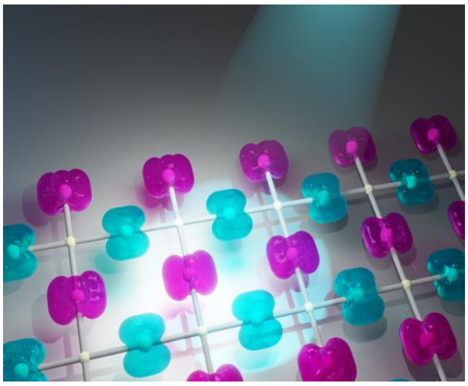

Figure 1: In altermagnets, not only the spin polarisation but also the spatial orientation of the adjacent magnetic atoms alternates. The cyan beam represents a photoemission experiment conducted at a synchrotron, which was used to demonstrate altermagnetism. First-principle calculation and visualisation by Libor Šmejkal and Anna Birk Hellenes (JGU Mainz).

In the first part of the talk, we will discuss how the prediction and observation of the unconventional anomalous Hall effect[3-5] inspired the development of a systematic spin symmetry classification for magnetic phases. In the second part, we will overview experimental confirmations of altermagnetic symmetries and effects in both reciprocal and direct space. Specifically, we will explain the band structure features described by spin group theory, which have been experimentally observed using photoemission studies in MnTe and CrSb[6-7]. Additionally, we will elaborate on how the unconventional time-reversal symmetry breaking in altermagnets was confirmed through combined XMLD-XMCD mapping of altermagnetic domains in the direct space[8]. Finally, in the last part of the talk, we will provide an overview of proposed applications of altermagnetism and spin group theory in spintronics [9], topological matter [10], multiferroics[11] and other research areas.

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Invited

Manipulation of the altermagnetic order via crystal symmetry

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Crystal symmetry guides the development of condensed matter. The unique crystal symmetry connecting magnetic sublattices not only distinguishes altermagnetism from ferromagnetism and conventional antiferromagnetism, but also enables it to combine the advantages of ferromagnetism and antiferromagnetism [1-3]. Altermagnetic order is essentially magnetic crystal order, determined by the magnetic-order (Néel) vector and crystal symmetry. Previous experimental works were concentrated on manipulating the altermagnetic symmetry by tuning the Néel vector orientations [4], but the manipulation of the crystal symmetry remains challenging, which holds great promise in opening a new paradigm of manipulating altermagnetic order.

In this talk, I will present that it is realized in altermagnetic CrSb films. The locking between Dzyaloshinskii-Moriya (DM) vector and magnetic space symmetry helps to reconstruct the altermagnetic order, from collinear Néel vector to canted one. It unprecedentedly generates room-temperature spontaneous anomalous Hall effect in a metallic altermagnet. The relative direction between the current-induced spin polarization and DM vector determines the switching modes of altermagnetic order, i.e. parallel for field-assisted mode in CrSb($1\bar{1}00$)/Pt and non-parallel for field-free mode in W/CrSb($11\bar{2}0$). The DM vector induces asymmetric energy barrier in field-assisted mode and generates asymmetric driving force in field-free mode. Particularly, the latter is guaranteed by the emerging DM torque in altermagnets [5]. Reconstructing crystal symmetry adds a new twist to the manipulation of altermagnetic order. It not only underpins the magnetic-memory and nano-oscillator technology, but also inspires crossover works between altermagnetism and other research topics.

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Wurtzite MnSe as an altermagnetic candidate

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The group of collinear magnetic materials with spin-split band structures [1-3], called altermagnets, have attracted a lot of attention recently. It is due to the combination of the features characteristic for both ferro- and antiferromagnets as well as numerous prospective applications for example very efficient spin current sourcing. With this work, we extend the array of materials available for physics of altermagnetism predicting that among Mn-based chalcogenides, not only hexagonal MnTe, but also MnSe in the wurtzite phase shows spin-splitting of the bands and compensated magnetic order [4].

Moreover, we show experimentally the possibility to grow high quality thin films of such unconventional phase of MnSe with molecular beam epitaxy (MBE). So far, it had been observed only as an unstable impurity or in the form of colloidal nanoparticles. We highlight the crucial role of the buffer layers grown on commonly used GaAs substrates.

We explore basic structural and optical properties of wurtzite MnSe. Additionally, the use of epitaxy allows us to obtain more complex structures, for example CdSe quantum wells with MnSe playing a role of a barrier. They exhibit efficient photoluminescence and energies of emission indicating the presence of internal built-in electric field. Consequently, wurtzite MnSe may be very interesting semiconductor due to the expected interplay of altermagnetism and built-in electric fields.

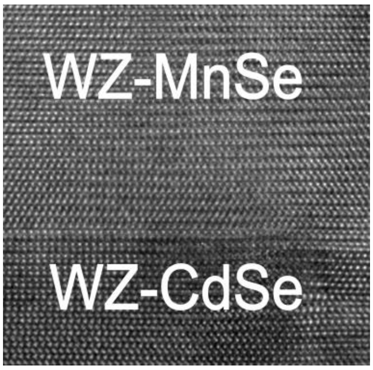

Figure: Transmission Electron Microscopy image of wurtzite MnSe thin film cross-section grown on CdSe buffer layer.

[1] L.-D. Yuan et al., Phys. Rev. B 102, 014422 (2022).

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Power efficiency of Hall-currents in NiFe, GdCo and Si_3Mn_5 altermagnet: a comparative study

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Two “Hall-like” effects are occurring in ferromagnets: the Anomalous Hall effect (AHE) and the Planar Hall effect (PHE) [1]. The former is analogous to the classical Hall effect and is defined by an antisymmetric conductivity matrix, while the latter is defined by a symmetric conductivity matrix. The difference is fundamental, as it is based on time-invariance symmetry breaking at the microscopic scale. We study theoretically and experimentaly the Hall-like current generated in both cases, together with the electric power that can be extracted from a load resistance (Fig.1 Left). The expressions of the distribution of the electric currents, the distribution of electric carriers, and the power efficiencies are derived at stationary regime from a variational method based on the second law of thermodynamics [1,2]. It is shown that the distribution of the transverse Hall-current is identical for both AHE and PHE (all other parameters being equals), and the power dissipated in a load circuit differ at the fourth order in the Hall angle Θ (Fig. right).

We have performed an experimental comparative study, based on GdCo ferrimagnet [3] and Si_3Mn_5 altermagnet [4] and NiFe 3d-ferromagnet (to be published). The difference of the dissipated power as a function of the Hall angle between AHE and PHE (as shown in the right figure below) gives an experimental criteria for the identification of the two effects in non-saturated altermagnet.

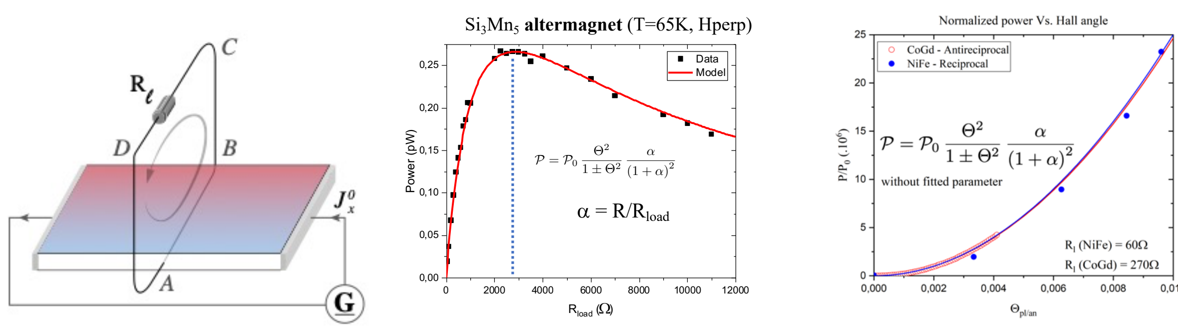

Figure 1 Left*: sketch of the Hall bar device with a load resistance.* Right*: Normalized power dissipated in the load resistance as a function of the load resistance for SiMn altermagnet and as a function of the Hall angle Θ.*

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[2] F. Faisant, M. Creff, J.-E. Wegrowe *The physical properties of the Hall current*, J. Appl. Phys. **129**, 144501 (2021)
[3] D. Lacour, M. Hehn, Min Xu, J.-E. Wegrowe, *Injection of anomalous Hall current: the role of impedance matching*, J. Appl. Phys. **135**, 193903 (2024)
[4] M. Leiviskä *et al. Anisotropy of the anomalous Hall effect in thin films of the altermagnet candidate Mn_5Si_3,* Phys. Rev. B **109**, 224430 (2024)

Antiferro- and Ferri-magnetic Spintronics

Invited

Spin dynamics in an exchange biased heterostructure coupled with a C_{60} molecular layer

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The demand for higher density and speed in magnetic information storage has sparked a significant search for alternative methods to control the magnetic moment beyond traditional magnetic fields. The stabilization of antiferromagnetic behaviour through interfacial interactions with organic molecules[1] presents a compelling opportunity to explore such interfaces as active elements for manipulating magnetic states in future information technologies.

In this work, we investigated the magnetization dynamics of an ultra thin 5nm thick Co layer exchange-coupled to an antiferromagnetic (AFM) CoO 3nm thick layer. The system was excited using a via a ultrashort laser pulses resonant with the absorption energy of a C_{60} organic layer deposited on top the AFM layer. At 80K the magnetization precession frequencies in the MHz range are higher in case of Co/CoO/C_{60} layer compared to the bare of Co/CoO, this difference diminishes with increasing temperature and eventually disappears when the temperature exceeds the AFM blocking temperature.

We calculated the additional anisotropy attributable to the presence of the molecule by measuring the difference between the anisotropy fields of the two samples. Our findings indicate that the presence of the molecule induces an additional anisotropy field of (0.17 ± 0.08) T for a pump power of 3.9 mW on the Co/CoO/C_{60} sample

[1] L. Gnoli et al., ACS Appl. Electron. Mater. **6** **(**2024), 3138–3146

Invited

Tailoring spin textures in multiferroic $BiFeO_3$

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Antiferromagnets are mainly appealing for their faster spin dynamics in the THz range. While complex topological spin textures were recently discovered in intrinsic antiferromagnets, mastering their nucleation, and manipulation is challenging as antiferromagnets are insensitive to magnetic fields. Targeting to replace the magnetic handle by an electric one, we select $BiFeO_3$ as a prototypical playground. $BiFeO_3$ is indeed the archetypal multiferroic with room temperature ferroelectric and antiferromagnetic ordering. In each ferroelectric domain, the competition between the superexchange and the magnetoelectric interactions results in the stabilization of an incommensurate cycloidal rotation of the Fe^{3+} moments. We take advantage of the magnetoelectric coupling in epitaxial thin films to deterministically control such non colinear antiferromagnetic spin textures via the ferroelectric polarisation.

The surface of bulk $BiFeO_3$ single crystals shows multiple antiferromagnetic cycloidal domains, an unexpected continuous rotation of the antiferromagnetic cycloid propagation vector, and topological defects [1]. In contrast, we observe a simpler one-to-one imprint of the ferroelectric order onto the antiferromagnetic one in epitaxial thin films. For instance, we are able to design a single antiferromagnetic domain by imposing an anisotropic strain [2]. This model system, containing both a single ferroelectric polarization variant and a single spin cycloid, opens further opportunities for investigations of the interplay between non-collinear antiferromagnetic orders and magnon excitations. In addition, when grown on an epitaxial $La_{0.7}Sr_{0.3}MnO_3$ bottom electrode, the electric-field control of the polarization seems to induce a reversible antiferromagnetic phase transition.

In self ordered ferroelectric multi-domains thin films, the magneto-crystalline anisotropy leads to a single antiferromagnetic cycloid within each ferroelectric domain, and chiral spin “bubbles” induced by the stitching of encountering cycloids can be observed at peculiar domain walls. Finally, in submicron devices, we stabilize topological centre polar states using a radial electric field. We show that such peculiar polar textures can contain flux closure of antiferromagnetic spin cycloids or quadrant of canted antiferromagnetic domains, depending on the epitaxial strain [5].

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Organic Molecular Adsorption Promotes Exchange Interactions in Antiferromagnetic Transition Metal Oxide

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In the production of spintronic devices, the use of antiferromagnetic materials shows the possibility to propagate coherent magnetic excitations, avoiding external perturbations. In these terms, the possibility to chemically tune or light-activate the properties of antiferromagnetic substrate, through the formation of an organic/inorganic interface [1, 2], seems quite promising. The work of Baldovì et al. has reported that upon molecular adsorption on the 2D CrSBr, the exchange interaction between the Cr atoms can be effectively regulated. [3]

Here, we study the interface obtained by the adsorption of C_{60} or CoTPP molecule on CoO(001) and NiO(001) surface, based on ab initio DFT+U methods [4]. We could thus understand the electronic and magnetic properties of the interfaces. Especially, by calculating the exchange coupling parameter *J* between Ni (Co) atoms, in NiO (CoO) surface before and after molecular adsorption, the changes in the spin-coupling strength in surfaces could be evaluated. Through a mapping into a simplified Heisenberg model for the magnetic interaction in the Hamiltonian, the value of *J* can be derived from a system of equations shown in the following:

$$E_k = \sum_{<i,j>} J_{i,j} S_{k,i} S_{k,j} \tag{1}$$

The calculated average value of *J* for Co-Co coupling in CoO(001) surface is -21 meV, which increases to -27 meV after C_{60} adsorption [2], and increases to -31 meV upon CoTPP molecule adsorption. As for NiO(001) surface, the calculated *J* for Ni-Ni coupling is -30 meV for clean surface, and increases to 31 meV after C_{60} adsorption and increases to -39 meV upon CoTPP adsorption. The results indicate that the molecular adsorption promotes the strength of magnetic coupling between Co (Ni) atoms and gives a greater promotion on Co-Co coupling than on Ni-Ni coupling. Our present study could give an insight into the design of magnonic based spintronic devices.

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Single-Shot Laser-Induced Switching of an Exchange Biased Antiferromagnet

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Ultrafast manipulation of magnetic order has challenged our understanding the fundamental and dynamic properties of magnetic materials. So far single shot magnetic switching has been limited to ferrimagnetic alloys and multilayers [1]. Whether a similar scenario can be observed in antiferromagnets remains unknown. In ferromagnetic (FM)/antiferromagnetic (AFM) bilayers, exchange bias arises from the interfacial exchange coupling between the two layers and results in a field shift (He) of the FM layer hysteresis loop. Exchange bias phenomena have found widespread use in fundamental scientific research and a large variety of spintronic devices, including sensors and magnetic random-access memory (MRAM) [2]. Many studies have already focused on the possibility to manipulate the exchange bias effect using thermal annealing with or without applied magnetic field and spin polarized current [3, 4]. Here we demonstrate the possibility to manipulate the exchange bias (change of the sign and amplitude of He) with a single femtosecond laser pulse in perpendicular to film plane magnetized IrMn/CoGd bilayers, as shown in Fig. 1. We have studied the influence of the laser fluence and the number of pulses for various IrMn thicknesses to determine the fastest and the most energy-efficient way to set the exchange bias field. Our results establish a method to set the exchange bias in a bilayer system that has potential application for ultrafast and energy-efficient spintronic devices.

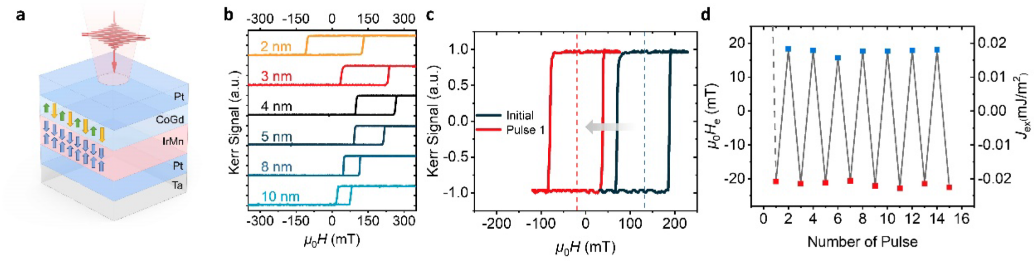

Figure 1: (a) Sketch of the IrMn/CoGd bilayer. (b) Hysteresis loops obtained on the annealed stacks for IrMn thickness from 2 to 10 nm measured by MOKE. (c) Hysteresis loop of IrMn(5)/CoGd(4) before and after exposure to a single linearly polarized laser pulse with a pulse duration of 40 fs and a fluence of 17 mJ/cm^2 (d) Modulation of the exchange bias field as a function of the number of pulses with a pulse duration of 40 fs and a laser fluence of 17 mJ/cm^2.

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On the Einstein–de Haas effect in van der Waals microelectromechanical systems

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In this paper, we consider the electro-induced gyromagnetic effect in antiferromagnetic 2D films, which is similar to the classic Einstein-de Haas effect observed in ferromagnetic materials. In antiferromagnets, a non-zero magnetic moment can be induced in the plane due to a magnetoelectric effect. An electric field reduces the symmetry of the crystal, leading to a decompensation of the antiferromagnetic sublattices and the induction of a magnetic moment. This results in a non-zero magnetization of the sample, which is proportional to the applied electric field, and a mechanical moment similar to that observed in the classical Einstein-de Haase experiment. CrI3 can serve as a model material for studying this phenomenon. [1]

In the oscillatory system shown in Fig. 1, which consists of a thin antiferromagnetic film sandwiched between two graphene electrodes, applying an electric field leads to the emergence of magnetization M and mechanical vibrations with a resonant amplitude:

$$\phi_{max} \approx \frac{3Q}{\gamma}\frac{M}{\rho\omega_0 L^2}\left(\frac{t}{d}\right)$$

Where Q is the quality factor of the system, ω_0 is the resonant frequency, ρ is the density, and γ is the gyromagnetic ratio. L, d, and t are the geometric parameters of the system. The magnetization induced by the application of an electric field is approximately 3 orders of magnitude smaller than the magnetization in ferromagnetic materials, making the effect relatively weak. However, reducing losses due to vacuum creation and using quasi-two-dimensional samples composed of multiple bilayers of antiferromagnetic material can significantly enhance the effect (as shown in Figure 2).

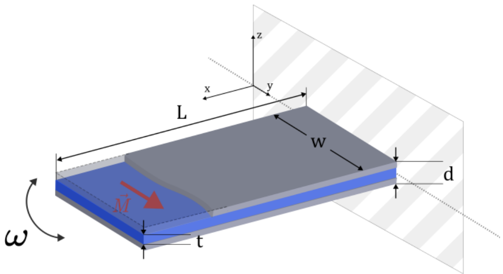

Figure 1: The geometry of the system under consideration

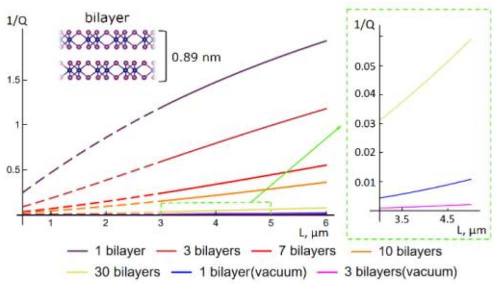

Figure 2: Dependences of losses in the system on the thickness of the sample

Calculations indicate that for a sample 10 nm thick in vacuum, an oscillation amplitude of approximately 10^{-4} radians can be achieved, exceeding the level of thermal noise and allowing for experimental observation. Thus, the geometry of vdW materials is not favorable for detecting the effect. However, when using multilayer quasi-vdW cantilever structures under resonant conditions, the effect can be large enough to be detected experimentally using an optical lever scheme commonly used in atomic force microscopy.

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Structural, electronic and magnetic properties of $Fe_3O_4/MgCr_2O_4/Fe_3O_4$ trilayers

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Fe_3O_4/Spacer/Fe_3O_4 multilayer heterostructures are distinguished by the richness of interface-induced phenomena as a function of the spacer, including thickness-dependent antiferromagnetic/ferromagnetic coupling, stabilization of thin magnetite layers, and modulation of saturation magnetization [1-3]. To date, only a few spacers (e.g., MgO, $MgFe_2$, Mn_3O_4, TiN, $PtSe_2$) have been investigated; additional phenomena can be observed using alternative materials. We have investigated the structure of all-spinel oxide $Fe_3O_4/MgCr_2O_4/Fe_3O_4$ trilayers with varying $MgCr_2O_4$ spacer thickness by combining scanning transmission electron microscopy (STEM), X-ray magnetic circular dichroism (XMCD) in X-ray absorption spectroscopy (XAS) and vibrating sample magnetometry (VSM), to investigate the occurrence of interface-induced phenomena. The isostructural characteristics and the small lattice mismatch between Fe_3O_4 and $MgCr_2O_4$ (0.7%) allow for epitaxial growth of the whole structure [Fig. 1(a)] favouring the observation of ferromagnetic properties in the thin magnetite film [Fig. 1(b,c)]. Despite the paramagnetic nature of $MgCr_2O_4$, we observe ferromagnetic behaviour of Cr ions [Fig. 1(b)]. The presence of a $Cr_xFe_{3-x}O_4$ mixed interface region is proposed to explain this behaviour.

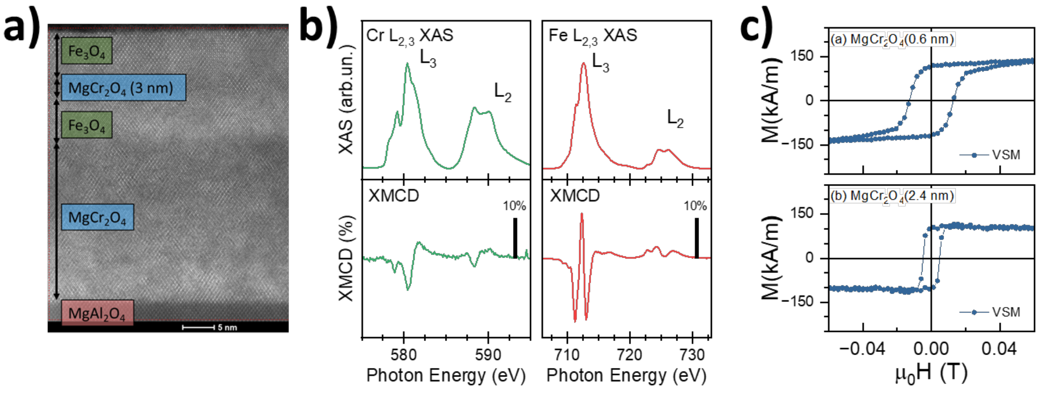

Figure 1: STEM image of one of the investigated heterostructure (a) and corresponding XAS and XMCD spectra around the Fe $L_{2,3}$ and Cr $L_{2,3}$ edges (b). (c) Hysteresis loops measured by VSM for two different $MgCr_2O_4$ spacer thicknesses.

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Domain wall properties, surface states and spin-flop transition in Cr_2O_3

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Magnetoelectric uniaxial antiferromagnet Cr_2O_3 (chromia) is a promising material for applications in spintronics [1] which exhibits rarely observed physical phenomena such as spin superfluidity or flexomagnetism [2]. Here we present a systematic study of the chromia's σ-model derived using the spin Hamiltonian for chromia. We focus on the properties of the domain walls and finite-size samples, confirming the analytical predictions with spin-lattice simulations and X-ray magnetic linear dichroism (XMLD) measurements.

While the commonly used σ-model of a bipartite antiferromagnet has a quadratic coupling between the Neel vector (antiferromagnetic order parameter) $\boldsymbol{n}$ and magnetic field $\boldsymbol{B}$, in chromia there is a linear coupling between $\boldsymbol{B}$ and the gradient of $\boldsymbol{n}$, previously predicted from the symmetry considerations [3]. We quantify this coupling in terms of spin lattice parameters including exchange integrals and interatomic distances. The resulting energy term modifies the boundary conditions for $\boldsymbol{n}$ and is responsible for the appearance of a new field-driven spin-reorientation phase.

The boundary conditions for $\boldsymbol{n}$ at a *c*-plane cut are modified by an additional term that mimics unidirectional surface anisotropy of the easy-axis type, with the axis aligned with the magnetic field. This term becomes active in the spin-flop state, leading to the near-surface tilt of $\boldsymbol{n}$ from the in-plane to the out-of-plane direction.

The domain wall (DW) lying in the basal plane of chromia possesses a finite magnetic moment $M_{\mathrm{DW}}(p, B)$ whose direction is determined by the DW polarity p. We found that in magnetic fields starting from of about 55% of the spin-flop field, the Zeeman energy associated with M_{DW} can lower the total energy below the energy of the collinear state. This is manifested as an additional field-driven phase transition preceding the spin-flop transition. While the contribution of $M_{\mathrm{DW}}(p, B)$ to the total magnetic moment of large single-crystal samples is negligibly small, it is comparable with the total moment of chromia films with a thickness below several hundredths of nanometers in the spin-flop state. This new phase in chromia effectively lowers the critical spin-reorientation field by almost a factor of two. Using XMLD measurements in thin films and single crystals of chromia in a wide range of temperatures, we show that thin-film samples possess a sizeable finite magnetization in magnetic fields about twice smaller compared to single-crystal samples, in accordance with theoretical predictions.

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Thermal stability of epitaxial and polycrystalline Mn_3Sn nanoscale single dots

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[2]International Center for Young Scientists, National Institute for Materials Science,
[3]Advanced Science Research Center, Japan Atomic Energy Agency

Antiferromagnets have attracted great interest owing to their unique properties, such as high-speed dynamics and negligible stray field [1,2]. In particular, non-collinear antiferromagnets exhibit intriguing topological phenomena [3,4]. Further, recent studies showed current-induced switching [5,6] and rotation of spin structures [7], and observed tunneling magnetoresistance [8,9] in thin-film systems. Meanwhile, the stability of the collective antiferromagnetic state against thermal fluctuation has not been studied well despite its importance as a figure of merit of the retention time as well as its crucial impact on the thermally activated probabilistic dynamics. Here, we investigate the thermal stability factor Δ in non-collinear antiferromagnetic Mn_3Sn nanodots with various sizes [10].

We prepare stacks consisting of MgO(110) sub./W(2)/Ta(3)/Mn_3Sn(20)/MgO(1.3)/Ru(1) and Si/SiO_2 sub./Ta(7)/Mn_3Sn(30)/MgO(1.3)/Ru(1) [in nm] using sputtering, having $(1\bar{1}00)$-oriented epitaxial and polycrystalline Mn_3Sn structures, respectively [10]. Stacks are processed into circular dot devices by electron beam lithography and Ar ion milling [11]. We then evaluate Δ of Mn_3Sn dot through the measurement of switching probability versus amplitude of pulse magnetic field. Figure 1 shows the dot size D dependence of the evaluated Δ with the scanning electron microscopy (SEM) image of the nanodot device. In both epitaxial and polycrystalline samples, Δ maintains similar values down to D ~ 300 nm, below which it decreases with decreasing D. At D > 300 nm, Δ values of 30-nm-thick spolycrystalline Mn_3Sn (~ 50–100) are smaller than that of 20-nm-thick epitaxial ones (~ 90–170), indicating a more thermally active nature in polycrystalline Mn_3Sn. Our result provides a basis for the design of reliable and efficient antiferromagnetic spintronics devices.

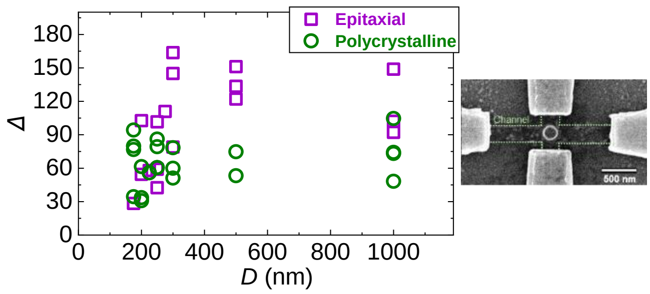

Figure 1: Δ versus D and SEM image of nanodot device.

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Field-like Torque Driven Switching in Rare-earth Transition-metal Alloys

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Spin-orbit torque (SOT) has been widely recognized and applied as the most promising approach for magnetic memory, primarily due to its lower energy consumption and longer device lifetime. However, the mechanism of SOT remains controversial in ferrimagnets, particularly regarding the role of field-like torque (FLT). This uncertainty arises from the presence of different gyromagnetic ratios of the sublattices [1], which generates significant variations particularly in the vicinity of the angular momentum compensation point [2]. We demonstrate that, near the angular momentum compensation point, FLT can act as driving term for magnetization switching through rigorous mathematical analysis and ferrimagnetic macrospin simulation, as seen on fig. 1. We also provide clear indications about the materials damping factor on how to tailor the magnetic layer where a charge current is injected. These findings shed light on the intricate behavior of SOT in ferrimagnets and pave a way for further advancements in high-performance magnetic memory devices

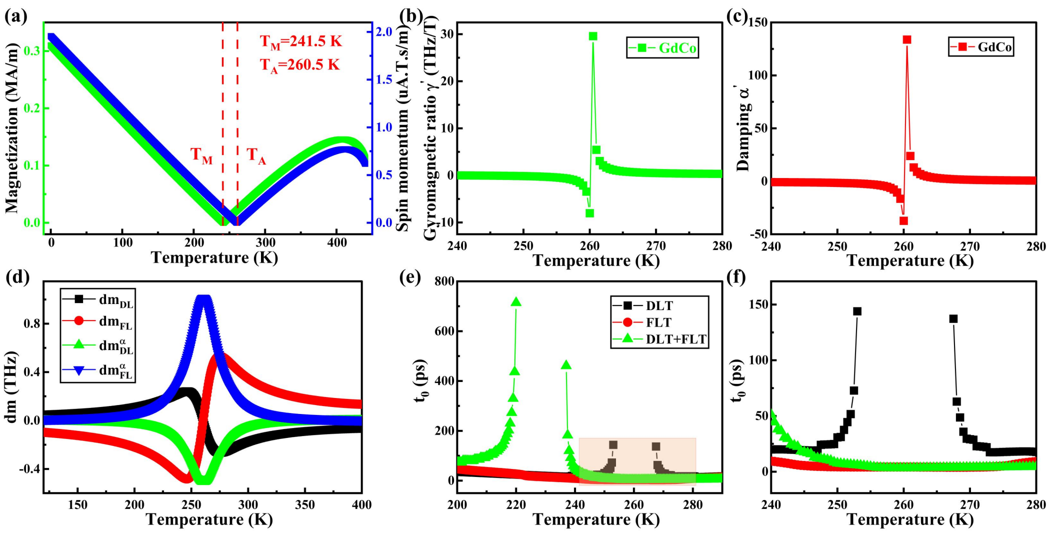

Figure 1: Magnetic properties of $Gd_{44}Co_{56}$: (a) Magnetization and spin momentum at different temperatures. (b) Modified gyromagnetic ratio γ' and (c) damping α' at different temperatures. (d) Magnitude of four SOT related terms at different temperatures. (e) Switching time $\mathbf{t_0}$ at different temperatures for three cases: (1) only considering DLT, (2) only considering FLT, and (3) considering both DLT and FLT together. (f) Partial enlarged graph of (e).

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Nanoscale studies of intrinsic surface magnetism and spin-texture manipulation in a magneto-electric antiferromagnet

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Antiferromagnets offer magnetic field hardness, high switching speeds and increased device density making them promising for future spintronic devices [1]. Hence, their manipulation and read-out properties are paramount for device operation. Magneto-electric antiferromagnets (MEAF) are particularly interesting as their ferroic order parameters can be controlled using both electric and magnetic fields and they necessarily carry a surface magnetization strictly linked to the bulk order [2,3,4].
Here we target Cr_2O_3 a ‘textbook’ uniaxial MEAF and conduct scanning nitrogen vacancy magnetometry studies to record its intrinsic surface magnetization strength and direction for several crystal facets. We compare our observations to the expected bulk order, theoretical descriptions and simplified models for the magnetization direction and magnitude for the different facets. These insights advance the fundamental understanding of the intrinsic surface magnetism in MEAFs and aid in future read-out electrode-design.
Next we characterize individual single domain walls [5], the basic elements for switching operations, that we nucleate using local electrodes. We then demonstrate control over the magnetic texture by different means, namely pinning at topographic steps or utilizing laser induced thermal gradients and in-situ applied magneto-electric pressure. Our results constitute the main ingredients for devices based on domain wall switching in magneto-electric antiferromagnets and considerations of single crystal facets.

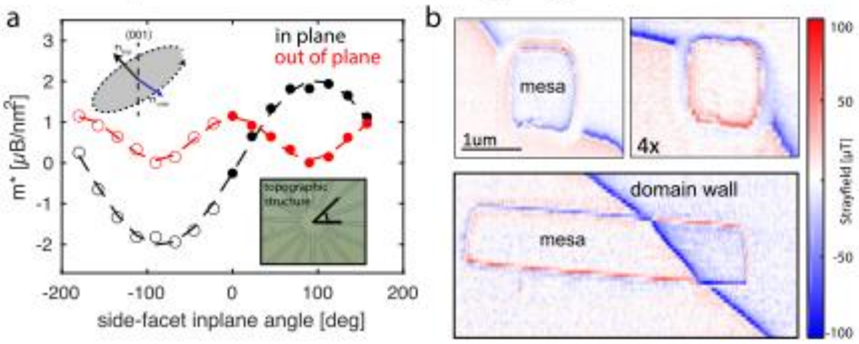

Fig.1 a) angular study of effective surface magnetization measured on topographic structures for a 104-cut single crystal of Cr_2O_3. b) top: pinning of domain walls and their controlled positioning using laser-induced thermal gradients. bottom: domain wall refraction on a larger topographic step as a

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Transfer of magnetic anisotropy in epitaxial Co/NiO/Fe trilayers

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Recently, we demonstrated that a ferromagnetic layer with strong uniaxial magnetic anisotropy dictates the spin orientation of an adjacent antiferromagnetic layer in NiO/Fe.[1] In this study, we extend this research to a trilayer structure. Using X-ray linear and circular dichroism (XMLD and XMCD), we examined the magnetic properties of an Fe/NiO(4nm)/Co(1nm) trilayer epitaxially grown on a W(110) substrate. In the Fe/W(110) system, the spontaneous magnetization direction switches from [001] to [1-10] as the Fe thickness decreases. We demonstrated that the exchange coupling at the NiO/Fe and Co/NiO interfaces, along with the well-defined and controllable magnetic anisotropy of the Fe layer, determines the magnetic properties of both the NiO and Co layers in the Co/NiO/Fe trilayer structure. XMCD and XMLD measurements of Co/NiO/Fe epitaxially grown on W(110) revealed that the thickness-driven spin reorientation transition in Fe is transferred to both the NiO and ferromagnetic Co layers (Fig. 1). We demonstrated that the magnetic anisotropy of the Co overlayer can be precisely controlled by adjusting the properties of the underlying Fe layer. Specifically, the reorientation processes in Co can be triggered by changing the Fe thickness or varying the temperature. Additionally, we showed that the strong interaction between ferromagnetic layers, mediated by an antiferromagnetic spacer, can be toggled on or off by antiferromagnetic size effects.[2]

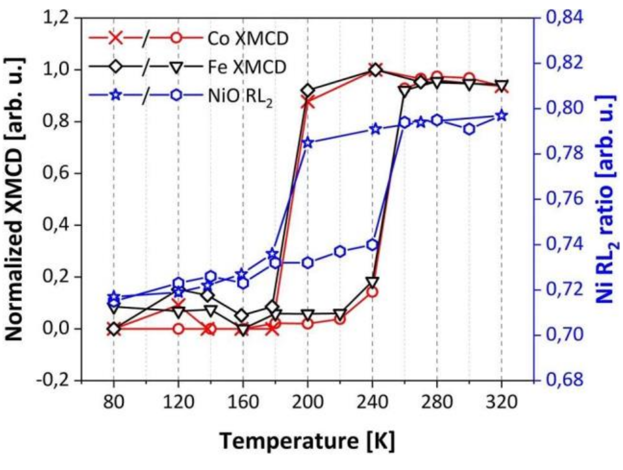

Figure 1: Temperature dependence of XMCD (black and red for Fe and Co respectively) and Ni XMLD (blue) in Co(10 Å)/NiO(40 Å)/Fe(104 Å) trilayer. Thermal hysteresis of the spin reorientation in Fe is mimicked by NiO and Co layers.

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Imaging of multiferroic coupling in freestanding bismuth ferrite films by means of soft X-ray ptychography

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Magnetic imaging using synchrotron-generated soft X-rays has been widely used for the investigation of magnetic systems, thanks to the large absorption cross sections at the L and M edges for transition metals and rare earths, respectively, combined with strong X-ray magnetic circular (XMCD) and linear (XLD) dichroism effects.

A significant number of studies have been performed utilizing scanning transmission X-ray microscopy (STXM) to acquire the images. In STXM imaging, a monochromatic X-ray beam is focused to a nanometric spot on an X-ray transparent sample by means of a diffractive optical element (Fresnel zone plate) and the intensity of the transmitted beam is recorded by means of a point detector. An image is then obtained by moving the sample with a piezoelectric stage and recording the transmitted intensity at each point of the scan. This method is however limited in spatial resolution to the spot size that can be achieved using the Fresnel zone plate, which is limited to approx. 7 nm in the current state of the art [1].

However, a spatial resolution beyond the limits imposed by the focusing optics can be achieved by ptychographic imaging, which is a technique combining STXM and coherent diffractive imaging (CDI). In ptychographic imaging, diffraction patterns from overlapping areas of the sample are recorded with a 2D detector in the far field geometry, and a high-resolution image is then reconstructed by means of a phase-retrieval algorithm, where the overlap between the different areas is used as a geometrical constraint [2].

In this presentation, we show the first results obtained using the newly commissioned SOPHIE (Soft X-ray Ptychography Highly Integrated Endstation) endstation (currently installed at the SoftiMAX beamline at the fourth generation MaxIV light source), which showcase the performances of soft X-ray ptychography for magnetic imaging and also achieved a breakthrough by directly visualizing the multiferroic coupling in freestanding bismuth ferrite (BFO) thin films at the nanoscale.

BFO is a room temperature multiferroic material exhibiting a ferroelectric order coupled with a spin cycloid. Soft X-ray ptychography at the Fe L_{3b} edge was used to successfully image both the ferroelectric domains and coupled spin cycloid state with a sub 10-nm resolution [3], visualizing the ferroelectric component by means of XLD imaging, and reconstructing the spin cycloid state from its diffraction peak under resonant scattering conditions. Direct evidence for the strong magnetoelectric coupling between the two orders was acquired, proving that soft X-ray ptychography can be used for the high-resolution imaging of multiferroic materials at the nanoscale.

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Electrically Controlled All-Antiferromagnetic Tunnel Junctions on Silicon with Large Room-Temperature Magnetoresistance

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Antiferromagnetic (AFM) materials have gained significant attention due to their potential to implement devices with improved scalability (their zero-net magnetization prevents cross-talking between adjacent devices) and speed (AFM dynamics occurs at the picosecond range). Research on AFMs has been focused on manipulating the AFM order parameter, known as Néel vector, either through directly applied electrical currents exploiting their intrinsic alternate local spin accumulation properties, as observed in materials like CuMnAs [1]; or by the use of extrinsic Spin Orbit Torques provided by a heavy metal layer, as the case of Mn_3Sn [2] or Mn_3Pt [3]. In all these cases, electrical reading of the AFM state has been achieved through the Anomalous Hall effect [5] or by effects related to the band topology of the AFM [6], but at the expense of small reading signals associate with the AFM switching or state change. This main drawback has recently addressed by using tunneling magnetoresistance (TMR) readout in epitaxial AFM tunnel junctions [7]. Nevertheless, these TMR structures were not grown using a silicon-compatible deposition process, and the control of their AFM order required external magnetic fields, making no possible their implementation in electronic circuits.

In this talk, I will show a three-terminal all-AFM tunnel junction (ATJ) based on the non-collinear antiferromagnet $PtMn_3$, sputter-deposited on silicon. The material stack is directly grown on Si/SiO substrates with the following structure: $Pt(5)/PtMn_3(10)/Al_2O_3(2)/PtMn_3(10)/Pt(5)$ (thickness in brackets and expressed in nanometers). X-ray Photoelectron Spectroscopy confirmed the $PtMn_3$ composition, while Transmission Electron Microscopy and X-ray Diffraction show that the AFM layer was texturized in the (111) direction. Switching experiments in ATJs based on this structure simultaneously exhibit electrical current induced switching, and electrical readout by a large room-temperature TMR effect, reaching a maximum variation of 100%. The magnetic origin of the resistance change is further confirmed by additional differential resistance measurements [4]. First-principles calculations explain the TMR in terms of the momentum-resolved spin-dependent tunneling conduction in tunnel junctions with noncollinear AFM electrodes. These results show for the first time an all-AFM tunnel junction with large room temperature switching, fully operating by electrical means, and compatible with Silicon fabrication processes.

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Efficient two-terminal magnetoresistive reading of ferrimagnetic insulators with perpendicular magnetic anisotropy

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Ferrimagnetic insulators (FMIs) are typically characterized by low damping, high magnon density, tunable magnetic properties, and high structural quality [1]. This fascinating set of properties makes them promising candidates for use as active components in spintronic devices. However, the lack of sufficiently strong electrical reading of their magnetization direction remains a challenge and limits the potential application of FMIs.

Magnetoresistive detection in a current-in-plane geometry can be used to probe the magnetization rotation of the free layer with respect to the reference layer, allowing for simple two-terminal device [2]. In our recent work, we report on magnetoresistive reading of perpendicular magnetization switching in an insulating ferrimagnet, terbium iron garnet (TbIG) [3]. We employed current-in-plane magnetoresistance (MR) measurements in a TbIG/Cu/TbCo spin-valve system where TbIG acts as a free layer, Cu is a non-magnetic spacer, and TbCo serves as a reference layer.

In the current study, we achieved a two-orders-of-magnitude increase in the MR readout signal by incorporating an ultrathin Co layer between the TbIG and the Cu spacer (fig. 1). Electrical measurements and X-ray Magnetic Circular Dichroism study demonstrate that this substantial enhancement in MR arises from the coupling-induced out-of-plane component of Co magnetization.

The efficient magnetoresistive reading of perpendicular magnetization in FMIs provides a novel approach for their technological application.

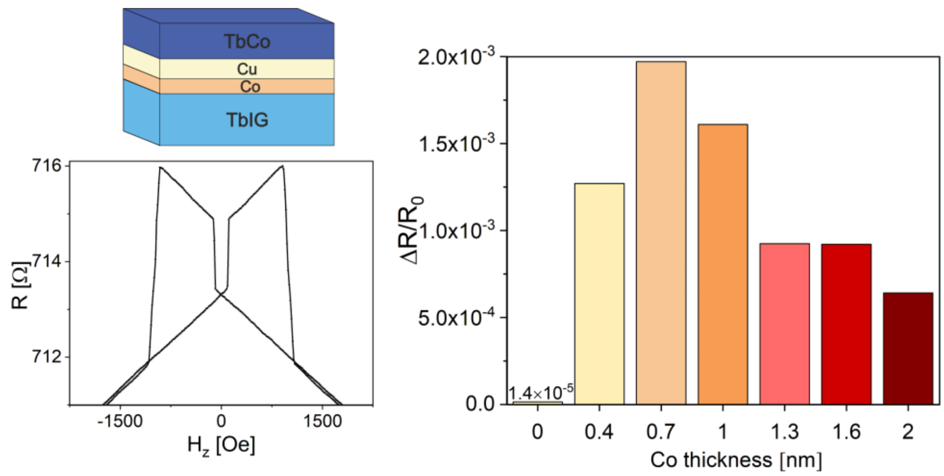

Figure 1: Left panel: Schematic of the TbIG/Co/Cu/TbCo spin-valve structure and resistance (R) as a function of out-of-plane field (H_z) for TbIG/Co (0.7nm)/Cu/TbCo. Right: Amplitude of the magnetoresistance ($\Delta R/R_0$) for different thicknesses of Co insertion layer.

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Magnetic phase transition in van der Waals magnet $CrCl_3$ induced by pressure

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Research on two-dimensional (2D) materials have attracted tremendous attention both from fundamental and applied sciences, accelerated by the discovery of graphene. Among a vast variety of 2D materials, chromium trihalides CrX_3 (X = Cl, Br, I) van der Waals (vdW) magnets have also raised a large interest due to the potential of being applied to spintronics devices and their magnetic subtleness not simply explained by their magnetic and/or structural transitions. Numerous studies were performed on CrI_3, especially at the monolayer limit [1], but only a few have been reported so far on its analogue $CrCl_3$. The vdW $CrCl_3$ is stabilized under a rhombohedral symmetry at temperature lower than 250 K, consisting of antiferromagnetically coupling honeycombs layers structured by edge-sharing $CrCl_6$ ferromagnetically coupling intralayer. The easy plane magnetic anisotrpy give rises to an XY model and theoretical prediction on its ability to host merons.[2] The vdW nature makes $CrCl_3$ an ideal system to study under external stimuli such as pressure or magnetic field, where new intriguing states of matter can be unveiled. With such expectations, studies of $CrCl_3$ under high pressures and room temperature have been reported. [3] However, its spin dynamics at low-temperature and high-pressure regimes remain unexplored.

Motivated by the intriguing properties of the spin degree of freedom and spin dynamics under such conditions, we have performed muon spin rotation (μ^+SR) and neutron powder diffraction (NPD) on ambient and hydrostatically pressured $CrCl_3$ up to 23 kbar down to 2 K. [4, 5] In this study, by incorporating the two techniques, we resolved new magentic grounds tate induced by pressure coexisting with the ambient phase accompanied by a suppression of transition temperature. This further extends the investigation into the interplay between the inter-, and intra-layer coupling of the vdW magnet family. Moreover, a linear extrapolation points toward a full extinction of magnetism at a pressure around Pc = 30 kbar, implying an existence of a tricritical point at Pc. [5] In the meantime, this pressure potentially is the lowest suppression pressure in the CrX_3 family [6, 7], showing a high tunability in its magnetic properties.

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Artificial Intelligence, Machine Learning and Soft-Computing for Magnetism

Invited

Realistic micromagnetic modelling of Nd-Fe-B permanent magnets based on FIB-SEM tomography

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The material design of rare earth-lean Nd-Fe-B permanent magnets and alternative systems such as $SmFe_{12}$ requires an understanding of the coercivity mechanisms and the balancing of multiple parameters including chemical composition, secondary phases, and microstructural features. Micromagnetic simulation is one of the main tools used to evaluate the effect of microstructure on coercivity, but it is often limited to oversimplified geometries that lack many key components such as realistic grain shape and orientation, intergranular phase, and secondary phases. On the other hand, advanced tools for 3D material characterization, including FIB-SEM and XMCD tomography, are becoming increasingly available and provide an unprecedented amount of information. In this work, we combine FIB-SEM microscopy with deep learning image processing to closely reproduce the real material microstructure in a micromagnetic model and use it to evaluate the effect of microstructural features on the coercivity of $Nd_2Fe_{14}B$-based magnets.

FIB-SEM tomography data were obtained for hot-deformed and sintered Nd-Fe-B magnets. The collected image series was pre-processed to correct drift and brightness variation and denoised. Information on the spatial phase distribution was obtained by contrast-based semantic segmentation of the voxelated volume. Information on the size and orientation of individual $Nd_2Fe_{14}B$ grains was obtained by instance segmentation of the volume. We considered two possible routes for micromagnetic modelling based on finite difference and finite element methods. The former method required minimal post-processing of the voxelized geometry, consisting mainly of the addition of a thin intergranular phase. The latter method required reconstruction of individual grains and thin intergranular phase, which was achieved using a custom algorithm [2]. For the hot-deformed magnet, we showed how the contribution of different factors such as grain size, texture, and magnetization of the intergranular phase to the coercivity reduction can be analysed and quantified [3]. For the sintered magnet, we developed a pipeline based on the finite difference method to demonstrate the role of the grain isolation and the presence of magnetic secondary phases on the coercivity. This work demonstrates that the micromagnetic simulation based on experimentally obtained microstructure can be a powerful tool for hypothesis testing and optimization of extrinsic properties of advanced magnetic materials.

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Invited

The AI toolbox for magnetic materials discovery and design

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The process of finding new materials, optimal for a given application, is lengthy, often unpredictable, and has a low throughput. Here, I will describe a collection of numerical methods, merging advanced electronic structure theory and machine learning, for the discovery of novel compounds, which demonstrates an unprecedented throughput and discovery speed. This is applied here to magnetism, but it can be used for any materials class and potential application.

Firstly, I will discuss a machine-learning scheme for predicting the Curie temperature of ferromagnets, which uses solely the chemical composition of a compound as feature and experimental data as target [1]. In particular, I will discuss how to develop meaningful feature attributes for magnetism and how these can be informed by experimental and theoretical results. Furthermore, I will show how the experimental data can be mined from published scientific literature with the help of natural language processing tools [2].

Then, I will describe how an accurate description of the structure of materials, which is amenable to be used with machine learning, can offer a quantum-chemistry-accurate description of local properties at virtually no computational costs. This is based on a newly developed cluster expansion formulated in terms of Jacobi-Legendre polynomials. Such general framework allows us to construct, on the same footing, extremely accurate force fields [3] as well as converged DFT charge densities [4]. These can both be integrated in material-discovery workflows generating unprecedented speedup.

Finally, I will present a novel rotationally invariant representation for generic vector fields. This can be used to generate linear and non-linear machine-learning models, where the total energy depends both on the atomic position and the vector field direction [5]. The scheme will be put to the test against a hierarchy of simple spin models, demonstrating an impressive ability to extrapolate away from the training region of the data. Application to complex potential energy surfaces, as those extracted from DFT are then shown.

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Constraint Free Physics-Informed Machine Learning for Micromagnetic Energy Minimization

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We investigate the full 3D static micromagnetic equations using a physics-informed neural network (PINN) ansatz to model continuous magnetization configurations. PINNs, being inherently mesh-free and unsupervised learning models, allow us to minimize the total Gibbs free energy with additional conditional parameters, such as the exchange length, using a single low-parametric neural network model. Unlike traditional numerical methods that require computing and storing numerous solutions to interpolate the spectrum of quasi-optimal magnetization configurations, our approach is more efficient.

To address the computationally intensive stray field problem, we employ extreme learning machines (ELM) within a splitting method for the scalar potential, as proposed by *Garcia-Cervera and Roma*. This reduces the stray field training to a linear least squares problem with a precomputable solution operator. For accurate evaluation of the single layer potential, we use a Taylor series approximation, which necessitates only a coarse discretization of the surface [1].

Moreover, we apply the Cayley transform to the neural network to ensure that the model output resides on the Lie group of rotation matrices *SO(3)*. We also introduce a modeling framework for constructive solid geometry that uses *R*-functions to precisely satisfy essential boundary conditions during stray field computation. This framework has potential applications beyond micromagnetics.

We further investigate efficient numerical optimization schemes for PINN training. Especially second order optimization routines are of interest for fast and stable micromagnetic energy minimization.

Our method demonstrates promising results on the *NIST* µMAG Standard Problem #3 and is also used to compute the demagnetization process of a hard magnetic cube. We validate our approach through numerical example comparisons from the literature, showcasing its effectiveness and potential for broader application [2].

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Data-driven design of high-performance and gap permanent magnets

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Magnetic materials research is an important part of green energy transition, as high-performance permanent magnets (PM) are a crucial element of electric motors and wind turbines. All these magnets that are commercially produced nowadays are based on expensive and environmentally-challenging rare earth (RE) elements. Hence, there is a desire to find RE-free or -lean alternatives with similar performance. There is also a need to fill in the gap between the inexpensive but week ferrite magnets and expensive RE high-performance PMs.

With the increasing power of supercomputers, computational search through the large amount of data becomes a common tool when looking for material with specific properties. For the permanent magnets, these properties are high saturation magnetization, large uniaxial magnetocrystalline anisotropy, and high Curie temperature.

In our research, we filtered through both a database of known materials (ICSD database [1]) and a database of materials created with machine-learning algorithms that have never been synthesized before [2]. Four promising systems were found in the latter that should be

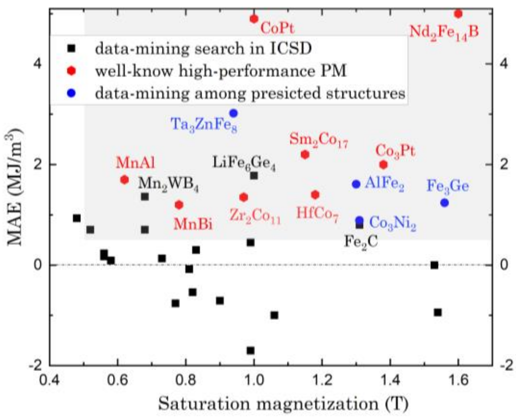

Figure 1: The saturation magnetization and magnetocrystalline anisotropy energy of some of the materials investigated in our data-mining searches.

further explored as the candidates novel RE-free PMs - Ta_3ZnFe_8, $AlFe_2$, Co_3Ni_2, and Fe_3Ge [3]. Several encouraging systems were also discovered in the former, e.g. Fe_2C (doped with Mn or V), $LiFe_6Ge_4$, etc. The results are shown in fig. 1.

Our investigations show, that the data-mining approach can be a useful guide for the further experimental studies.

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STT-MRAM technology for energy-efficient 2-D and 3-D associative in-data processing architectures

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The trend toward big data and data-intensive workloads leads to several changes in the computing paradigm and in particular to the notion of moving computation closer to data. In response to this, several in-data processing architectures have been developed [1], minimizing data movement by computing data in memory. Among them, associative processors (APs) have recently gained attention mainly due to their massively parallel processing [1, 2]. An AP is a non-von-Neumann in-memory computer system. As shown in Fig. 1(a), a typical AP features a content-addressable memory (CAM) array, which serves both as a memory and as an in-memory processor. The CAM allows for the comparison of an entire dataset to a search pattern (KEY). The peripheral circuitry, including the TAG, KEY, and MASK, supports the associative operation of the AP and enables inter-PU connectivity.

STT-MRAM-based CAMs are optimized for search operations, limiting their use into APs due to their power-hungry write operations. To address this challenge, this work introduces a non-volatile CAM (NV-CAM) cell shown in Fig. 1(b). It is based on the double-barrier magnetic tunnel junction (DMTJ) technology, and a modified version of the highly reliable STT-MRAM CAM presented by Wang, *et al* [3]. Although, the CAM presents large area footprint, this overhead becomes less significant when amortized over the entire area of a single layer in monolithic 3D integration, which was recently demonstrated in [4].

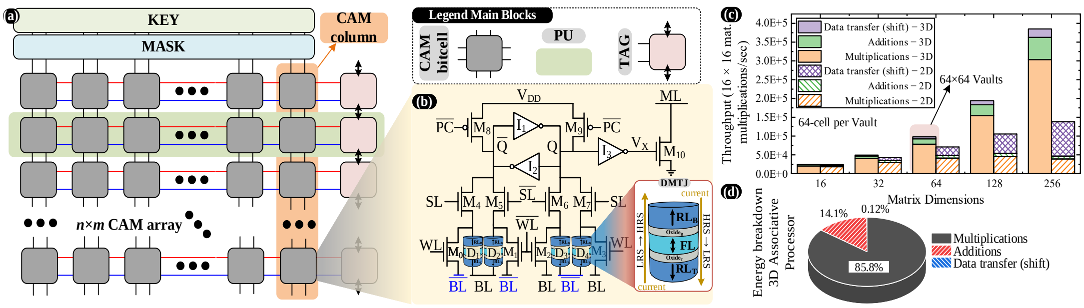

Figure 1: (a) CAM array. (b) STT-MRAM CAM cell. Matrix multiplication results: (c) performance and (d) energy breakdown.

We functionally evaluate the STT-MRAM-based AP by implementing a matrix by matrix multiplication, a critical kernel and frequent bottleneck in deep learning tasks. We compare the STT-MRAM-based 3D AP with 2D AP counterpart design. The performance results are shown in Fig. 1(c). The main difference between 2D and 3D implementations is in data transfer. In 3D AP, data transfer time scales linearly with the matrix dimension and hence consumes almost a constant fraction of the overall execution time. On the contrary, in 2D AP, data transfer scales as the matrix dimension square. Hence the relative portion of the execution time wasted on data transfer grows quickly, outpacing even the multiplication time. This difference emphasizes the efficiency of 3D AP as a processing-in-memory platform, where data transfer consumes almost negligible amount of time and energy budget. Fig. 1(d) shows the energy and breakdown on 3D AP matrix multiplication. Due to its efficient processing-in-memory operation, 3D AP spends about 86% of its energy budget on multiplication operations. The energy cost of data transfer is 0.12%.

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Magnetic Particles Imaging: solving the inverse problem with machine learning approaches

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Magnetic Particles Imaging (MPI) is a technique where magnetic nanoparticles (NPs) with a typical diameter in the 10-20 nm range are driven in correspondence of tumour masses and are triggered with a static magnetic field gradient to form a sensitive region that is excited to produce a measurable signal by an external, low intensity ac electromagnetic field. By scanning with a suitable device (an antenna) over the patient's body, maps of the magnetic response of the magnetic NPs can be obtained, which can be used to identify the cancer masses and characterise some of their properties. With respect to other imaging diagnostic techniques, MPI does not use ionising radiation or intense magnetic fields, and is therefore attracting much attention.

The maps acquired during scanning report the real and imaginary components of the third harmonic of the signal detected by an antenna that is capturing the magnetic response of the magnetic NPs excited by the rf field. For each point in the map, the signal does not come only from the NPs immediately underneath the antenna, but it is the integral of the contribution of all the particles, given their distribution and their distance from the antenna. The solution of the direct problem, i.e. the calculation within the sensitive region of the real and imaginary parts maps given the initial NPs distribution and their magnetisation vs. field curve, is straightforward (although time consuming), whereas the inverse problem, i.e. the calculation of the NPs distribution from the real and imaginary parts maps, is not trivial and may be severely affected by incomplete or inaccurate knowledge of the physical properties of the NPs. Nonetheless, it is the inverse problem that is mostly relevant for diagnostic applications.

In this work we approach the solution of the inverse problem of MPI exploiting a machine learning model. First, NPs with different size and magnetic properties (blocked or superparamagnetic), distributed in one or more clusters, with different shape and size, are randomly generated with a numerical approach (see an example in Fig. 1(a)). Then, by using the cyclic magnetisation associated to the considered NPs, the complex third harmonic response (Fig. 1(b)) is calculated for each point of the map, and numerically integrated (Fig. 1(c) and (d)). A large dataset is therefore compiled, whose entries are the real and imaginary parts of the signal, used as inputs, and their initial NPs distribution, used as output, of a convolutional neural network. After training the machine learning model, it is possible to test its predictions by comparing the true (numerically generated) NPs distribution, and the calculated one (Fig. 1(e)). The model is shown to efficiently reconstruct isotropic and anisotropic NPs distributions without the need of entering the details of their magnetic properties of the particles themselves (which are often difficult to check and control in a living environment). Different machine learning models, all exploiting convolutional neural networks, are tested and compared.

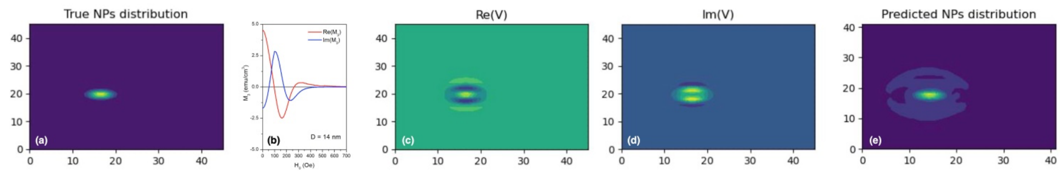

Figure 1: (a) Simulated distribution of magnetic nanoparticles. (b) Calculated third harmonic response at the peak of the distribution. (c) Real part and (d) imaginary part of the integrated third harmonic maps. € Recalculated magnetic nanoparticles distribution by a convolutional neural network.

Clustering magnetisation vector-fields using unsupervised machine learning

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The study of nanoscale magnetic materials has gained significant attention due to their diverse applications. Understanding magnetisation states and their behaviour is crucial for advancing this field. However, in-depth studies generate vast amounts of data, requiring considerable effort for evaluation.

In our previous research, we automated this process using unsupervised machine learning (ML) to analyse 2D magnetisation vector fields, each representing an isolated state. In this study, we extend our approach to a 3D system with periodic boundary conditions. By varying the Dzyaloshinskii–Moriya interaction (DMI) constant and external magnetic field in a micromagnetic simulation, we obtained equilibrium states and aimed to cluster them within a phase diagram.

Direct clustering of the high-dimensional feature space (2.5 million dimensions) of the magnetisation fields resulted in poor performance. To address this, we first used a Variational Autoencoder (VAE) to reduce the dimensionality to a 9-dimensional latent space, then applied KMeans for clustering.

Our approach identified four primary clusters: helical, skyrmion, saturation, and mixing of the three former states (Fig. 1), which are well-studied. We note that the clusters are not completely separated, however, the overwhelming majority of the vector fields within a cluster belong to a given magnetisation state. The algorithm successfully clusters known states and demonstrates stability even when the magnetisation show a significant amount of disorder. The VAE's generative capability also allows extending the phase diagram by generating new realistic states.

This study shows the potential of unsupervised ML in assisting researchers with evaluating extensive magnetisation data. We could effectively cluster thousands of simulation results with minimal human intervention. The model showed robustness against perturbations

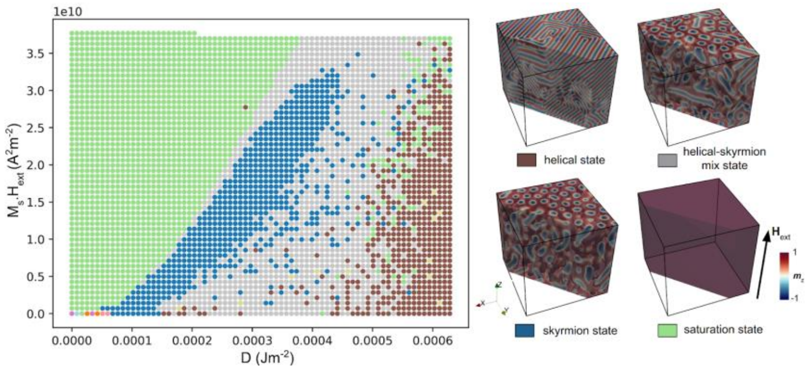

Fig.1 Phase diagram showing different clusters and their magnetisation field examples.

within clusters, and thus, holds promise for handling noisy experimental data. We acknowledge support from the MaMMoS project, Horizon Europe ID: 101135546 and the Marie Sklodowska-Curie grant agreement ID: 101152613.

Breaking the O(M×N) scaling in magnetostatic calculations with symmetry-respecting hypernetworks

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In magnetostatics and micromagnetism, it is necessary to perform repeated evaluations of the magnetic field resulting from a magnetic material, often represented as a collection of sources small enough to be uniformly magnetized. Thus, the magnetic field from N sources must be evaluated in M locations. Making use of the superposition principle, we can evaluate the magnetic field from a single source and find the resulting field by summing all the contributions. This leads to the well-known O(M×N) scaling, which ends up being the most time-consuming part in e.g. magnetic hysteresis curve calculations.

Recent work [1] uses hypernetworks to approximate the magnetic field inference to obtain a preferable O(M+N) scaling on a collection of spherical sources. Independently for each source, a neural network finds the optimal coefficients of a basis function expansion of the evaluation locations to represent the resulting magnetic field. The linear additivity of the expansion coefficients then allows for the preferable scaling.

We extend this framework to handle magnetic sources shaped as prisms. Further, we make use of known symmetries, e.g. translation and rotation, to make the learning of the machine learning setup more effective. Moreover, we show that the magnetization vector can be multiplied to the hypernetwork instead of using it as an explicit input to the neural network, which reduces complexity of the learning task drastically. Our initial scaling results on evaluating the magnetic field from several thousand prism sources show a flat scaling behavior, as shown in Fig. 1, where we additionally depict the traditional O(M×N) scaling from magnetostatic frameworks such as MagTense [2] for comparison.

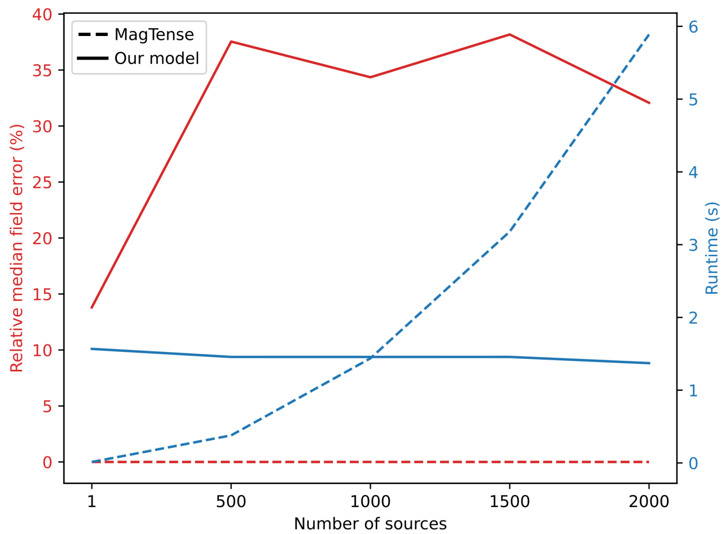

Figure 1: Flat scaling behavior with our machine learning model compared to the open-source analytical framework MagTense [2].

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Magnetism and spin dynamics in low-dimensional materials

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In this talk, I will give an overview of our recent theoretical work on spin textures and spin dynamics in low-dimensional systems and our recent efforts to develop methods to identify both local and global minima in highly convoluted spin-Hamiltonian potential energy surfaces. We have, for example, discovered complex magnetic textures in the vanadium stibnites [1], a class of Kagome systems, and large spin-lattice couplings, i.e, how the magnetic interactions depend on atomic displacement, in CrI_3 [2,3]. Employing fully relativistic first-principles calculations, we extract an effective measure of the spin-lattice coupling in the prototypical two-dimensional magnet CrI_3, finding that they are up to ten times larger than what is found for bcc Fe. Furthermore, we have identified a large number of metastable topologically nontrivial spin textures in two-dimensional systems with frustrated exchange, using our newly developed metaheuristic conditional neural-network-based method (see Figure 1) [4]. We have also developed an efficient genetic-tunneling based algorithm to identify skyrmionic ground states, which in contrast to simulated annealing correctly converges to the correct topological charge state as a function of magnetic field [5].

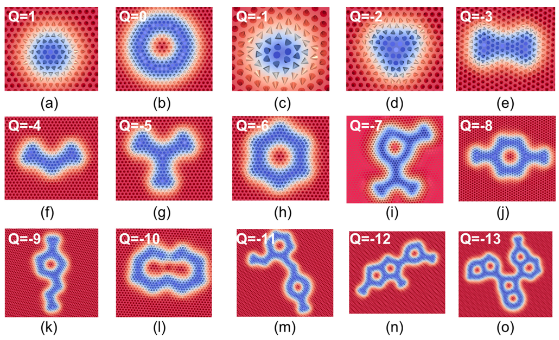

Figure 1: A subset of identified topological metastable spin textures in the frustrated exchange Pd/Fe/Ir(111) system with an external magnetic field of 3.5 T.

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Magnetic Materials for Energy Applications

Invited

The magneto- and baro-caloric properties of $Hf_{0.84}Ta_{0.16}Fe_2$

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Refrigeration based on effects such as the barocaloric effect (BCE) and magnetocaloric effect (MCE) are considered as alternatives to gas-compression for future refrigeration applications. In this context we report a conventional giant MCE and inverse giant BCE in $Hf_{0.84}Ta_{0.16}Fe_2$.

This compound crystallizes in a Laves phase with hexagonal $MgZn_2$-type structure and $P6_3/mmc$ space group [1]. The studied system exhibits a transition from a low-temperature ferromagnetic to a high- temperature antiferromagnetic state at T_C = 262 K, followed by a second transition from this antiferromagnetic state to the paramagnetic state at T_N = 321 K. While the transition at T_N is of the second type, the transition at T_C is clearly first-order making it sensitive to both magnetic field and pressure.

We have studied both the magnetocaloric and the barocaloric effects associated to the change of magnetic field and pressure, respectively, around the first-order ferro to antiferro phase transition. The magnetocaloric effect was probed using both magnetometry and in-field calorimetry in fields up to 2 T. The phase transition is found to be very sensitive to the applied field with a dT_C/dB of approximately 9 K/T and an extremely low thermal hysteresis of about 1 K at low fields. The high field sensitivity counters the entropy change since $\Delta S = -\Delta M(\Delta T_C/\Delta B)^{-1}$ and a maximum ΔS of 3.8 J/KgK (ΔB = 2 T) which is fully reversible was calculated from magnetization data, while in-field calorimetry gives a lower value of about 3 J/kg K (ΔB = 1.8 T). The adiabatic entropy change reaches a maximum of 2.6 K for a 1.8 T field change.

The barocaloric effect was studied using a combination of magnetic measurements under hydrostatic pressure and ambient pressure differential scanning calorimetry [2]. The material contracts when going from the ferro to the antiferro state by 0.35%, therefore the resulting barocaloric effect is inverse since the low volume – high temperature phase is favored and the transition shifts to lower temperatures with increasing pressure at a rate of -9.8 K/kbar. The barocaloric entropy change of $|\Delta S_{BCE}|$ = 4.8 J/(kg K) for heating and cooling is found to be very close to the total entropy change of the transition given by the latent heat and is comparable to the 4.13 J/(kg K) reported by Wada et al. for a similar composition $Hf_{0.8}Ta_{0.2}Fe_2$ [3]. It is also found to be mostly reversible due to the low hysteresis of the phase transition and high sensitivity to pressure. The barocaloric effect is found to saturate at very low pressures and an adiabatic temperature change with a magnitude of 3.8 K was observed at 3.7 kbar.

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Invited

Greener permanent magnets without or with less critical raw materials for electric motor application

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Permanent magnets (PM) are vital components of the green transition. However, the criticality of rare-earth elements (REE) [1] needed for their manufacture makes them of great strategic, geopolitical, and socio-economic importance, making it an urgent need to develop alternative REE-free magnets. The best-performing PMs are based on REEs, while lower-performance PMs use ferrites. [2] Due to the high performance of REE magnets, most modern devices employ them, as they are lighter and lead to better efficiency. Unfortunately, REEs are critical raw materials owing to their supply risk and price volatility, and also their harmful environmental impacts. [3,4] One of the solutions focuses on improving the performance of alternative rare-earth-free or rare-earth-lean magnets co-designed with electric motors or generators for greater efficiency.

To address these challenges, the magnets presented here are produced solely by recycling of injection moulded PM scrap material, with the recycling done in several stages, by milling, or milling followed by polymer removal and annealing to recover the magnetic properties of powders. The milled (or milled and annealed) material serves as a feedstock for consolidation by conventional or advanced sintering techniques (Spark Plasma Sintering, or Pressure-less Spark Plasma Sintering). Processing and consolidation parameters were tailored to achieve dense magnets. The phase composition, microstructural analysis and magnetic properties of starting powders and sintered magnets were evaluated.

Acknowledgement:
This research has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 101003575 (ERA-MIN3, project GENIUS), and Slovenian national research agency (P2-0087, P2-0405, P2-0412).

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Invited

Materials for efficient conversion of low temperature waste heat

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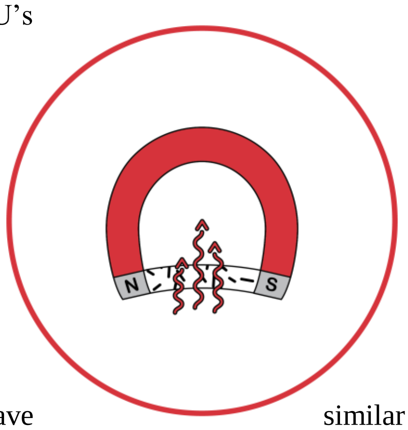

The production and use of energy account for more than 75% of the EU's greenhouse gas emissions. Decarbonising the EU's energy system is therefore critical to reach our 2030 climate objectives and the EU's long-term strategy of achieving carbon neutrality by 2050. At the same time, we will generate vast amounts of low-grade heat in e.g. datacenters, food, pulp and paper industries that is available 24/7. Efficient machines or devices to convert this low-grade heat in an economically sound way are however lacking. Upgrading only a small percentage, as dictated by laws of thermodynamics, of this otherwise wasted heat into electricity, can already be significant due to the sheer amount of heat in the temperature range below 390 K. As the heat is available and often needs to be downgraded before it can be safely released into the environment, we have similar to PV and offshore wind mainly to consider the cost of investment to determine the economic framework of such a generator. The existing prototypes [1, 2] are essentially proofs of principle but have demonstrated where we can gain efficiency by improving designs and by tailoring materials properties. Promising materials have to fulfill a few requirements [3]: Low and adjustable Curie temperature for low-grade heat, low remnant magnetization (Mr), which is generally fulfilled as one operates near or at the critical temperature. Significant and steep magnetization change at the Curie temperature as the figure of merrit of this type of materials is proportional to the change in magnetization, and inversly proportional to the heat input required to induce this change in magnetization. A high thermal conductivity to facilitate a rapid temperature change, and last but not least low-costs, which implies the preferred use of earth-abundant elements. A few of these materials requirements are very similar to the requirements for magnetocaloric materials. However, e.g. latent heat that helps for magnetocaloric applications is detrimental to thermomagnetic applications, as it implies more heat is needed to induce a change in temperature. We will discuss current state of the art devices and review developments in tailoring the performance of novel magnetic materials for efficient energy conversion.

Keywords: Energy conversion, magnetic materials, thermomagnetic devices, energy efficiency

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Opto-mechanical control over FeGa magnetic properties via liquid crystalline networks

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Composite magnetic materials with multiple responses to environmental stimuli, such as light, are expected to have a significant impact on various applications, particularly in sensing and actuation systems.

This work explores the combination of a 30 nm magnetostrictive FeGa layer with soft photo-responsive polymers, specifically liquid crystalline network (LCN). This composite material allows to finely tune the magnetic properties of thin film without the need for a magnetic field, but only through light irradiation, leading to an advantage in terms of energy consumption compared to the use of conventional magnetic field applicators.

Specifically, UV light irradiation (λ = 385 nm) leads to polymer contraction along the x-axis and expansion along the y-axis, exploiting the isomerisation of the dye in the LCN. This photo-actuation transfers a mechanical stress to the magnetostrictive FeGa thin film, whose magnetic domains rearrange under the effect of uniaxial stress anisotropy. As a result, the magnetic properties of the FeGa thin film depend on the duration and intensity of UV irradiation. On the other hand, irradiation with green light (λ = 505 nm) is able to restore the original molecular order in the polymer, gradually releasing the stress in the FeGa thin film and, consequently, recovering its pristine magnetic properties.

Hysteresis loops of the FeGa/LCN photoresponsive sample were measured by applying a magnetic field *H* in the film plane along both *x* and *y*-directions after irradiation with UV (see Figure 1a) and green lamps for a selected time. Magnetic parameters, including normalized magnetization remanence (M_r/M_s), coercive field (H_c) and magnetic susceptibility (χ_{Hc}) have been evaluated as a function of the duration and intensity of the light illumination.

Moreover, to assess the actuation mechanism, anisotropic magnetoresistance measurements were performed under opto-mechanical control of the magnetization. Specifically, the $\Delta R/R$ value is recorded for an interval of time during which UV light and green light are properly switched on and off, revealing a magnetic memory effect (see Figure 1b).

This study presents a detailed analysis of the coupling between the opto-mechanical properties of the substrate and the magnetostrictive behavior of the FeGa layer, demonstrating the potential use of these photoresponsive materials.

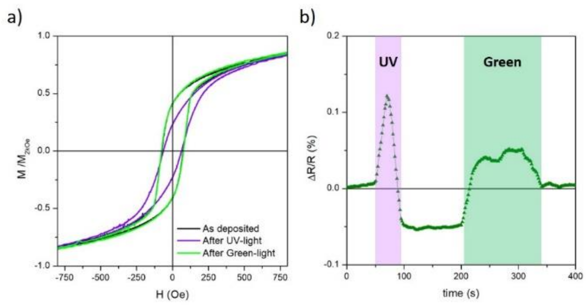

Figure 1: a) hysteresis loop of the FeGa/LCN sample in as-deposited state and after UV and green light irradiation time; b) evolution of the $\Delta R/R$ curve triggered by UV irradiation and green light.

Facile and fast synthesis of highly ordered $L1_0$-FeNi nanoparticles from cyano/nitrosyl-metal complexes

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The $L1_0$-FeNi binary alloy is a promising candidate for next generation rare earth-free permanent magnets (PMs) [1], which can revolutionize the high-performance PM market currently dominated by the Nd-Fe-B [2]. However, the fabrication of the $L1_0$ phase is extremely challenging owing to the low atomic mobility below the chemical order/disorder transition temperature that kinetically limits the formation of the $L1_0$ phase [3]. Despite many efforts, the experimental results are still far from the theoretical predictions and the proposed approaches mainly involve complex and expensive protocols, which cannot be easily scaled-up for bulk production and/or result in a low proportion of the $L1_0$ phase [3].

To overcome current limitations, we exploited an effective and easily scaled-up chemical synthesis method, already successfully applied for other $L1_0$ alloys [4], which is based on the use of crystalline precursor complexes consisting of an ordered arrangement of the metallic elements on alternating atomic planes that resembles the atomic arrangement of the $L1_0$ structure. The perfect atomic order of the precursors allows reducing the energy required to order the atoms thus driving the formation of the $L1_0$ phase that can be obtained by low-temperature reduction in H_2 atmosphere. To apply this concept to the $L1_0$ FeNi alloy, crystalline cyano/nitrosyl-metal complexes with a 1:1 ratio of Fe and Ni were used as precursors [5,6]. Aggregates of FeNi alloy nanoparticles (20 – 120 nm) with a >55 % of $L1_0$ phase (as determined by Mossbauer analysis), quite high coercivity (up to 65 mT) and large saturation magnetization (~ 135 Am^2/kg, close to the bulk value) were obtained in the best experimental conditions. Despite the coercivity is still far from optimal for a high-performance permanent magnet, the results clearly prove the effectiveness and high potential of the developed strategy, which can be exploited, after further optimization, for mass production of highly ordered $L1_0$-FeNi nanoparticles for next generation critical-element-free permanent magnets.

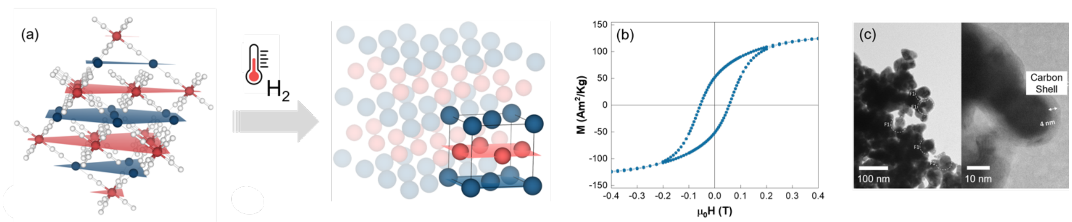

Figure: (a) Schematic representation of the synthesis process: from crystalline Ni-Nitroprusside complexes (left) to $L1_0$-FeNi alloy (right). (b) Representative M(H) loop of FeNi powders and (c) corresponding TEM image

[1] J. Cui et al., Acta Mater. **158** (2018), 11
[2] J. M. D. Coey, Engineering **6** (2020), 119
[3] S. Mandal et al., Crit. Rev. Solid State Mater. Sci. (2022)
[4] G. Varvaro et al., J. Alloys Compd. **846** (2020), 846
[5] G. Varvaro et al., Scripta Materialia 238 (2024) 115754
[6] A. Capobianchi et al., Patent Application Filed PCT/IB2023/062068 (2023)

Study of the laser-induced modulated Antiferromagnetic-Ferromagnetic phase transition in a magnetocaloric FeRh Film

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The near equiatomic FeRh alloy exhibits an antiferromagnetic (AF) to ferromagnetic (FM) first-order phase transition near 360 K [1] accompanied by lattice expansion, and by several physical properties changes, such as electrical resistivity, and optical reflectivity. This makes FeRh a prototypical multifunctional material promising for technologies as different as magnetic cooling, and spintronics [1]. Understanding the mechanisms underlying the phase change and the associated thermal hysteresis is the key for harnessing its functional properties. In this study, we use the remarkable change in optical reflectance between the AF and FM phase (≈4%) [2] to probe phase-coexistence in a temperature driven hysteretic phase transition. A modulated thermoreflectance setup [3], where a pump and a probe laser (532 nm modulated at 500 Hz and 488 nm, respectively) are focused on a 4 µm radius spot, is used on a 195 nm thick FeRh film grown on a MgO(001) substrate. The pump induces a fast, and periodic (square modulated at 500 Hz) temperature pulse ΔT on the sample surface (≈10 K/µs) while the probe measures the reflectance (see voltage in Fig.1a,1b). Starting from the pure AF phase, the pump laser induces ΔT temperature increment pulses over the spot, reaching the onset of the quasi-static phase-coexistence region as shown in Figure 1c.
The consequent modulation of the FM phase fraction shows a random behavior (Fig.1a). The FM fraction does not systematically follow the temperature modulation. The statistics of the modulated FM phase (i.e. relative frequency, amplitude, and time delay of the FM phase nucleation bursts with respect to the temperature pulses) is studied, and its relationship with hysteresis is discussed. **Acknowledgments:** this research has received funding from the project LabEx LaSIPS (ANR-10-LABX-0032-LaSIPS) program (ANR-11-IDEX-0003).

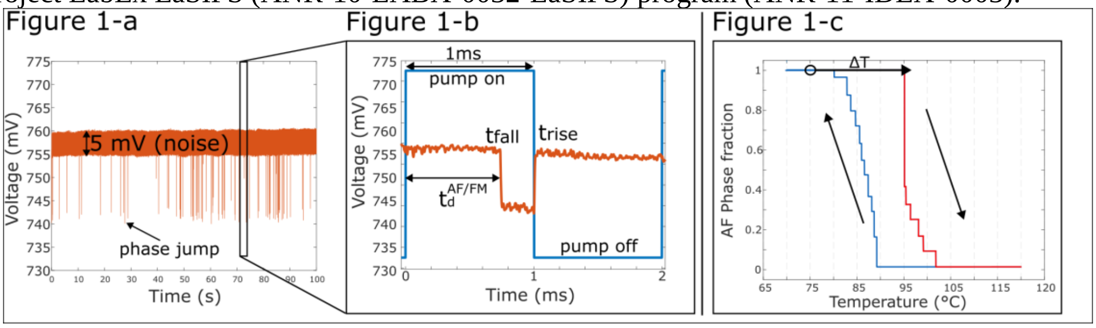

Figure 1. (a): Diode signal giving the time-dependent reflectance (orange line) illustrating the transition randomness under 500 Hz modulated pump (blue line in zoomed plot). (b): zoom on the figure 1a. (b): Schematic quasi-static cycle acquired without pump where ΔT is the temperature pulse induced by the laser.

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[2] V Saidl et al 2016, New J. Phys. 18 083017

[3] D Fournier et al 2020, *J. Appl. Phys.* 128, 241101

Electric Field Control of Magnetization in FeGa microstructures on PMN-PT

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The recent era of information technology largely focusses on energy saving and cost efficiency. Manipulation of magnetic state of a micro element solely with the use of electric fields has attracted new attention due to its potential ability to be used in low-power magneto-electronics [1]. Artificial magnetoelectric materials are suitable candidates due to its coupling between magnetization and electric-field induced strain, which consumes less power and reduces heat losses [2,3].

In the framework of artificial multiferroic heterostructures and their interfacial magnetoelectric interplay, we have investigated the properties of FeGa microstructures fabricated on PMN-PT (Fig. 1(a)). The in-plane strains (ε_x, ε_y) generated in the PMN-PT substrate were measured using a strain gauge (Fig. 1(b)). Due to the [011] crystal orientation, the in-plane strains are anisotropic resulting in significant difference in remnant strain values marked by the blue (-0 kV/cm) and red (+0 kV/cm) dots. The magnetic hysteresis of elliptical disks (long axis of 5 µm) were recorded using Magneto-Optic Kerr effect (MOKE) as represented by the -0 and +0 kV/cm curves in fig. 1(c). A difference in the shape of the hysteresis is observed which marks the rotation of anisotropy of the system. A vortex domain state is observed in reversal at -0 kV/cm whereas a S-shaped multidomain is recorded at +0 kV/cm. This influence in domain patterns marks the presence of strain-induced anisotropy in the system. Further, an electric field pulse of +6 kV/cm was applied to the magnetic remanence state. A single domain state is observed before application of electric field (Fig. 1(d)). Under electric field application of +6 kV/cm, the magnetic state changes to a S-shaped multidomain state which remains stable even after the field is removed. This marks the manipulation of magnetic state with the sole use of electric field.

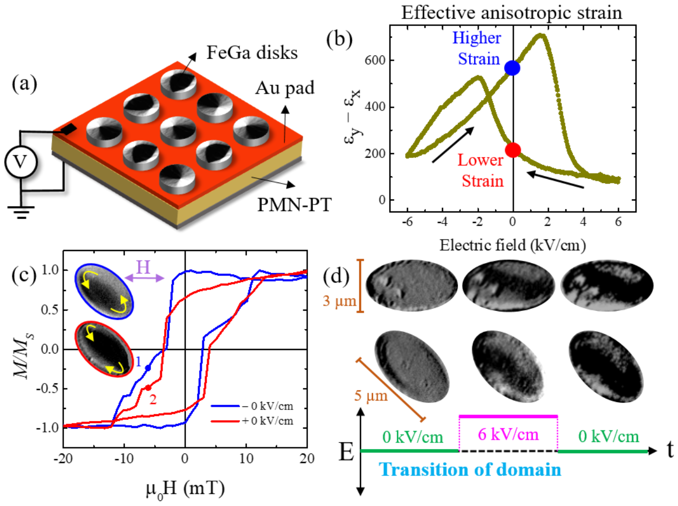

Figure 1: Schematic of FeGa/PMN-PT heterostructure for voltage application. (b) Effective strain measured in PMN-PT. (c) Magnetic hysteresis and domains structures recorded at remanent strain states. (d) Magnetic state change under electric field pulse.

[1] N. A. Spaldin and R. Ramesh. Nature materials 18.3 (2019): 203-212.
[2] R. Lo Conte, et al. Nano letters 18.3 (2018): 1952-1961.
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Effect of porosity on the magnetic and magnetostrictive properties of Galfenol sputtered on porous silicon

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Magnetostriction, the ability of a magnetic material to change its shape in response to a magnetic field, is widely employed in magnetoelectric (ME) composite structures. Galfenol (FeGa) is an emerging smart material, ideal for these applications with superior mechanical and physical properties compared to other materials due to its rare earth-free composition, lower production cost, higher operating range, lower saturation field, and coercivity [1]. When grown on rigid substrates, these thin films suffer from the clamping effect which hinders the magnetic field-induced strain propagation. To address this issue, porous silicon (pSi) substrates, fabricated by anodization, are used to sputter Galfenol thin films, and their morphology and magnetic properties are subsequently analyzed.

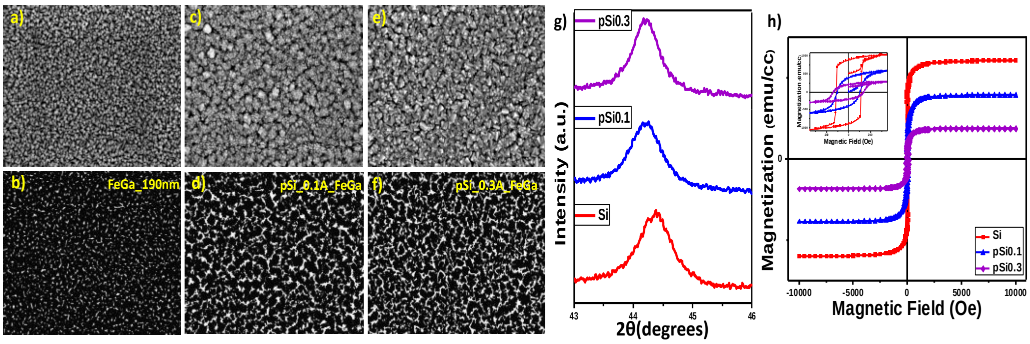

Figure 1: a-f : SEM top view images of the FeGa thin films sputtered on pSi substrates, of varying porosity, and their corresponding porosity analysis g: XRD patterns and h: hysteresis loops of the samples

Image analysis and magnetic properties are used in tandem to evaluate the degree of porosity. The growth of FeGa thin films on these pSi substrates significantly alters film porosity, even though the films inherently possess some level of nanoporosity between the columnar grains. The varying degree of the pSi porosity influences the FeGa thin film growth, increasing porosity relative to the substrate. Consequently, magnetization decreases and coercivity increases with higher porosity. The High-Resolution X-ray diffraction (HR-XRD) measurements show peak shifting to a lower 2θ value, indicating lattice relaxation. The magnetostrictive response of the films is further investigated by XRD, under in-situ magnetic field application [2]. The effects observed in porous FeGa films open new avenues for designing various strain-engineered nanomaterials and devices, such as high-performance microelectromechanical systems (MEMS), energy transducers, and ME composites.

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[2] A. Nicolenco, A. Gómez, X. Z. Chen, E. Menéndez, J. Fornell, S. Pané, E. Pellicer, J. Sort, Appl. Mater. Today **19** (2020) 100579

Temperature controlled magnetic modifications in Ni/$KNbO_3$ artificial multiferroic heterostructures

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In recent years, multiferroic heterostructures have gained attention for their combination of ferromagnetic (FM) and ferroelectric (FE) materials, interfacially coupled through converse magnetoelectric effects [1,2]. This combination represents a spintronic opportunity, as it allows for the modification of the FM response using external stimuli, such as electrical bias [3] or via fully optical means [4]. The fact that the interfacial coupling between FM and FE components is influenced by many parameters, along with a wide range of available materials, provides a rich playground for further developments and for the exploitation of characteristics that have previously been overlooked.

In this framework, we reported the preliminary results of the temperature-dependent modifications of magnetic properties of multiferroic heterostructures, having deposited Ni thin film down to 4 nm thickness on highly photovoltaic $KNbO_3$(111) and $KNbO_3$(001) single crystals as FE substrates. Ni coercive field (H_C) temperature dependence, measured via Magneto-Optic Kerr Effect (MOKE) measurements in ultra-high vacuum [5], proves to be sensitive to $KNbO_3$ structural transitions (Figures a and b). In addition, the large $KNbO_3$ photocurrent in the visible range opens the way for further investigations exploiting possible photostrictive effects [4].

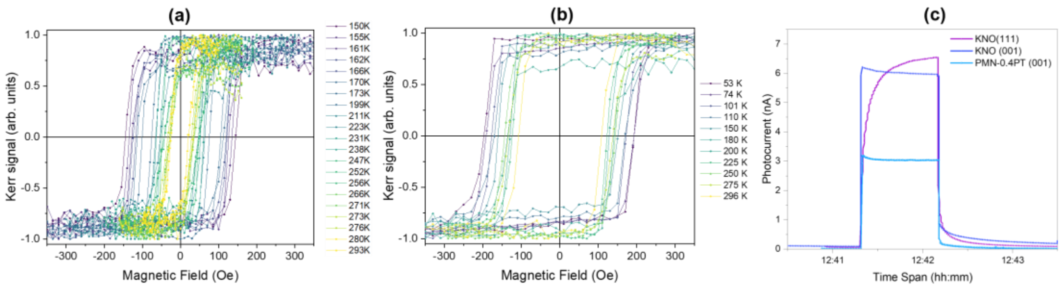

Figure: Magnetic hysteresis loop temperature dependence of Ni/$KNbO_3$(111) (a) and Ni/$KNbO_3$(001) (b); (c) photocurrent measurements of $KNbO_3$ (001) and (111) under 405 nm illumination, compared to PMN-0.4PT (001) substrate.

[1] W. Erenstein *et al*., Nature 442 (2006) 759.

[2] C.A. Fernandes Vaz, J. Mater. Chem. C 1 (2013) 6731.

[3] G. Vinai *et al*., Adv. Electron. Mater. 5 (2019) 1900150.

[4] D. Dagur *et al*., Adv. Mater. Interfaces 9 (2022) 2201337.

[5] G. Vinai *et al.*, Rev. Sci. Instrum. 91, (2020) 085109.

Influence of secondary phases on the determination of the order of thermomagnetic phase transitions: model and experiment

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The identification of the first-order thermomagnetic phase transitions (FOMT) fingerprint based on the exponent *n* quantitative criterion [1] has significantly impacted the assessment of newly developed materials and their performance within the scientific community [2,3]. Its application is not restricted to any theoretical model and does not require a fitting procedure, thus showcasing its versatility. By resolving the limitations encountered by traditional methods in determining the order of phase transition, the FOMT fingerprint, i.e., overshoot of $n>2$ near the transition temperature, has proven instrumental. Additionally, the exponent *n* criterion has significantly advanced the identification of the critical point at which the first-order crossovers to second-order thermomagnetic phase transitions (SOMT). This allows a clear identification of the borderline regime that combines the benefits of both FOMT and SOMT, thereby leading to a significant magnetocaloric effect without hysteresis. The boundary of this regime has been challenging to determine quantitatively until the discovery of this method.

In this presentation, we are excited to unveil our latest advancements in the *n* exponent criterion, pushing the boundaries of previously established limits. Numerical simulations prove that an overshoot with $n>2$ occurs in multiphase materials despite that its value is affected by the amount of secondary phases and their transition temperatures. This prediction is experimentally validated using high-performance MnCoGe and textured/non-textured Mn-Co-Ni-Ge-Si families of compounds [4] as examples. Furthermore, we will emphasize the criterion's remarkable capability to identify magnetic impurities, even when they are not readily apparent.

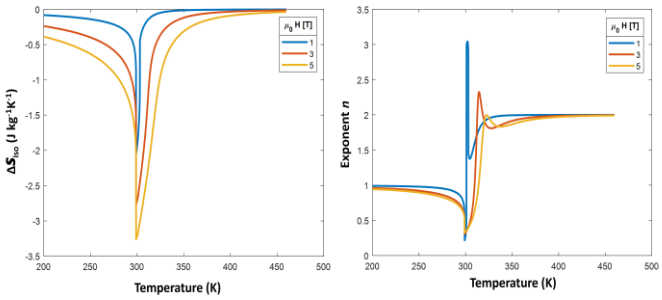

Figure 1: Temperature dependence of (left) isothermal entropy change and (right) corresponding exponent *n* behavior for a simulated biphasic FOMT+SOMT material.

[1] J.Y. Law, V. Franco, …, O. Gutfleisch, Nature Communications **9** (2018) 2680.

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[3] J.Y. Law, V. Franco, Handbook of Physics and Chemistry of Rare Earths **64**, Chapter 332 (2023) 175–246, Elsevier.

[4] J.Y. Law, T. Samanta, X. Miao, L.Caron, V. Franco, To be submitted (2024).

Light-induced interfacial ion migration on thermally treated PMN-$_{0.4}$PT/Fe multiferroic heterostructures

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Within the field of spintronics, artificial multiferroics, composed by ferroelectric/ferromagnetic heterostructures, have gained in the last years particular attention due to the possibility of tuning the magnetic properties by playing with the rich number of external stimuli that can alter the ferroelectric properties. Notably the application of electric field, mechanical stress, or light illumination leads to a series of interfacial effects, such as strain, ion migration, charge accumulation/depletion.[1] The coexistence of different interfacial effects often makes it difficult to pinpoint the leading mechanism.

In this context, here we present how a combination of different external stimuli can modify the chemical composition of a Fe thin film at the interface with a $[Pb(Mg_{1/3}Nb_{2/3})O_3]$-$_{0.4}[PbTiO_3]$ (PMN-$_{0.4}$PT) (001) single crystal, a ferroelectric substrate that already proved to experience exotic behaviours after polarization switching [2,3] and light illumination.[4]

The heterostructure has been annealed up to 200°C in inert atmosphere, crossing PMN-$_{0.4}$PT Curie temperature (*i.e.* passing from a tetragonal to a cubic structure). Once cooled, the ferroelectric domain population of the substrate is substantially modified, passing from mostly out-of-plane to mostly in-plane orientation (Figure 1a), leading to a strain-induced modification of the interfacial Fe magnetic anisotropy (Figure 1b-c).[5]

Interestingly, x-ray absorption spectroscopy (XAS) characterizations showed that partial Fe oxidation, which occurred during the thermal treatments, could be reversibly removed via 405 nm light illumination (Figure 1d). Ongoing investigations via hard x-ray photoemission spectroscopy aim to understand the origin of such light-induced interfacial ion migration, which represents a first-ever reported case in the framework of multiferroic heterostructures.

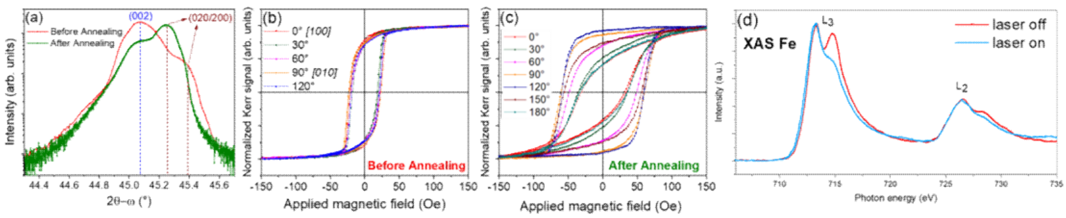

Figure 1: (a) 2θ-ω scans of PMN-$_{0.4}$PT (002) peaks before and after thermal treatments; (b,c) angular dependent MOKE hysteresis loops on PMN-$_{0.4}$PT/Fe heterostructures before (b) and after (c) annealing; (d) XAS measurements at Fe $L_{2,3}$ edges after thermal treatments, taken before (red) and after (blue) 405 nm laser illumination.

[1] J.-M. Hu *et al.*, Adv. Mater. **28** (2016), 15.

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[3] F. Motti *et al.*, Phys. Rev. Materials **4** (2020), 114418.

[4] D. Dagur, …, G. Vinai, Adv. Mater. Interfaces **9** (2022), 2201337

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Room temperature magnetocaloric materials $(MnFe)_{1.9}(PSi)$ Fe-rich compounds for heat pump application

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First-order magnetic transitions involve structural, magnetic and electronic changes that are relatively well described at the scale of a unit cell. They have established spectacular consequences on bulk physical properties such as magnetization, transport or thermal properties, which form the basis of their applications [1,2]. In this work, simultaneous substitutions of Mn for Fe and Si for P on structure, magnetic property and magnetocaloric effects of Fe-rich $Mn_xFe_{1.90-x}P_{1-y}Si_y$ compounds are studied. The transition temperature of the compounds increases linearly with simultaneously increasing Mn and Si content, from 295 K to 332 K. This fulfils one important application requirements of MCMs that the transition temperature can be adjusted continuously over the temperature range relevant for the heat pump application. The maximum isothermal magnetic entropy change ($-\Delta S_m$) increases from 12 $Jkg^{-1}K^{-1}$ (x= 0.60, y=0.34) to 16 $Jkg^{-1}K^{-1}$ (x= 0.68, y= 0.38) for a field change of 2 T. The adiabatic temperature change was derived from the S-T diagram, with the maximum ΔT_{ad} of 5 K for the $Mn_{0.66}Fe_{1.24}P_{0.63}Si_{0.37}$ compound at magnetic field of 2 T. This makes Fe_2P-type materials promising candidates for heat pump applications. The separation of latent heat and specific heat was implemented by heat capacity measurements using the commercial semi-adiabatic option in Versalab, which providing an possiblity to demonstrate the correlation between latent heat (L) and elastic strain energy (U_e). The compound with Mn = 0.66/Si = 0.37 exhibits a latent heat of 4.35 kJ kg^{-1} and a calculated strain energy of 4.37 kJ kg^{-1}, resulting in a U_e/L ratio of approximately 1 ($U_e/L = 4.37/4.35 \approx 1$). The n-value is used to define the type of magnetic phase transition. The magnetic entropy change scales with the magnetic field as $\Delta S_M \propto H^n$ in the vicinity of the phase transition. The index of the magnetic field can be expressed as $n = d\ ln(|\Delta S_M|)/\ d\ ln(H)$ generally shows a significant variation near the transition temperature [3,4]. In particular, $n > 2$ was proposed for materials characterized by a first-order magnetic phase transitions (FOPT). With the simultaneous changing of the Mn/Fe and P/Si content, the maximum value of n near the phase transition is found to be greater than 2 for all compounds.

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[2]. J. V. Leitao, M. V. D. Haar, A. Lefering, Journal of Magnetism & Magnetic Materials, 49-54 (2013)

[3]. L. J . Yan, F. Victorino, Nature Communications, 9:2680 (2018)

[4]. C. Bean & D. Rodbell, Physical Review, 126, 104–115 (1962)

From electromagnet to electro-permanent magnet for magnetocaloric heat pumps

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Magnetocaloric energy conversion represents a promising alternative to conventional technologies for cooling, heat pumping and energy harvesting. A key component of magnetocaloric devices is the magnetic field source, which typically consists of rare earth-based permanent magnets. Existing systems rely on rotating magnets to generate alternating magnetic fields, which requires moving parts and drive systems that reduce energy efficiency and increase costs. In addition, these systems are limited by the slow speed of magnetization/demagnetization cycles and limited control over the magnetic field, which affects the compactness and efficiency of the device.

To overcome these challenges, a rare-earth-free electromagnet with magnetic energy recovery was presented as a first step [1] (Fig. 1). By using the electromagnet in combination with magnetic energy recovery, the magnetization and demagnetization times were reduced to a few ms, enabling operation at high frequencies. However, the energy efficiency was still lower than with the comparable arrangement with a rotating magnet. In a second step, an electro-permanent magnet was introduced [2]. An energy efficiency of these magnets of over 80 % and operation at frequencies of up to 50 Hz was demonstrated, which is crucial for future magnetocaloric devices with high power density and high frequencies.

Given the high energy efficiency at high operating frequencies, such electro-permanent magnets would allow miniaturization, making them a viable option for future compact magnetocaloric devices.

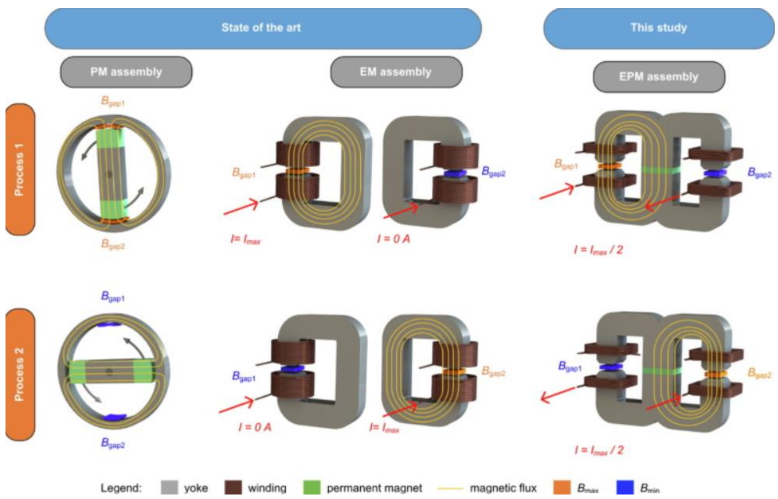

Figure 1: Example operation of equivalent permanent magnet (PM), electromagnet (EM) and electro-permanent magnetic assemblies (EPM) [2].

[1] K. Klinar et al. *Appl Energy*, **236** (2019), 1062-1077.

[2] U. Tomc, et al., *J Adv Res*, **45** (2023), 157–181.

Structural and magnetocaloric properties in rare-earth free high-entropy alloys.

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High-entropy alloys (HEAs), in contrast to conventional alloys and intermetallics, mix five or more elements at equal or near-equal compositions in a single crystalline phase. In principle, they form an ideal solid solution stabilized through a high configurational entropy of mixing [1]. This huge compositional space of HEAs offers opportunities to discover new functional materials with improved properties. Yet this ideal scenario is met only rarely, and rational approaches are needed to design HEAs with the desired properties. Inspired by recent reports on rare-earth free HEAs with promising magnetocaloric performances [2], we present some new results on the structure and magnetic properties of some ultra-pure single phase HEAs in different systems.

Samples have been prepared by arc-melting or induction furnace, followed by post-annealing treatments. In order to enhance the magnetocaloric effect, the compositions of the samples were designed by applying chemical substitutions to systems known to present a magnetostructural phase transition. They are derived either from the MnNiSi ternary system or from the Ni_2MnGa Heusler type of compounds. In the first case, high entropy alloys are obtained in $(Fe,Mn,Ni)_{66.6}(Ge,Si)_{33.3}$ or $(Fe,Mn,Ni,Co)_{66.6}(Ge,Si)_{33.3}$. In the second case, a high entropy compound is formed instead in $(Fe,Mn,Ni,Co)_{75}Sn_{25}$. The first family of alloys undergoes a structural transformation from hexagonal at high T into orthorhombic upon cooling, as evidenced by temperature dependent powder and single crystal XRD as well as HRTEM. The specific heat indicated a paramagnetic to ferromagnetic (PM/FM) transition followed by a first order phase transition. The T of the transition depends on the chemical composition, and can be tuned close to room temperature in $(Fe,Mn,Ni,Co)_{66.6}(Ge,Si)_{33.3}$. The magnetization versus field M(H) curves reveal magnetic hysteresis at temperatures close to the transition reflecting a field induced first-order transition. The magnetocaloric effect has been evaluated from magnetic measurements using the Maxwell relation and from the direct adiabatic temperature change measurements. An isothermal entropy change as large as about 40 J.kg-1.K-1 is attained at 5 T. In the Heusler-derived HEA, the PM/FM transition occurs at 550 K but can be tuned to lower T by Cu doping.

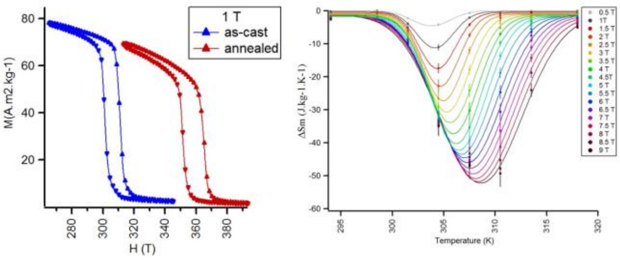

Figure 1: Thermomagnetic curves (left) and isothermal entropy change at various field in $(Fe,Mn,Ni,Co)_{66.6}(Ge,Si)_{33.3}$.

[1] E.P. George *et al.*, Nat. Review, **4** (2019) 515.
[2] J.Y. Law *et al.*, J. Alloys. Comp., **855** (2021) 157424. Y. Guo *et al.*, APL Mater. **10**, 091107 (2022).

Oscillating Gadolinium Thermal Switch for Efficient Heat Flow Management

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This paper presents a millimeter-scale oscillating gadolinium (Gd) thermal switch designed for active heat flow control in thermal management applications. The switch, utilizing electrostatic forces, achieves a switching ratio of 2.3, with thermal conductance values of $2.42 \cdot 10^{-1}$ W/K (ON state) and $1.22 \cdot 10^{-1}$ W/K (OFF state). The device demonstrates reliable actuation over 10^5 cycles, making it suitable for applications such as caloric cooling. Built using commercially available materials, the Gd thermal switch offers a compact and effective solution for environments requiring precise thermal regulation.

Efficient thermal management is essential for energy efficiency, especially in systems with high power density. Conventional thermal management methods often struggle to meet these demands, leading to the development of thermal switches, diodes, and regulators. Thermal switches offer the ability to toggle between high and low thermal conductance states, providing a dynamic solution for heat flow control. In this study, we present an electrostatic thermal switch that can be used to influence the heat flow between the hot spot and the heat sink. First, we experimentally investigated the behaviour and switching ratio of the thermal switch under different conditions and demonstrated its ability to actively control the heat flux in low power density applications at room temperature. Later, the performance of the device is predicted theoretically using the online simulation tool TCC builder [1]. The main part of the evaluated device consists of an oscillating 161 μm thick Gd plate and two Si plates with a thickness of 516 um, which serve as hot and cold heat exchangers. The Gd plate oscillates due to electrostatic forces, enabling thermal contact when in the ON state and minimizing it in the OFF state. The thermal conductance in the ON state G_{on} is primarily influenced by surface roughness, contact pressure and convection losses, while in the OFF state G_{off} the thermal conductance is dominated by parasitic losses through the air gap and the housing. The switching ratio is defined as $r_{switch} = G_{on} / G_{off}$ and is the primary metrics for evaluating thermal switch performance. The analysed thermal switch achieved a maximum switching ratio of 2.3 at 0.25 Hz and a power input of 95 W/m^2. Experimental findings showed that larger air gaps improved the OFF state insulation, leading to higher switching ratios. Simulations using the TCC Builder shows higher thermal conductance values in the ON state, compared to the experimental results. One of the main reasons are the heat losses to the environment, which were not considered in the numerical model. In the OFF state, the experimental thermal conductance value is 5 times higher than numerically determined value. During the OFF state in the numerical simulations, heat gains from the electric heater to the cold heat exchanger occur only through heat conduction within the air gap. Conversely, in the experimental set-up heat gains extend towards the ambient surroundings, consequently resulting in a reduced amount of heat leakage towards the cold heat exchanger.

This study demonstrates the feasibility of an oscillating Gd thermal switch for controlling heat flow in low-power density systems. With further optimization, including operation in a vacuum and improved contact resistance through higher electrostatic forces, the switch's performance can be significantly enhanced.

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[1] TCC Builder – simulation tool for the evaluation of thermal control elements and circuits https://tccbuilder.org/

Cool BatMan project: Digital Microfluidic Magnetocaloric Cooling

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Today's state-of-the-art devices are based on the so-called Active Magnetic Regeneration, which is moderately efficient at low operating frequencies (up to 5 Hz). To achieve considerable cooling power and magnetic fields at such low frequencies, a significant amount of magnetocaloric and permanent magnet material is required, which also affects the cost. Therefore, a new research direction has emerged in recent years in which researchers are trying to develop devices that operate efficiently at much higher frequencies. This would increase the power density, which in turn would allow miniaturization of the devices and the use of drastically less magnetocaloric and magnetic material. There are two major challenges to be solved. One concerns the application of new magnetic field sources that can generate a fast and efficient alternating magnetic field at high frequencies. The other one deals with the application of new thermal management principles in a form of thermal control devices. One particular sub-domain of thermal control devices are thermal switches.

An interesting field, to look for thermal switch mechanisms, is microfluidics, which has enabled the development of integrated lab-on-chip devices. Although most microfluidic devices are based on a continuous flow of liquids in microchanells, there has been an increasing interest for the past couple of years in devices that rely on manipulation of discrete droplets using surface tension effects. One such technique is ElectroWetting On Dielectric (EWOD), which is based on wettability of liquids on a dielectric solid surface by varying the electrical potential. EWOD system's similarity to the digital microelectronic systems has led to the term ″digital microfluidics″.

In this contribution we will present a new concept of magnetocaloric device which couples magnetocaloric effect and EWOD droplet actuation as thermal switch mechanism. We will show different potential designs of such a devices and their operation. Furthermore, the materials and its properties, which constitute the whole device will be discussed.

A thin and light Gd-based thermomagnetic generator

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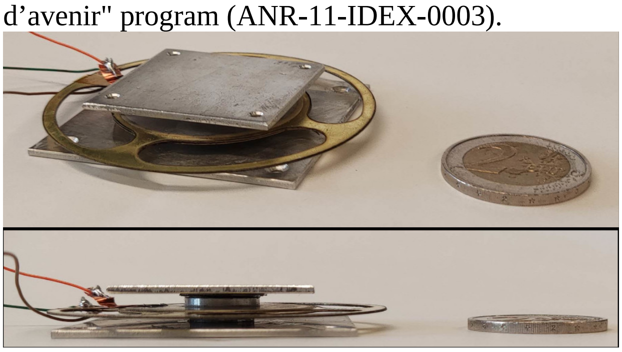
Low grade waste heat represents a cheap and easily accessible source of energy in anthropized environments. The amount of waste heat has been estimated at more than 50% of the global energy production. Within that, up to 60% is available in ultralow-grade form (i.e, in a temperature range from 25°C to 80°C) [1] representing a natural energy source to power small low-consumption devices like wireless sensor nodes, wearable devices, and implants. This makes efficient heat harvesting over small temperature gradients, together with compactness, and low-weight of the harvesting device an entwined technological challenge to which thermomagnetic generators (TMG) may offer some unique answers. Indeed, self-actuation [2], magnet miniaturization [3], and the use of flexible magnetocaloric films [4] are the keys for developing miniaturized magnetic generators. The device presented here has been designed to work over a small temperature interval (ΔT = 20°C), using a freestanding flexible 16 μm thick Gd film vibrating at a working frequency of 50 Hz over a 40 μm gap. A patterned NdFeB hard-magnet film of thickness 50 μm induces self-oscillation (bistable dynamics) and triggers the magnetocaloric effect. A power output of 5 μW is recovered using piezoelectric cantilevers. The main characteristics of the device, focusing on its self-actuating dynamics, will be discussed. **Acknowledgments:** this research has received funding from the French National Research Agency under the project HiPerTher-Mag (ANR-18-CE05-0019), and the LabEx LaSIPS (ANR-10-LABX-0032-LaSIPS) "Investissements d'avenir" program (ANR-11-IDEX-0003).



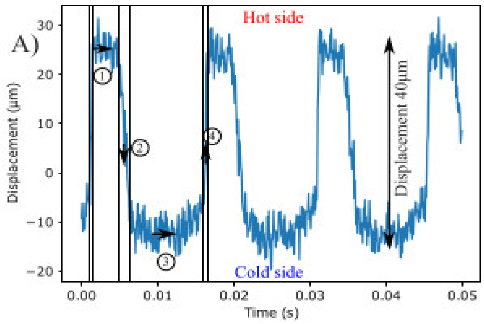


Figure: right) measured bistable dynamics; left) pictures of the TMG device.

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[4] D. Nguyen Ba, et al. , Phys.Rev. Appl. 15, (2021) 064045.

Fe_2P-based hard magnetic materials for permanent magnets applications

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The permanent magnet market is currently divided into two main material types. On one side are ferrite magnets, which are inexpensive but offer lower performance. On the other are rare earth (RE) magnets, which are more costly but deliver superior performance. RE magnets play a crucial role in the shift from fossil fuels to renewable energy sources. However, in the past decade, concerns have grown over supply risks, price volatility, and environmental impact. The emergence of a new class of non-critical magnets, known as "gap magnets" [1], with intermediate properties, could help reduce the demand for these critical materials by substituting RE magnets in applications that do not require maximum efficiency or performance. Since iron is one of the most common magnetic elements, iron-based intermetallic materials such as Fe_2P are desirable for this new class of magnets. Fe_2P shows high magnetic saturation and anisotropy, but its Curie temperature is below room temperature. Simultaneous substitution of Co and Si for Fe and P respectively can increase the Curie temperature way above room temperature and at the same time preserve the hexagonal structure with easy-axis of magnetization and a high value of anisotropy [2]. In this work we synthesized and characterized the structural and magnetic properties of different $Fe_{2-x}Co_xP_{1-y}Si_y$ intermetallic compounds with different quantities of Co and Si substitutions. Curie temperature (T_C), saturation magnetization (M_S) and anisotropy field (H_A) have been measured by means of AC susceptometry, Vibrating Sample Magnetometry (VSM), Singular Point Detection (SPD) and Nuclear Magnetic Resonance (NMR). We have performed a detailed characterization of the intrinsic properties of polycrystalline samples, with particular attention to the anisotropy field, which is a notoriously difficult parameter to measure in polycrystalline materials (fig 1). We have measured high intrinsic magnetic properties, with anisotropy and saturation magnetization superior to ferrites, in particular $M_S \sim 1T$ and $H_A > 2$ T and $T_C > 400$ K. By varying the Co and Si content we can tune the intrinsic properties in order to have larger anisotropy or saturation magnetization. This makes $Fe_{2-x}Co_xP_{1-y}Si_y$ one of the most promising materials as a possible gap magnet and can open the way for optimization of the microstructure and sintering processes in order to achieve significant values of coercivity and remanence.

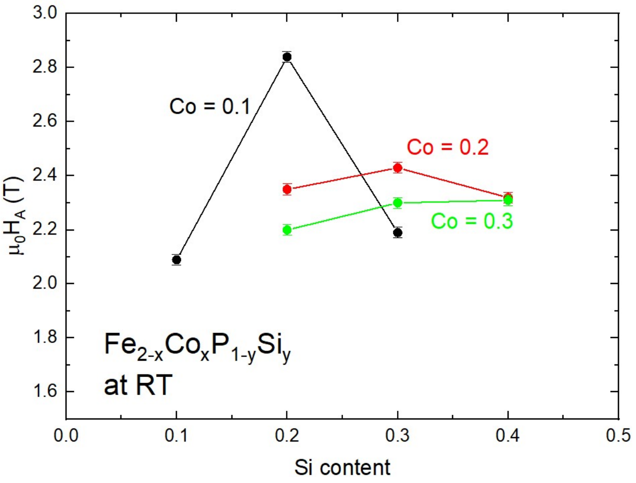

Figure 1: Anisotropy field H_A as a function of Si content in $Fe_{2-x}Co_xP_{1-y}Si_y$.

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Soft Magnetic Composite materials based on thermal resistant boron nitride layer

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Energy saving, green deals, efficiencies, and performance improvement in several industrial sectors depend on materials science research. In that context, the devolvement of new magnetic materials plays a crucial role. Recently, various studies have been carried out in order to resolve critical points: substitutions or recycling of Rare Earth permanent magnets and improving the soft magnetic materials performance with possibilities to prepare the core in the complex shape required for the new designs for electromechanical devices. A potential solution for soft magnetic materials is Soft magnetic Composites.

SMC materials are coated ferromagnetic powders with a specific layer. The layer plays the primary role because it provides electrical insulation (reduction of eddy currents), mechanical strength and affects the magnetic properties. The critical points are high hysteresis losses and low mechanical resistance. The easy solution consists of increasing the heat treatment temperature, but practically all layers are seriously damaged or destroyed over 500°C. From this point of view, we propose a new layer based on the epoxy resin filled by boron nitride nanoparticles.

Boron nitride (BN) is a thermally resistant material, and it fills the epoxy resin in several percentages: 5%, 10%, 20% and 40%. The resin contents, corresponding to the final SMC, are 0.2%, 0.5% and 1%. In Figure 1, the specific iron losses at several operating frequencies are shown; the effect of BN is to maintain thermal stability, and its increment slightly affects the energetic performances. The higher resin content helps the layer in order to increase thermal resistance. Also, magnetic permeability shows good results. These results can be considered suitable for organic layers. The same boron nitride nanoparticle can be used in another coating technique to prepare hybrid layers [1].

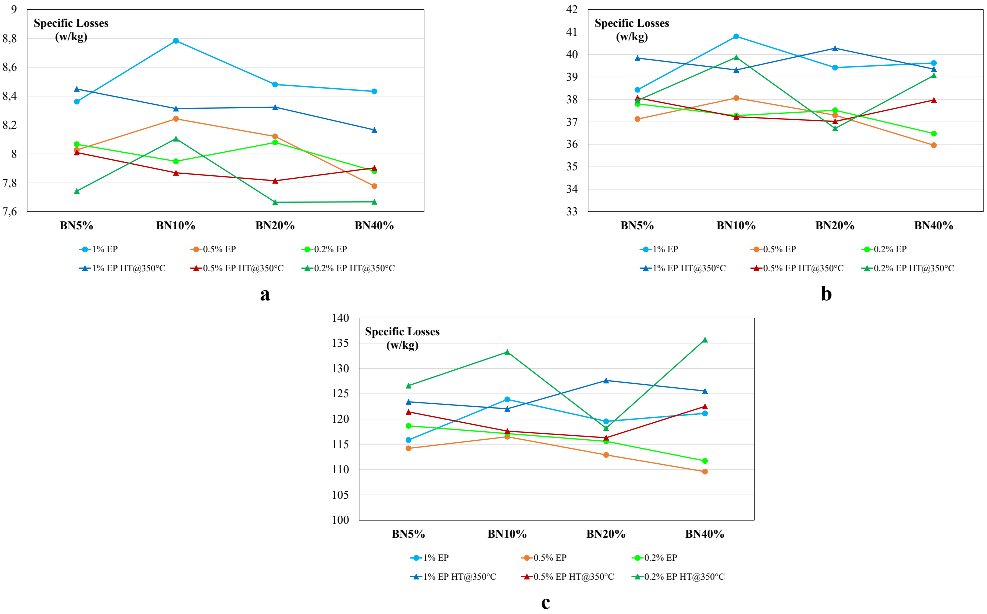

Figure 1 - Specific iron losses at 1T for different boron nitride fillers for proposed epoxy contents at room and 350°C temperature for the following operating frequencies: **a** 50 Hz, **b** 200 Hz and **c** 500 Hz

[1] Emir Pošković et al., “A new approach in the implementation of insulating layers in soft magnetic composite materials”, J. of Magnetism and Magnetic Materials, Vol. 597, 2024.

Magnetocaloric effect by micromagnetic simulations based on the Landau–Lifshitz–Bloch equation

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Solid-state magnetic refrigeration systems offer a promising alternative to conventional gas compression/expansion refrigerators due to their higher energy efficiency and lack of toxic/harmful gases [1]. This technology is based on the magnetocaloric (MC) effect, i.e. the temperature/entropy change of a magnetic material produced by the modification of the applied magnetic field in adiabatic/isothermal conditions which is maximized in the vecinity of a thermomagnetic phase transition. At this stage, a better understanding of the relation between MC properties and materials microstructure is of great interest to push forward this technology.

In this work, we reproduced the MC effect by micromagnetic simulations based on the Landau–Lifshitz–Bloch (LLB) equation in the vicinity of a second-order ferromagnetic to paramagnetic phase transition [2]. This transition is modelled by the mean-field approach (MFA) in the classical limit where the equilibrium magnetization is obtained by means of the Langevin function. The obtained magnetization as well as the parallel susceptibility are introduced as inputs into the LLB equation which is solved in a customized software. Within this approach, after the system reaches the equilibrium state, the obtained magnetization, isothermal entropy change and field dependence exponent *n* shows an excellent agreement with the solutions from MFA (see **Figure 1** using a selected set of material parameters). The influence of the sample's geometry, magnetocrystalline anisotropy and microstructure on the MC effect is studied, paying special attention to the scaling behaviour (universal curves and field dependence exponent *n*). In addition, the rotating MC effect is also explored.

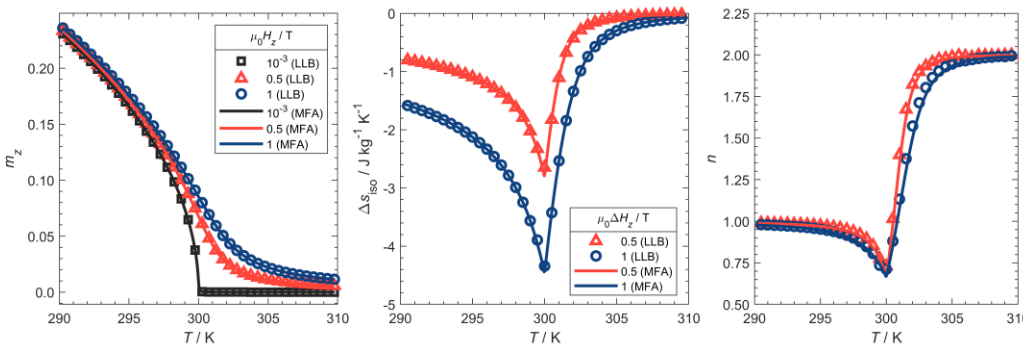

Figure 1: Temperature dependence of the reduced magnetization along the applied field (left), isothermal entropy change (center) and exponent *n* (right) for micromagnetic simulations together with their counterpart MFA solutions (Curie temperature of 300 K).

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[2] D. A. Garanin, Phys. Rev. B **55** (1997), 3050.

Preparation and characterization of MnxZn1-xFe_2O_4 nanofibers via a water-assisted solvothermal method

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Abstract: MnZn ferrite fibers have received wide attentions due to their unique structures, properties and potential applications in energy, health, communications and so on. However, there are relatively few synthetic routes for fabricating MnZn ferrite fibers, the morphology and particle size of fibers are not uniform by the existing methods. In this paper, MnZn ferrite fibers (see fig. 1) have been controllably synthesized by a water-assisted solvothermal method. The effects of experimental parameters such as ratio of ethylene glycol (EG) and water, reaction time and temperature, and annealed temperature on crystalline structure, size and morphology of MnZn ferrite were discussed systematically. The results indicated that the optimum experimental conditions for the formation of fibrous MnZn ferrite with uniform fiber-like morphology, smooth surface and the largest aspect ratio were as follows: the volume ratio of EG/water was around 3:1, the reaction time and temperature were respectively around 24 h and 120 ℃, and the annealed temperature was 500 ℃ or so. The MnZn ferrite fibers prepared at the optimum synthetic condition had ferromagnetic nature, the saturation and remanent magnetization and coercivity of them were respectively 6.5 emu/g, 0.23 emu/g and 161.5 Oe. Besides, the dependence of composition, morphology, size, and property of MnxZn1-xFe_2O_4 nanofibers on the ratios of Mn^{2+} to Zn^{2+} was studied. The results demonstrated that MnxZn1-xFe_2O_4 (x = 0.3, 0.5, 0.7) nanofibers exhibited high purity, good crystallinity, and uniform 1D fibrous structures, which varied in sizes and arrangements by controlling the Mn content. The lattice parameter gradually decreased and the saturation magnetization (Ms) increased with the arising of Mn content from x = 0.3 to 0.7. When the Mn content was x = 0.7, the nanofibers had finer size and superior magnetic property.

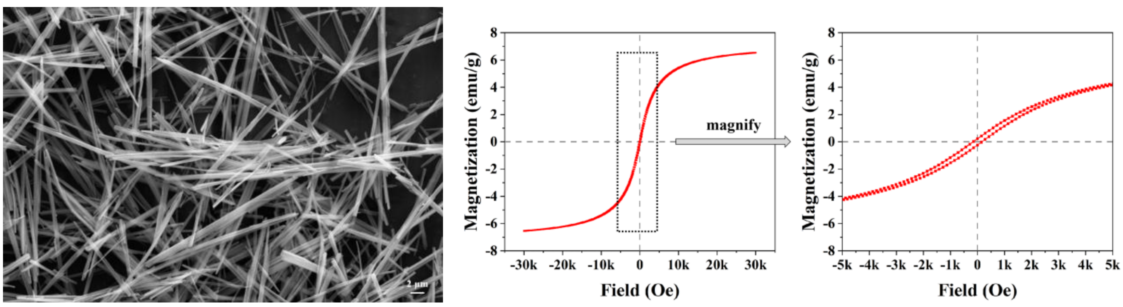

Figure 1. Left: SEM image of the MnZn ferrite fibers prepared at the optimum experimental conditions. Right: Magnetic hysteresis loop of the fiber-like MnZn ferrite prepared at the optimum synthetic condition.

Keywords: MnZn ferrite fibers, Solvothermal method, Ratio of EG/water, Reaction time and temperature, Annealed temperature, the ratios of Mn^{2+} to Zn^{2+}

Materials for the thermomagnetic energy harvesting technology devices

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The efficiency of the thermomagnetic energy harvesting technology devices is fundamentally linked to the properties of the materials used as working bodies in thermomagnetic generators. One of the most suitable materials for this purpose are pyromagnetics, which exhibit high magnetocaloric effect, high magnetization values and significant changes in magnetization in response to temperature variations in the region of the magnetic phase transition. Important parameters include the transition temperature, as well as the magnetothermal, thermal, and mechanical properties of the material.

We have analyzed magnetic materials that show promise for use in thermomagnetic energy harvesting technology. Special attention was paid to materials with high temperatures of magnetic phase transition (above 500 K) and adiabatic temperature change values $\Delta T_{ad} > 2$ K/T. These temperatures correspond to medium and high grades of waste heat source quality/temperature where the most end uses for energy harvesting can be effectively realized.

The properties of these materials and their characteristics are discussed, along with the latest advancements made by researchers in the development of new materials.

Tuning Magnetic Anisotropy in Fe_3Y: An Ab-Initio High-Throughput Study with Transition Metal Doping

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The advancement of permanent magnet systems is essential for a wide range of applications, including energy generation and information technology. This research focuses on developing and optimizing a new magnetic material to meet the demands of these applications. Using an ab-initio-based first-principles approach, the Fe_3Y system was initially selected for its in-plane magnetic anisotropy with a Curie temperature of 550 K [1], which, although advantageous, constrains its use in scenarios that require uniaxial (out-of-plane) anisotropy. The main goal of this study is to transition the magnetic anisotropy from the in-plane to a uniaxial configuration. To facilitate this shift, various transition metals were systematically introduced into both the Y and Fe sites of the Fe_3Y structure. This doping approach enabled the tuning of the magnetic properties and provided insight into the mechanisms governing magnetic anisotropy. As a result, we identified several promising compositions with significant alterations in magnetic behavior, including systems that exhibit uniaxial anisotropy, making them suitable for high-performance magnetic applications. Initial findings suggest that certain transition metal dopants can significantly modify spin-orbit coupling and crystal field effects, achieving the desired anisotropy realignment. These results pave the way for designing magnetic materials with anisotropy oriented along the out-of-plane axis, thereby increasing their potential in energy storage, magnetic recording, and other advanced technological fields. This study establishes a basis for further investigation of Fe_3Y-based compounds with dopants, with the potential to discover a new category of high-performance permanent magnets. Future research will aim to thoroughly characterize the magnetic, structural, and electronic properties of these materials to assess their full potential for industrial use.

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Magnetic Measurements

Invited

Magnetic Characterisation at the Nanoscale: Challenges and Reliability

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Magnetic characterization at the nanoscale is a critical tool for understanding and optimizing the behavior of nanostructured materials in advanced technological applications. However, this task is particularly challenging due to the complexity of magnetic interactions at reduced dimensions together with the limitations of current measurement techniques. Ensuring the reliability of magnetic measurements is therefore essential to design functional materials for application in fields such as spintronics, energy storage, and biomedical applications. Magnetic nanoparticles (MNPs) have gained in the last decades considerable attention in biomedicine due to their potential applications in diagnostics, drug delivery, and therapeutic treatments such as magnetic hyperthermia [1]. Accurate magnetic measurements are critical for understanding and optimizing the performance of these nanoparticles in effective biomedical applications.

This talk will focus on the techniques and challenges associated with characterizing the magnetic properties of MNPs. Key measurement techniques, including vibrating sample magnetometry (VSM), SQUID and AC susceptibility will be discussed in the context of their ability to reveal important parameters such as magnetic moment, coercivity and more generally in hysteresis properties. Special emphasis will be placed on how factors such as particle size distribution, surface functionalization and magnetic interactions affect their magnetic behavior.

Additionally, the role of measurements for the design of MNPs for applications in magnetic hyperthermia, targeted drug delivery, and in magnetic particle imaging (MPI) will be highlighted. By understanding the magnetic properties of nanoparticles, we can optimize their performance for safer and more effective biomedical applications, paving the way for advances in personalized medicine and targeted therapies.

[1] P. M. Martins et al., ACS Applied Bio Materials 2021 4 (8), 5839-5870

Invited

Primary Tesla standards at the German metrology institute PTB

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The talk gives an overview on the primary Tesla standard as realized at the German metrology institute PTB and as disseminated along traceability chains to stakeholders, industry and end-users.

Currently, the primary Tesla standard is realized by nuclear magnetic resonance (NMR) techniques on protons with nuclear spin $I = ½$. The Larmor frequency of the spin precession $\omega_L = \gamma * B$ in a magnetic field is directly proportional to the magnetic flux density B in units Tesla. The proton gyromagnetic ratio γ is known with one part in 10^8 precision from particle-physics experiments [1]. Hence, the Larmor frequency traces B back to the SI standard time (t). Traceable calibration services are carried out at PTB in the range of 10 µT to 0.3T. The method of free induction decay (FID) on pure water samples with a typical diameter of 4 cm for the glass cells is used between 10 µT and 2mT reaching lowest measurement uncertainties (MU) of one part in 10^6 (1 ppm) at around 1m T [2]. It is important to note that proton FID in water samples cannot be easily extended to fields above 2mT, because of a relatively short M_{xy} relaxation time T_2 in the order of seconds. T_2 further decreases with increasing magnetic fields due to dephasing effects caused by field gradients. Therefore, at higher fields between 1mT and 0.3T, a NMR absorption technique [3] is utilized. Here, the NMR resonance/absorption frequency of an RC circuit is measured by means of a marginal oscillator. Samples of aqueous $CuSO_4$ solution enhance NMR absorption rates for a reasonable signal to noise ratio, however, $CuSO_4$ impurities also cause a systematic field distortion by the probe itself, which adds parasitic contributions to the measured magnetic field value. The accuracy, namely $\Delta B/B$ of the absorption method is therefore limited to 10^{-4}. Fig. 1 summarizes the magnetic field dependence of the MUs for both NMR techniques.

For magnetic fields above 0.3T, no primary Tesla standard exists, and it is highly desirable to address this metrology need. In the talk, we present results of recent research and development efforts made at PTB Berlin and Braunschweig to close the traceability gap with NMR methods utilizing hyperpolarized ^{3}He gas instead of protons in water samples.

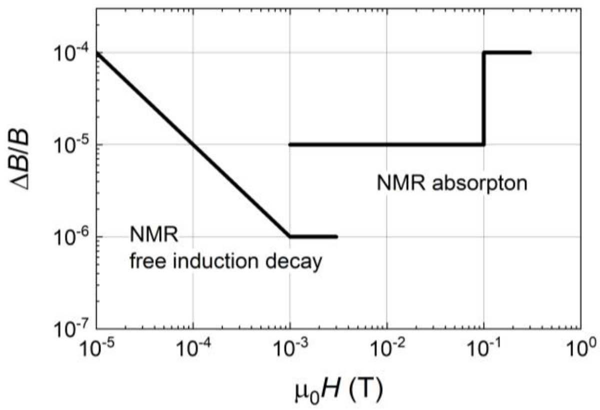

Fig. 1) Measurement uncertainty of the primary Tesla standards at PTB in the range 10µT to 0.3T.

[1] P. J. Mohr, D. B. Newell, and B. N. Taylor, Rev. Mod. Phys. **88** (2016) 035009.

[2] K. Weyand, IEEE Trans. Instr. Meas. **50** (2001), 470 – 473.

[3] K. Weyand, IEEE Trans. Instr. Meas. **38** (1989), 410 – 414.

Invited

Dynamics of magnetic fluctuation in magnetite nanoparticles probed via coherent X-rays

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Magnetic nanoparticles (NPs) have generated an increasing interest due to their potential use in nanotechnologies such as high-density magnetic recording and in medical applications such as drug delivery, hyperthermia or medical imaging.[1] In many of these applications, the ability to fully control the magnetic response of the nanoparticles to a applied magnetic field, in particular their dynamics of magnetic switching and magnetic fluctuations, is crucial for the proper implementation and optimal performance of the device.

Magnetite (Fe_3O_4) NPs are good candidates for many of these applications, in particular in the medical field, as they are non-toxic and carry a strong magnetic moment, which can be manipulated by a distant magnet. When their size is smaller than about 100 nm, magnetite NPs are magnetically monodomain, leading to each NP behaving as a single nanomagnet, or nanospin. When their size is below about 25 nm, a collection of such NPs shows superparamagnetism (SPM) where the nanospins freely fluctuate until they are cooled down below a certain blocking temperature below which they are magnetically blocked at the observation timescale. [2] Understanding the dynamics of the magnetic fluctuations depending on the temperature throughout the SPM-blocking transition for various particle sizes and shapes is crucial for the proper use of the NPs in nanotechnologies.

We are here showing unique time correlation data collected on 5 – 20 nm Fe_3O_4 NPs via coherent x-ray resonant magnetic scattering [3] using synchrotron light. For a given particle size and at a given temperature, coherent x-ray scattering patterns, also known as speckle patterns, are collected at subsequent times and carefully cross-correlated [4], as illustrated in Fig.1a. The resulting two-time correlation maps, as seen in Fig.1b, reveal inherent timescales for the dynamics of fluctuation throughout the SPM transition. We found that the characteristic time of internal magnetic fluctuations abruptly shortens when warming the NPs throughout the superparamagnetic transition. Furthermore, the characteristic fluctuation time drastically increases with particle size and with the presence of interparticle magnetic couplings.

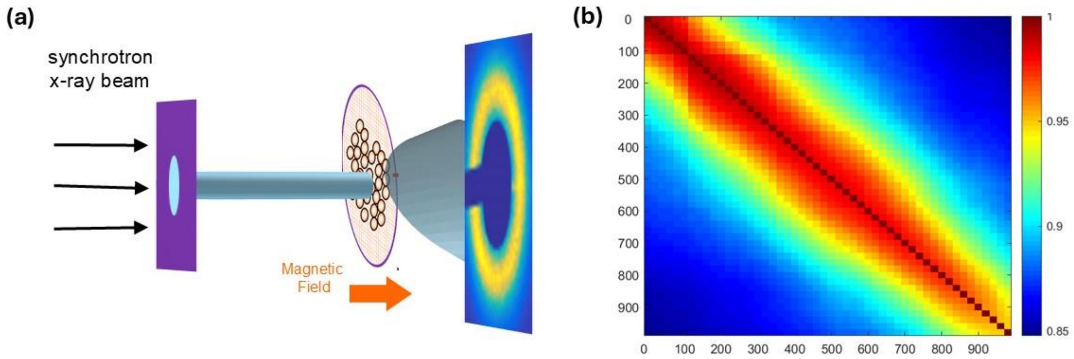

Fig. 1 Illustration of magnetic fluctuation measurements on NPs (a) Setup for coherent x-ray magnetic scattering measurements on NP monolayers in transmission geometry. (b) Two-time correlation map resulting from cross-correlating magnetic speckle patterns collected at subsequent times.

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[3] Chesnel et al., Phys. Rev. B **66** (2002), 172404
[4] Chesnel at al., Nature Comm. **7** (2016), 11648

Determination of Magnetic Symmetries by Convergent Beam Electron Diffraction

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Convergent-beam electron diffraction (CBED) is a well-established probe for spatial symmetries of crystalline samples, mainly exploiting the well-defined mapping between the diffraction groups (symmetry group of CBED patterns) and the point-group symmetries of the crystalline sample [1]. In this work, we extend CBED to determine magnetic point groups. We construct all magnetic CBED groups, of which there exist 125. Then, we provide the complete mapping of the 122 magnetic point groups to corresponding magnetic CBED groups for all crystal orientations. In order to verify the group-theoretical considerations, we conduct electron-scattering simulations on antiferromagnetic crystals and provide guidelines for an experimental realization.

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Tuned deposition parameters for control the magnetic properties of SmCo thick films

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The application of SmCo films in MEMS systems is very attractive; however, there are a number of technological barriers to their realization. Here we present a series of experimental technological steps that can improve the coercivity and residual magnetization of the W/SmCo/W films and avoid their delamination [1, 2]. We optimized the deposition parameters for the formation of crystalline films that are stable after annealing (Fig. 1). We verified the effects of plasma cleaning of the substrate surface before deposition, the effects of deposition temperature and annealing parameters. The polycrystalline structure of the SmCo films appears after annealing. Grain size and magnetic properties of films can be easy controlled by annealing time and temperature. The effect of intergrain coupling distinguished by FORC measurements.

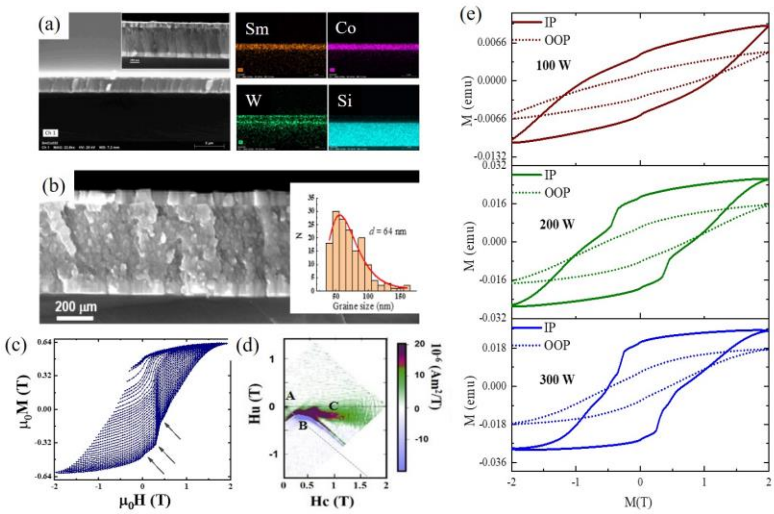

Figure 1: (a) SEM image of as-deposited W/SmCo/W heterostructure cross-section and EDX mapping of Sm, Co, W and Si layer. (b) SEM cross section of SmCo film after annealing at 650°C and the grain size histogram. (c) Series of FORC curves recorded in the in-plane field in sample deposited at 300 W and annealed at 650°C. (d) FORC plots presented in H_u and H_c coordinates, where H_u is the shift of the center of symmetry of the corresponding FORC curve from zero field, due to the intergrain coupling and H_c is grain switching field. (e) The in-plane and out-of-plane magnetic hysteresis *M(H)* dependencies of SmCo film after 650◦C, deposited at different power 100 W, 200 W and 300 W.

A clear effect of the deposition power on the formation of the phase composition was found (Fig. 1). We have determined the optimal processing parameters that affect the phase transformation and functional properties of W/SmCo/W films.

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[2] O. Koplak, F. Maspero, F.Marson, et al, JMMM, **605** (2024), 172323.

Investigating Physical Properties in $Tb_2Ni_{1-x}Co_xMnO_6$ Double Perovskites

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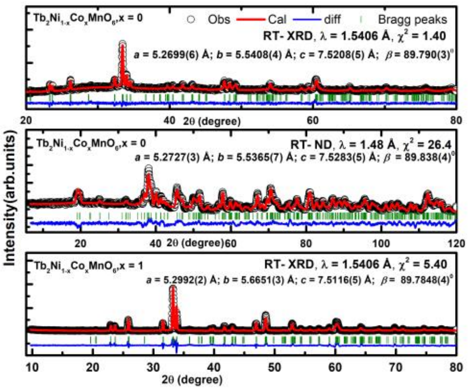
Double perovskites (DP) are fascinating class of materials which are derived out of simple perovskite *ABO_3*, where A and B site can be large electropositive cation and small transition metal anion. These materials exhibit unique structural and physical properties like ferroelectricity, electrical conductivity, magnetoresistance etc [1-4]. DP compounds, showing magnetic behavior are at forefront of material science research due to their crucial role in various industrial applications. Hence research on these class of materials enriches our understanding of fundamental physical principles and leads to development of advanced materials.

Here, we discuss results on polycrystalline $Tb_2Ni_{1-x}Co_xMnO_6$ double perovskite synthesized by solid state route using high purity (≥ 99.9%) precursors in stochiometric ratio with calcination and intermediate grinding with final sintering at 1250 ^{0}C. Phase formation was confirmed by XRD and ND recorded at PD-3, Dhruva, India [5].

Fig shows Rietveld refined XRD and ND patterns of $Tb_2Ni_{1-x}Co_xMnO_6$ (x = 0) and XRD pattern of $Tb_2Ni_{1-x}Co_xMnO_6$ (x = 1) fitted with monoclinic *$P2_1/n$* space group by employing Fullprof suite along with crystal structure [6]. Magnetization study carried out by employing PPMS in VSM mode (M/s. Quantum Design) on $Tb_2Ni_{1-x}Co_xMnO_6$ (x = 0) ascertain, paramagnetic to antiferromagnetic transition at 112 K. Isothermal magnetization at 5 K, 50 K and 300 K further elucidate ordering. Physical and structural properties are further being comprehended by temperature dependent neutron diffraction, dielectric, specific heat, AC Susceptibility study which will clearly depict role of Ni and Co ion in tailoring properties and magnetic structure of Tb_2Ni1-xCoxMnO_6.



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[4]. Rituparna Das and R.N.P Choudary, *Ceram. Inter.*,47, (2021) 439-448.
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Quantum sensing with NV centers: magnetometry and beyond

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Sensing with Nitrogen-vacancy centres, where a single spin defect in diamond is used as an atomic scale magnetic field sensor, is seeing increased adoption through the academic community [1]. The capabilities of the NV as a sensor, however, offer much more than the quantitative mapping of weak magnetic fields.

In this talk I will present our most recent progress towards the development of scanning NV technology as a commercial product [2] to image weak DC as well as AC fields with resolution approaching the nanometre scale and speeds that are comparable with other SPM techniques. I will also show how in recent years, NV sensing had been proven to be a powerful technique to perform surface analysis beyond conventional magnetometry.

Application of the technique include imaging of antiferromagnetic films, skyrmions, multiferroics, surface current density, spin waver and FMR resonance, magnetic noise as well as microwave field imaging. In the last part of the talk, I will also discuss applications for failure analysis of nanoscale devices and magnetic memories.

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Measurement of magnetic losses in soft magnetic materials for power electronics under DC-bias and non-sinusoidal operation

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The research aims to measure and characterize magnetic losses in various soft magnetic materials, including ferrites, amorphous, and nanocrystalline cores, under both DC-biased conditions and non-sinusoidal flux density waveforms with a versatile measurement setup. Characterizing these materials under unconventional flux waveforms is essential for optimizing the performance of magnetic cores in power electronics, where inductors and transformers operate across a broad range of conditions. The proposed analysis uses the two-winding flux metric measurement setup principle [1], described in Fig. 1, without needing an auxiliary winding to control the DC bias value. The system is driven by voltage waveforms generated by a power supply stage consisting of an arbitrary waveform generator and a power amplifier. This setup provides precise control over the shape and dynamics of the waveforms, ensuring they meet the specific requirements of power electronics applications. The bias value is regulated by properly controlling the flux density waveforms, as represented in Fig. 2. The setup is applied for the experimental characterization of different soft magnetic materials suitable for application in power converters.

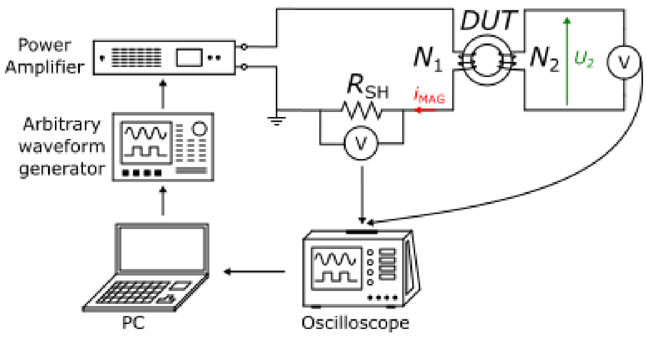

Figure 1: Scheme of the conventional two-winding fluxmetric setup used for the characterization.

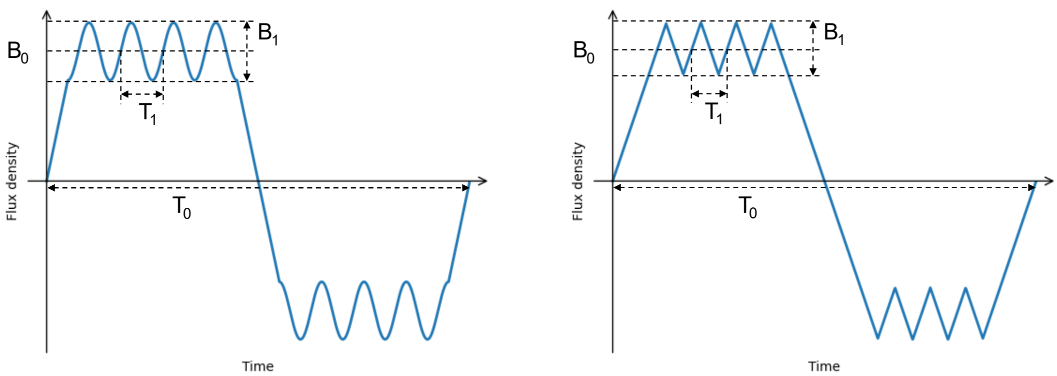

Figure 2: Qualitative behavior of flux density waveforms applicable for measuring the energy losses of soft magnetic materials under DC-biased conditions, under different waveform shapes.

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Magnetic Nanoparticles and Biomedical Applications

Invited

Measuring the heating power and temperature of magnetic nanoparticles

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Localized heating of magnetic nanoparticles in an ac-field due to hysteresis is widely explored for biomedical applications such as drug delivery and magnetic hyperthermia in cancer treatment. In order for these applications to be efficient, it is crucial to be able to control the heating of magnetic nanoparticles. To this end, understanding how and on which time scales the heat is dissipated in nanoparticles and their near surroundings is important.

Nevertheless, quantifying the heating power and temperature at the nanoscale is notoriously difficult. As a matter of fact, the standard ac-calorimetry method commonly used to determine the heating power is subject to large systematic errors; a recent inter-laboratory study across 17 state-of-the-art laboratories displayed a standard deviation of up to 40% [1]. Moreover, the local temperature profile inside and around magnetic nanoparticles is a topic of controversy, with studies reporting hot-spot effects (see fig. 1) with significant temperature gradients (tens of K over a few nm) in the proximity of the particles [2], while other studies find no temperature gradients between the particles and their surroundings [3].

In this talk, we give an overview of results and models from the literature and relate it to our recent findings [4,5]. We show how the standard method for ac-calorimetry can lead to erroneous results if the temperature increase in the sample is measured relative to its initial temperature and not relative to the temperature of the surroundings in accordance with Newtons law of cooling [4]. Moreover, by use of in-situ synchrotron x-ray diffraction, we simultaneously determine the temperature of both nanoparticles and their support through their thermal expansions [5]. This thermometry method is versatile since it requires no modification of the materials [3,5]. With unprecedented sub-K temperature resolution, we observe no temperature difference between nanoparticles and their support, and hence question the existence of hot spots [5].

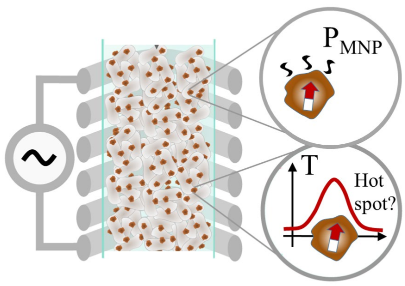

Figure 1: Heating power P_{MNP} and temperature T of magnetic nanoparticles in an AC-coil.

[1] J. Wells et al. International Journal of Hyperthermia 38 (2021) 417.

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[3] S. Faure et al. J. Phys. Chem. C 124 (2020) 22259.

[4] L. G. Hanson et al. IEEE Magnetics Letters 14 (2023) 6100505.

[5] L.G. Hanson et al. Preprint (2024).

Invited

Nanoparticle Innovations: Harnessing Magnetic Iron Nanoparticles for Obesity and Hybrid Gold-Iron Nanourchins for Advanced Lung Cancer Therapies"

Anna Laurenzana[1], Giorgia Papini, Jessica Ruzzolini[1] Martin Albino[2], Cecilia Anceschi[1], Elena Balica[2], Francesca Scavone,[1] Lisa Giovanelli[3], Daniele Guasti[4], Mirko Severi[5], Rita Traversi[5], Oliviero Gobbo[6], Claudio Sangregorio[2].

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Nanotechnology is revolutionizing the landscape of medical treatments, offering transformative approaches to address complex health challenges. The presentation will explore the pioneering applications of nanoparticles in the treatment of two critical conditions: obesity and lung cancer. We will delve into the advanced use of nanoparticles, examining how their unique properties can be harnessed to target and modulate specific disease mechanisms effectively.

In the fight against obesity, we focus on octahedral iron-oxide (Fe3O4) magnetic nanoparticles (MNPs) functionalized with meso-2,3-dimercaptosuccinic acid (DMSA) and chitosan (CHITO). Combined with low-frequency alternating magnetic fields (LF-AMF), these nanoparticles induce magneto-mechanical stress on key cells involved in adiposopathy—macrophages and adipocytes. Our research demonstrates that this magneto-mechanical treatment (MMT) significantly inhibits macrophage proliferation and stimulates the production of reactive oxygen species (ROS). Concurrently, it promotes lipolysis in adipocytes, facilitating the reduction of fat stores and offering a novel approach to managing obesity.

For lung cancer treatment, we investigate the use of hybrid gold-iron nanourchins, a cutting-edge nanoparticle design with distinct therapeutic potential. These nanourchins have shown remarkable efficacy in targeting A549 lung cancer cells by inducing oxidative stress and mitochondrial damage. The increased production of reactive oxygen species (ROS) and the subsequent impairment of mitochondrial function lead to cellular damage and disruption of cancer cell invasiveness. This innovative nanoparticle design highlights a promising strategy for overcoming the limitations of current lung cancer treatments.

This presentation will provide a comprehensive overview of these groundbreaking nanoparticle applications, highlighting how their specific mechanisms can be tailored to address the unique challenges posed by obesity and lung cancer. By showcasing the innovative use of nanoparticles in these distinct therapeutic contexts, we aim to demonstrate their transformative potential in enhancing treatment efficacy and improving patient outcomes.

Invited

Magnetic nanoparticles and magneto-mechanical effects: A novel approach to preventing adiposopathy

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[a] School of Pharmacy and Pharmaceutical Sciences, [b] School of Medicine, [c] Electronic and Electrical Engineering, Trinity College Dublin, Ireland.

In recent decades, industrialized nations have seen a concerning rise in obesity and overweight rates. In individuals with obesity, structural and functional changes in adipose tissue can induce systemic inflammation, leading to a pathological condition known as adiposopathy. Overweight status ranks as the fifth leading risk factor for global mortality, with around 50% of cancers being strongly associated with obesity. Addressing adiposopathy is therefore crucial [1].

This project explores the use of magnetic nanoparticles (MNPs) and the application of magneto-mechanical stress through an external alternating magnetic field as a potential treatment for adiposopathy. While MNP technology has shown promise in cancer therapy [2-3], this research focuses on its application for adiposopathy. Specifically, 20 nm octahedral magnetite-based MNPs were synthesized and functionalized with chitosan and di-mercapto-succinic acid (DMSA) to enhance their stability in biological environments and improve cellular interactions.

The MNPs were incubated with macrophages and adipocytes—key cells involved in adiposopathy regulation in adipose tissue—and exposed to the alternating magnetic field. Additionally, interactions with blood components were assessed to evaluate potential toxicity associated with this therapy [4]. DMSA-MNPs did not impair platelet function or red blood cell integrity but did induce DNA fragmentation and reactive oxygen species production in macrophages, as well as lipolysis and lipid droplet fragmentation in adipocytes following magneto-mechanical treatment.

These results suggest that the synthesized nanoparticles are compatible with blood and that the proposed treatment can promote the morphological and functional recovery of adipose tissue. MNPs show potential as a promising tool for treating adiposopathy and could contribute to preventing the onset of cancer and other obesity-related diseases.

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The perspectives on using magnetorelaxometry imaging in clinical hyperthermia applications

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Magnetic nanoparticles (MNP) offer promising biomedical applications, one of them being magnetic hyperthermia [1] where the tumorous area is enriched with MNP by direct injection or targeting [2]. Then, an RF magnetic field (f = 50-1000 kHz, with H a few tens of kA⁄m) is applied, heating up the MNP and therefore the tumour tissue. The induced heat leads to tumour cell death due to multiple factors, e.g. protein denaturation and apoptosis or necrosis [3]. For a safe and efficient treatment, it is crucial to precisely predict and monitor the local temperature increase. Therefore, the knowledge of the quantitative spatial MNP distribution is beneficial [3,4]. Magnetorelaxomety imaging (MRXI) is a non-invasive imaging technique for quantitative detection of MNP to provide this information.

In MRX, the MNP distribution is first magnetized by applying a DC magnetic field in the millitesla range. After switching off the field, (the stray field of) the relaxation of the MNP's net magnetic moment is measured by sensitive magnetic field sensors. Spatial encoding is achieved by repeating the MRX procedure with spatially different excitation fields and by measuring the relaxation with multiple sensors. Since para- and diamagnetic tissue possess no magnetic moment without an applied field, MRXI is MNP specific and furthermore provides quantitative information about the MNP distribution with cm resolution.

So far, MRXI has been used only for preclinical studies, though it is equally suited for clinical applications, since there are no constraints about the size of the object under investigation and since the same experimental equipment can be used for humans sized bodies, as well.

In this contribution, we examine the technical requirements to perform MRXI for MNP detection in the clinical setting of a magnetic hyperthermia treatment in a pancreatic cancer scenario. We discuss the constraints of an MRX setup to be operated in a conventional treatment area (type of sensor, magnetic shielding, timing/combination with RF field application) and we estimate the relaxations amplitudes, resolution and overall performance of MRXI experiments assuming a conventional dose of MNP (typically tenths of milligrams) administered to a patient by simulations and test measurements.

We will demonstrate that MRXI is ideally suited for quantification and imaging of an MNP distribution used for human magnetic hyperthermia applications.

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[3] S. Fernandes et.al., ACS Appl. Mater. Interfaces (2021)

[4] I. Rubia-Rodríguez et.al., Materials 14 (4) (2021) 706

[5] For details: https://vhio.net/2022/03/18/vall-dhebron-enrolls-the-first-patient-in-a-clinical-trial-designed-to-treat-locally-advanced-pancreatic-cancer-with-nanoparticles/

Developments in human-sized quantitative imaging of magnetic nanoparticles with optically pumped magnetometers

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Magnetic hyperthermia is a promising biomedical application of magnetic nanoparticles (MNP). The basic idea is to inject MNP into a tumor region, which is then locally ablated by AC magnetic field heating (e.g. 100 kHz, 20 kA/m) of the MNP (hysteresis losses). A prerequisite for precise treatment control is the knowledge of the quantitative MNP distribution in and around the tumor. It is possible to obtain such quantiative information by means of magnetorelaxometry (MRX) imaging, where the MNP's response to pulsed DC magnetic excitation fields is measured, and an ill-conditioned inverse problem is solved. For measuring the relaxation signals, we use optically pumped magnetometers (OPM). We will report our current developments in human-sized MRX imaging, highlighting human-head-sized imaging and human-torso-sized imaging of MNP [1,2] (Fig. 1). In both cases we use clinically relevant MNP concentrations in the range of 2 mg/cm³. We apply strong excitation fields of up to ~20 mT, at a distance of ~10 cm, to sufficiently magnetize the MNP. We integrate a nonlinear relaxation model into our inverse problem and exploit the high bandwidth, high sensitivity and high magnetic field gradient robutstness of our OPM. We will present the challenges we solved from the first proof-of-principle measurements to a fully integrated setup. The currently achievable imaging resolution for point-like phantoms is in the single digit cm scale region, and strongly depends on the location of the MNP, i.e. with high resolution near the surface of the human body, and weaker resolution in deep regions. Still, the resolution is sufficient for the application of magnetic hyperthermia. We are currently working towards unshielded imaging, which strongly limits the application from its use in daily clinics.

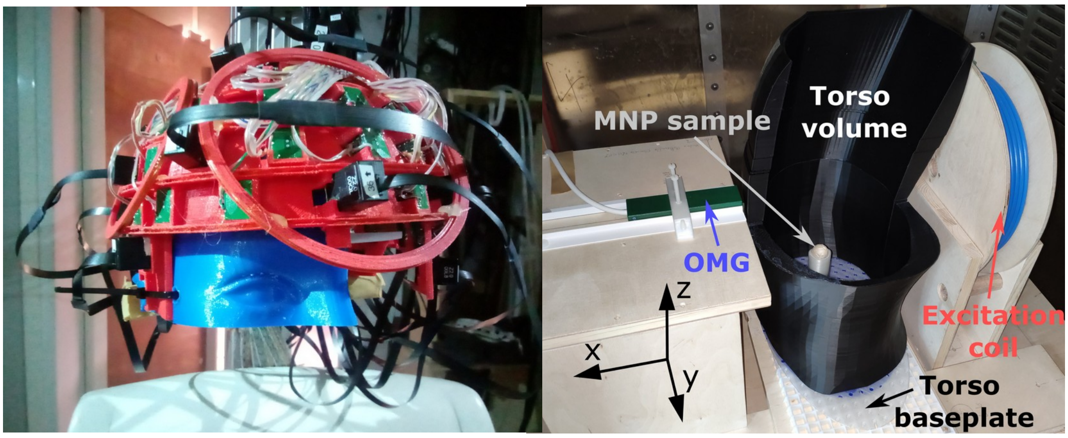

Figure 1: Setups for human-head (left) and human torso (right) sized quantitative imaging of MNP with optically pumped magnetometers.

[1] P. Schier et al., Physics in Medicine & Biology, **68**(15) (2023), 155002.

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Controlled transport of magnetic cuboidal particles in dynamic potential energy landscapes for lab-on-chip applications

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The controlled interaction of magnetic colloids amongst themselves and with surfaces in the presence of magnetic fields is a useful tool for studying and manipulating complex biological systems in microfluidic devices [1]. We, therefore, present the remotely controlled transport mechanism for 3D elongated brick-shaped particles, fabricated using two-photon polymerization lithography. We have thoroughly characterized the particles in terms of their size and magnetic properties.

The magnetic moment of the polymer brick particles is fixed along the elongated lateral axis by sputtering a magnetic exchange bias thin film on its surface. The transport occurs within a periodic stay field landscape, artificially created by parallel stripe domains that were fabricated via ion bombardment induced magnetic patterning [2]. The potential energy landscape of the cuboidal particles when subjected to the stray field landscape, is modulated by weak external magnetic field pulses resulting in a controlled transport and manipulation of the particles inside a quiescent liquid environment.

We discuss the influence of particle geometry and size in relation to the periodicity of the underlying stripe domain pattern on the transport behavior. The shape anisotropy contributions and the rotation dynamics of the particles in a microfluidic environment leading to the lateral walking and flipping modes of the particle transport are characterized using optical microscopy. We find that the experimental observations compare favorably with theory.

This transport mechanism is promising for the detection of biomolecules in Lab-on-Chip device [3] and for probing the effective field direction of dynamically transformed magnetic stray field landscapes.

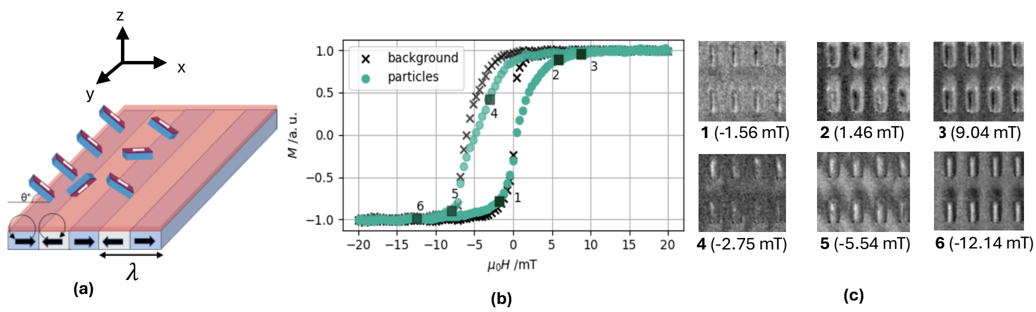

Figure 1: (a) Schematic of transport experiment with periodicity λ = 10µm, (b) magnetization curve of fabricated brick particles and (c) magnetic Kerr contrast of domains for the particles at various points on the magnetization curve.

[1] Afsaneh, et. al., *Talanta Open*, **2022**, 5, 100092, ISSN 2666-8319

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[3] Lowensohn, et. al., *Langmuir*, **2020**, 36, 7100-7108, PMID: 32013444

Magnetophoretic distinction of differently surface-functionalized magnetic microparticles by close-to-surface transport in a quiescent liquid

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Superparamagnetic beads (=magnetic particles, MPs) transported in a quiescent liquid close to the surface of a topographically flat substrate containing a periodic magnetic domain pattern is a promising lab-on-a-chip (LOC) technology for the detection of MP-bound analytes, even when their size is negligible compared to the MP size [1]. As a proof of principle, we show that simple observation of MP motion via optical microscopy is sufficient to distinguish MPs of the same nominal size, but surface-functionalized with two different functional groups. Their different surface chemistry changes the liquid-mediated MP-to-substrate forces acting in the close-to-surface transport [2], which resulted in the experiment in significant variations for the observable MP velocity. More specifically, MPs measuring 2 µm in diameter with a polymer coating of solely carboxyl (COOH) end groups, or a mixture of carboxyl and amino (NH_2) groups, respectively, have been studied. Transport of these MPs in double-distilled water showed a remarkable difference in the average velocity where the COOH MPs were almost twice as fast as the NH_2 counterparts. This result enables the magnetophoretic distinction of MPs with respect to their surface properties.

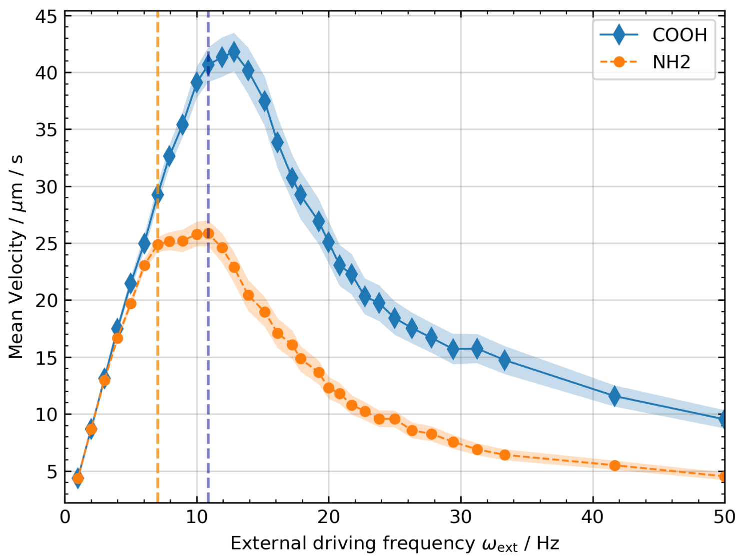

Figure 1: Mean velocity *v* as a function of the external field frequency ω. Following a linear increase of *v* with rising ω, *v* decays exponentially beyond a critical frequency. Both *v* and the critical frequency are significantly smaller for NH_2-functionalized MPs, enabling magnetophoretic distinction from COOH-functionalized MPs.

[1] M. Reginka, Langmuir, **37** (2021), 8498–8507.

[2] R. Wirix-Speetjens, IEEE Transactions on Magnetics, **41** (2005), 4128–4133.

Magnetic Shape-Memory Heuslers Turn to Bio

Milad Takhsha[a], Francesca Casoli[a], Riccardo Cabassi[a], Simone Fabbrici[a], Franco Furlani[b], Silvia Panseri[b], Francesco Cugini[c,a], Federica Celgato[d], Gabriele Barrera[d], Massimo Solzi[c,a], Oliver Gutfleisch[e], Paola Tiberto[d], Vojtěch Uhlíř[e,f], Franca Albertini[a],

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Magnetic-shape-memory Heuslers (MSM) are among the most important classes of materials for multiple-stimuli actuation and multi-caloric applications. This multifunctionality stems from a reversible martensitic phase transformation. These materials have been considered in many studies for technological applications but have been rarely investigated for medical purposes, albeit – at least in theory – they could have promising applications in medical fields similar to the conventional shape-memory alloys [1].

Thin films, coating layers and micro/nanostructures open up a perspective towards new-concept applications, taking also the advantage of the microstructure tunability and possibility of integration into microsystems. Over the past years, we have comprehensively investigated the structure, microstructure, magnetic properties, down-scaling processes and the effects of different external stimuli on the martensitic transformation of Ni-Mn-Ga epitaxial thin films [2,3 and references therein].

In this study we highlight the biomedical perspective for these types of materials highlighting the most interesting functionalities of MSM Heuslers, which can be exploited towards the potential biomedical devices or therapies.

Among the critical steps towards the realization of medical applications for MSM Heuslers is the evaluation of cytotoxicity. We report also the cytocompatibility and cell morphology analysis of human fibroblast cells cultivated on Ni-Mn-Ga epitaxial thin films by *in vitro* biological tests. Our qualitative and quantitative biological characterizations reveal that Ni-Mn-Ga films are able to promote the adhesion and proliferation of human fibroblasts without eliciting any cytotoxic effect.

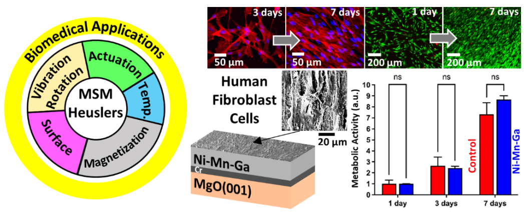

Fig. 1 Biomedical perspective for MSM Heuslers, cytocompatibility and cell morphology analysis of human fibroblast cells cultivated on Ni-Mn-Ga epitaxial thin films.

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Understanding magnetic hyperthermia performance within the Brezovich criterion: beyond the uniaxial anisotropy description

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Careful determination of the heating performance of magnetic nanoparticles under AC fields is critical for magnetic hyperthermia applications [1]. However, most interpretations of experimental data are based on the uniaxial anisotropy approximation, which in first instance can be correlated with particle aspect ratio. This is to say, the intrinsic magnetocrystalline anisotropy is discarded, under the assumption that the shape contribution dominates. We show in this work [2] that such premise, generally valid for large field amplitudes, does not hold for describing hyperthermia experiments carried out under small field values. Specifically, given its relevance for in vivo applications, we focus our analysis on the so-called "Brezovich criterion", H·f = 4.85×108A/m· s. By means of a computational model, we show that the intrinsic magnetocrystalline anisotropy plays a critical role in defining the heat output, determining also the role of shape and aspect ratio of the particles on the SLP. Our results indicate that even small deviations from spherical shape have an important impact in optimizing the heating performance (See Fig. 1). The influence of interparticle interactions on the dissipated heat is also evaluated. Our results call, therefore, for an improvement in the theoretical models used to interpret magnetic hyperthermia performance.

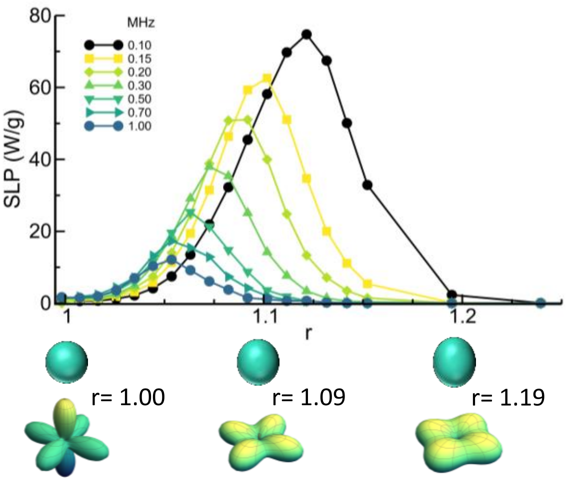

Figure 1: Specific loss power dependence on the aspect ratio (r) of magnetite NP of size D= 25 nm at different frequencies and ac field values complying with the Brezovich criterion.

[1] H. Gavilán et al., Nanoscale 13, 15631 (2021)

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Magnetic nanoparticle formulations for early diagnosis of Alzheimer's disease

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Synthetic controls enable the precise manipulation of size, shape, composition, surface chemistry, and certain properties of nanoparticles during fabrication. Specifically, for magnetic nanoparticles (MNPs), key aspects correspond to tuning their magnetism following approaches to: a). Control size: Adjusting the size distribution of MNPs during synthesis, results in magnetic property tuning, b). Control composition: Varying the composition of MNPs can significantly influence their magnetic behavior i.e. magnetic moment, magnetic anisotropy, and Curie temperature. c). Modify surface: Can shield nanoparticles from agglomeration or specifically target biomedical probes and d). Control shape: The shape of MNPs also plays a critical role in determining their magnetic properties by adjusting the aspect ratio or geometry of the nanoparticles.

This work focuses on the synthesis, characterization and implementation of magnetite (Fe_3O_4) nanoparticles as carriers and enablers, in an electrochemical sensor for early diagnosis and monitoring of Alzheimer's disease (AD). These MNPs facilitate sample purification, minimize non-specific signals, and enhance flow control during various stages, such as bioreceptor incubation, purification, recognition, and signal acquisition.

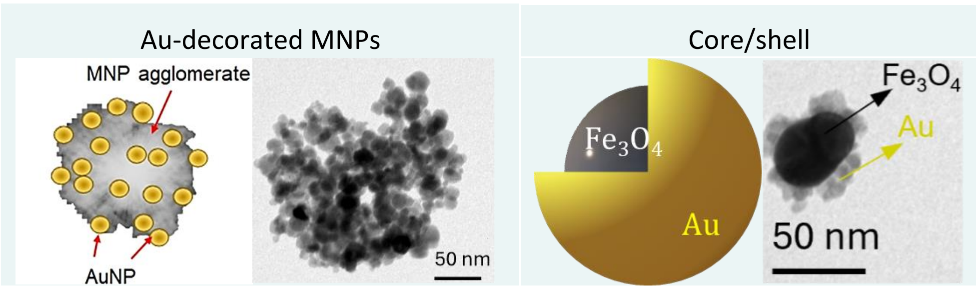

Figure 1: Nanparticle Au/Fe_3O_4 schematic formulations and TEM images.

Magnetite MNPs of different sizes are synthesized following wet chemistry approaches and rigorously characterized structurally, morphologically, and magnetically (TEM, XRD, VSM). To provide electrochemical sensing biphasic nanostructures are manufactured composed of a gold contact and a magnetic part in variable formulations (Figure 1). Such nanostructures with diameters ranging from some tens of nm up to 200 nm are exploited for the immobilization of AD aptamers to eventually bind to AD blood biomarkers like Aβ40, Aβ42, and p-Tau with good selectivity, specificity, fast response, and low limits of detection (LOD), across different stages of AD.[1,2]

This work is Funded by the European Union under GA no. 101120706 - project 2D-BioPAD.

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Magnetism for Neuromorphic and Unconventional Computing

Invited

Paving the way towards high-performance spin-wave Ising machines.

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We present a versatile platform for low-power Ising machines that support and rapidly solve combinatorial problems and consider a way for their upscaling using the advances in magnetism. Spin-wave Ising Machines (SWIMs) are a new class of time-multiplexed Ising machines [1,2] that we implemented with an interconnected array of spin-wave radio frequency (RF) pulses propagating in a ring oscillator with additional measurement and control feedback system implemented with an FPGA. The SWIM main loop consists of linear and parametric amplifiers, a pulse generation switch and a delay line where RF pulses, i.e. Ising spins, propagate. Spin-waves propagate orders of magnitude slower than the speed of light and can be easily interconverted into RF signals which are easily manipulated by usual electronic RF components. Thus, the use of spin-waves allows for dramatic miniaturization, reduction of power consumption, and significant improvement of frequency stability in time-multiplexed Ising machines. Here we consider different magnetic media, which can be employed for the storage and processing of Ising spins.

We show fully operational proof-of-concept SWIM, based on the conventional YIG spinwave delay line, and discuss our advances in SWIM design and optimization, which allow to boost its capacity and performance. Particularly, we demonstrate a hybrid magneto-acoustic delay line, with the effective hybridization and information transduction between acoustic and spin waves. It allows to increase the capacity of Ising spins by an order of magnitude, due to extremely large delay times and low damping of the waveguide. We also show a chirp design of input and output transducers, which allows to compensate the natural dispersion of SWs and to further increase the Ising spin density.

To optimize the performance of SWIM we developed a numerical model suitable for the description of the time-multiplexed Ising machine with a delay line for spins storage and evolution [3]. The model allows to find out the optimal parameters of a SWIM circuit for the highest probability and the minimum time to find an optimal solution. Particularly, we found a certain region of nonlinear frequency shift in the loop and amplifier compression gain, where the convergence to solution is maximized. The model allows us to design optimal schemes and annealing schedules for time-multiplexed SWIMs.

We believe that our work creates a pathway for miniature low-power and commercially feasible Ising machines for solving a wide range of large-scale optimization problems.

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Invited

Engineering stochastic magnetic tunnel junction for probabilistic computing

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Conventional electronics relies on deterministic operation of electronic devices, where stochastic behavior is attempted to be minimized. In contrast to this perspective, in 1981, R. P. Feynmann gave a suggestion of unconventional computing paradigm, so-called the probabilistic computing. This approach leverages intentionally enhanced probabilistic behavior of physical system within computing hardware to simulate physical phenomena that are inherently probabilistic. The demand for such probabilistic computers has risen recently as a rapid increase in computing tasks that can be efficiently addressed by probabilistic algorithms. Probabilistic bit (p-bit) is a fundamental unit constituting the probabilistic computer and recent studies have revealed that probabilistic spintronics devices, in particular, the stochastic magnetic tunnel junction (s-MTJ), shows promise for constructing the p-bit.

In this talk, I show various proof-of-concepts for the spintronic probabilistic computers and also discuss the physics and engineering of s-MTJ. I first outline the basic properties and characteristics of the p-bit with s-MTJ and then showcase several demonstrations including combinatorial optimization [1], Boltzmann machine learning [2], quantum simulation [3], and Bayesian inference [4]. After that, I delve into the physics of the stochastic magnetic tunnel junction elucidating the time-domain [5,6] and time-averaged [7,8] properties. I also discuss advanced design of the s-MTJs [9-12] tailored for reliable, large-scale computers.

These studies are carried out in collaboration with H. Ohno, S. Kanai, W. A. Borders, K. Hayakawa, K. Kobayashi, R. Ota, H. Kaneko, S. Datta, and K. Y. Camsari, and were partly supported by JST-CREST JPMJCR19K3, JST-AdCORP JPMJKB2305, JST-ASPIRE JPMJAP2322, MEXT X-NICS JPJ011438 and RIEC Cooperative Research Projects.

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Invited

Solving Combinatorial Optimization Problems and Generating Random Numbers with Stochastic Magnetic Tunnel Junctions

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Can stochastic magnetic tunnel junction arrays solve complex optimization problems better than existing methods? The first part of this talk addresses this question by presenting the Sherrington–Kirkpatrick (SK) spin-glass model, an NP-complete problem with a known solution in the thermodynamic limit. Remarkably, we show by numerical modeling that coupled macrospins emulating the SK model and evolving according to Landau-Lifshitz Gilbert dynamics can get closer to the true ground state energy than state-of-the-art numerical methods [1].

In the second part of my talk, I will present our work on stochastic magnetic tunnel junctions based on perpendicular magnetic tunnel junctions. In contrast to superparamagnetic MTJs, we experiment with magnetically stable MTJs and actuate them with nanosecond pulses to make them behave stochastically. We denote this a stochastic magnetic actuated random transducer (SMART) pMTJ device because a pulse generates a random bit stream on-demand, much like a coin flip [2]. SMART-pMTJs produce truly random bit streams at very high rates while being more robust to environmental changes, such as their operating temperature and device-to-device variations, compared to other stochastic nanomagnetic devices [3]. By interfacing a pMTJ to an FPGA, we have generated over 1 trillion bits at rates greater than 100 MHz that pass multiple statistical tests for true randomness, including all the NIST tests for random number generators with only one XOR operation [4]. Finally, I will discuss opportunities to advance the science and applications of stochastic MTJs toward creating better sources of random numbers and addressing complex optimization problems.

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Advancing Neural Network Performance through Magnetic Tunnel Junctions implementations

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Unconventional computational features such as scalability, short-term memory, nonlinearity, and stochasticity are naturally realized in magnetic tunnel junctions (MTJs). This talk presents three spintronic-based hardware approaches to improve the performance and efficiency of neural networks, see Figure 1.

First, we present an MTJ-based spiking neuron that emulates the Hodgkin-Huxley model and achieves GHz spiking rates at 200 mV by combining magnetization dynamics and thermal fluctuations [1]. This provides a robust platform for spiking neural networks.

Second, we propose spin-transfer nano-oscillators as dynamic neurons [2]. These neurons project inputs into an output space for easy classification by linear regression, and can be optimized using dynamic control parameters trained by optimal control theory.

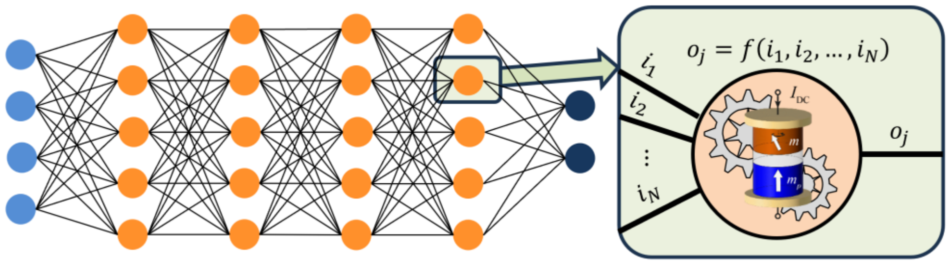

Figure 1: Schematic of the MTJ-based implementation of neural networks.

Finally, we show how MTJs can implement nonlinear activation functions and their gradients, allowing efficient forward and backward propagation in conventional neural networks. Small discrepancies between device-obtained and software-generated activation curves do not significantly affect backpropagation performance.

Our results show that MTJ implementations are robust, scalable, and low-power, making them ideal for deploying deep neural networks in edge applications. Advances in MTJ and spintronic technologies promise significant improvements in the performance of artificial neural networks and address challenges to their widespread adoption.

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Glassy synaptic time dynamics in molecular La0.7Sr0.3MnO3/Gaq3/AlOx/Co spintronic crossbar devices

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The development of neuromorphic devices is a pivotal step in the pursuit of low power artificial intelligence. A synaptic analogue is one of the building blocks of this vision. We study the synaptic behaviour of molecular $La_{0.7}Sr_{0.3}MnO_3$/tris(8-hydroxyquinolinato)gallium/AlOx/Co [1] spintronic devices, where the conductance plays the role of the synaptic weight [2]. We arrange the devices in a crossbar configuration, the most effective architecture for the purpose. We control the conductance of each cross point separately by the application of voltage pulses: when set in the high conductance potentiated state, the devices show spin-valve magnetoresistance, while in the low conductance depressed state, no magnetoresistance is observed.

The time dependence of the resistive switching behaviour is an important parameter of the synaptic behaviour and is very revealing of the underling physical mechanisms. To study the time dynamics of the resistive switching after the voltage pulses, we measure the response of the device to trains of potentiation and depression pulses and the time-resolved conductivity relaxation after the pulses, as shown in Fig. 1.

We describe our results with the conductivity model based on impurity energy levels in the organic semiconductor's gap. The activation energies to move these impurities have a flat distribution, that can explain the glassy behaviour[3].

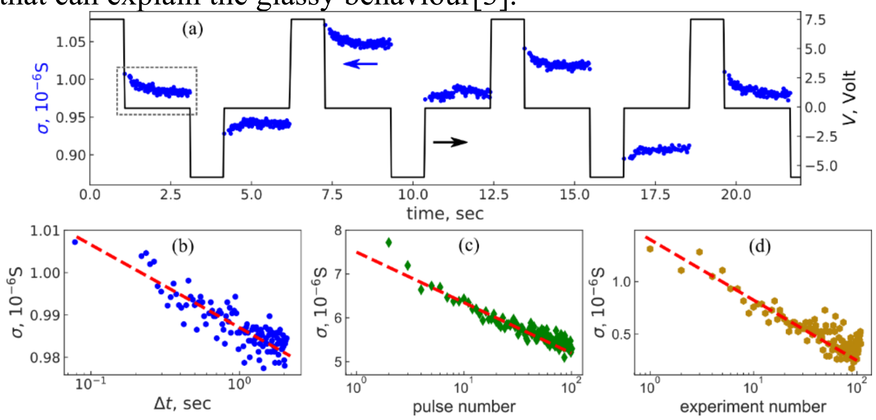

Fig. 1. The slow dynamics of conductivity. (a) The response of a 3×1 sample to a series of +7.5 V and -6 V pulses; the duration of the pulses was 1 s, while reading in between lasted for 2 s and was carried out at -0.1 V. (b) The detailed plot of one such response (dashed rectangle in the panel (a)) compared with the logarithmic decrease. (c) The conductivity after –3V, 1 ms duration pulses applied to a device in a 4×3 sample. (d) The conductivity of a device in a 4×3 sample at the beginning of each of a series of experiments, after a -4 V, 1 s duration erasing pulse.

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Towards a programmable Ising Machine using a network of coupled vortex spin-torque nano-oscillators

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Ising machines (IMs) are physics-inspired computing platforms that can efficiently solve combinatorial optimization problems (COPs). IMs emulate a binary-valued spin-lattice that inherently seeks to minimize its total energy, where spin-coupling interactions encode a COP and lowest energy states represent COP solutions. Instead of fine-tuning annealing schemes [1, 2] to gradually stabilize the system onto the ground state, an alternative is to use thermal noise to stochastically explore the spin state configurations and infer the lowest energy states from the maxima of the resolved probability distribution. This alternative scheme is well adapted when implementing an IM using the stochastic phase dynamics of coupled spin-torque nano-oscillators (STNOs) whose phases are binarized via synchronization to a microwave signal at frequencies f_s two-times the STNO frequency $f_s=2f_{STNO}$ [3].

Here, we present the first results for implementing a spatial and programmable IM using vortex STNOs that operate at frequencies around 200MHz. We experimentally demonstrate that thermal noise induces stochastic transitions between the binarized phase states, that these states are perfectly equiprobable, and that they can, therefore, be exploited for random number generation [3]. Then, we show that this equiprobability is disrupted when adding an external microwave signal at $f_s/2$. In this way, the phase-state probability can be controlled similarly to a p-bit. Finally, we present the first proof of concept of a two-spin IM (N=2), with programmable coupling strength via an adjustable coupling resistance R_c, see Fig. 1. Scaling to larger arrays (N>2) will be discussed to build a full spatial and programmable stochastic IM using vortex STNOs.

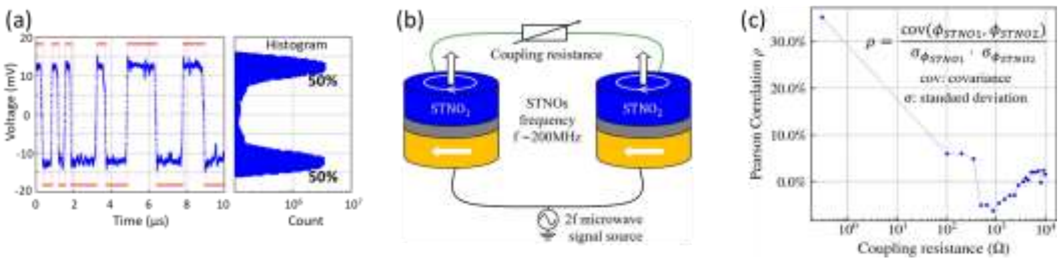

Fig. 1: (a) Example of equiprobable stochastic phase jumps. (b) Schematic of an STNO-based two-spin IM; (b) The Pearson correlation between the two STNO phases decreases and changes sign upon increasing R_c.

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Non-Destructive Testing

Invited

Ultrasonic nondestructive evaluation of lithium-ion cells

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The internal state of a lithium-ion battery cell is usually described through several parameters such as the state-of-charge, the state-of-health, the state-of-safety, etc., which cannot be directly measured but only estimated starting from a combination of electrical measurements, models, and data-driven approaches [1].

In this contest, nondestructive evaluation methods applied to lithium-ion cells are attracting more and more research efforts, as they can effectively complement electrical measurements to provide information that can improve the estimation of the cell parameters, and hence lead to a better and safer management of the cells-battery system, and more accurate models [2-4].

In particular, ultrasonic nondestructive evaluation has been demonstrated to be sensitive to the state-of-charge, health, and safety, as well as useful to reconstruct the cell's multilayered structure and to detect internal defects by analysing the ultrasonic time-of-flight and attenuation. However, the complex structure of a cell, and the nonlinear and hysteretic behaviour of the time-of-flight with respect to the cell voltage and charge, poses some challenges to a straightforward use of features extracted from ultrasonic data to estimate the cell parameters [5-6].

To increase the effectiveness of the ultrasonic analysis for the estimation of the state-of-charge, we apply a nonlinear ultrasonic analysis on the cells [7-8].

Then, the comparison and fusion of features from linear and nonlinear terms is implemented to increase the accuracy in the state-of-charge estimation.

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Invited

Modes and Fields in Multimodal Resonant Inductor Arrays

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Arrays of tightly spaced inductive coils are common in magnetic resonance coupling power-transfer and non-destructive sensing applications. In particular eddy-current array sensing technologies use densely packed high inductance elements in order to maximise their resolution when searching for flaws [1]. The close proximity of these inductive elements can lead to complex and surprising resonant phenomena [2] which have traditionally been ignored or suppressed to aid operational and analytical simplicity. However, understanding the physics and behaviour of these resonant phenomena could lead to significant advances in the design and operation of more sophisticated sensing and power-transfer technologies.

In this paper, the theory and practical operating principles behind multimodal resonant inductor arrays exhibiting multiple resonant modes are presented [3]. Matrix notation circuit theory models are employed to predict the resonant frequencies (eigenmodes) and eigenvectors of the arrayed systems, as well as recreating and optimising the resonant spectra of these arrays for novel non-destructive sensing applications.

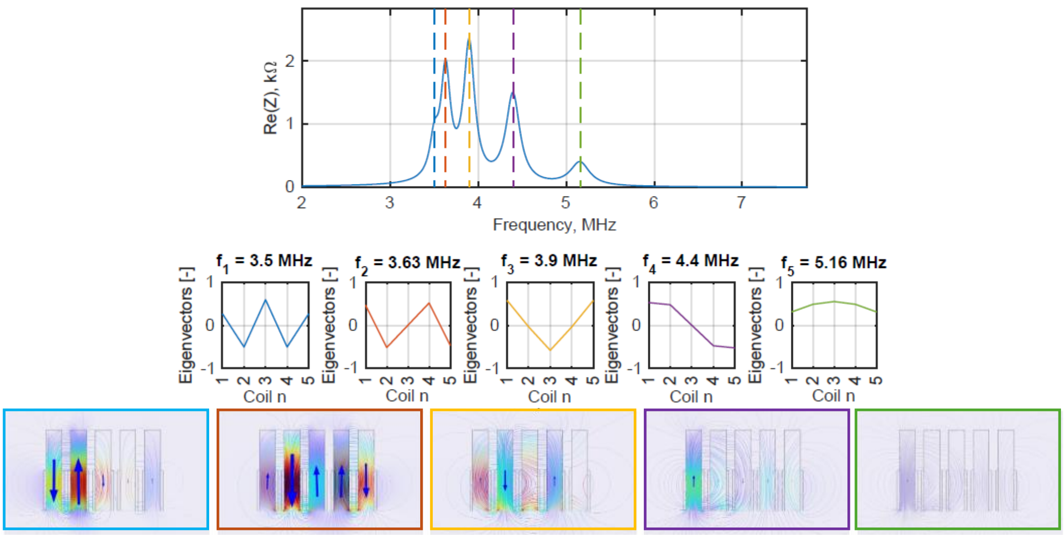

Figure 1: Circuit model calculated impedance spectra (top) of a 5-coil linear array, showing resonant frequencies (dashed lines) and eigenvectors, compared to FE modelled magnetic field directions in coil elements at each eigen-frequency (bottom row).

A detailed finite element analysis study, conducted in 2D and 3D in COMSOL, is presented, evaluating the inductor properties and unique magnetic field morphologies in different arrayed configurations when operated at their unique resonant modes (see Figure 1). The results are compared to experimental measurement of arrays and the challenges, applications and opportunities discussed.

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Analysis of magnetic-mechanical symptoms occurring near the plastic area in order to estimate material effort.

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The article discusses the assessment of magnetomechanical symptoms near the yield area in steel materials, focusing on the implications of these phenomena for material diagnostics. The research explores how localized plastic deformation, particularly the formation of Lüders bands, affects the magnetic properties of materials. Lüders bands, which occur during the transition from elastic to plastic deformation, significantly influence magnetic domain structures [1], leading to detectable changes in magnetic signals, such as Magnetic Barkhausen Noise (MBN) and Magnetic Flux Leakage (MFL). The study presents a novel approach using a custom measurement setup to analyze the magnetic field distribution and magnetic susceptibility (denoted as the S parameter) on the surface of steel samples under mechanical stress (Fig.1).

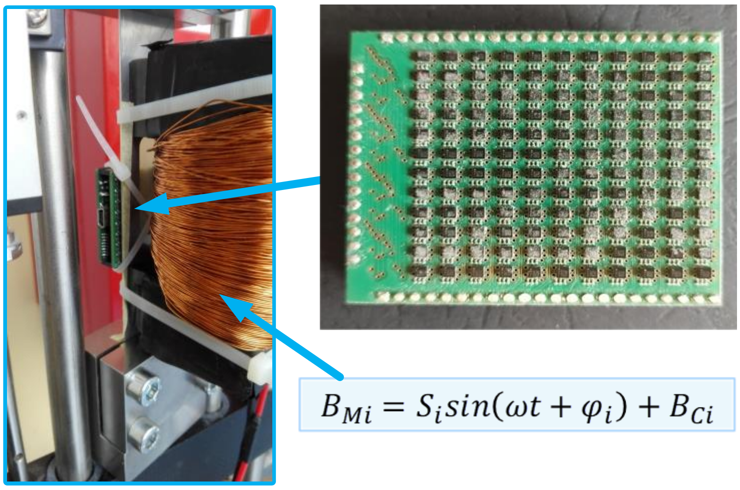

Figure 1: Test stand with measurement magnetometers matrix and measurement model used for parameters estimation.

The experimental results highlight how changes in the magnetic properties correlate with different deformation phases, emphasizing the importance of identifying key diagnostic signals that indicate early stages of material degradation. The findings have practical applications for monitoring the structural health of steel components in critical industries, enabling early detection of fatigue and plastic deformation before catastrophic failures occur. The research contributes valuable insights into the complex interactions between mechanical stresses and magnetic properties, supporting the development of more advanced diagnostic techniques.

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Numerical Modeling and Micromagnetics

Invited

Extending length scales of micromagnetic simulations

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Computational micromagnetics is a widely used tool in the design and development of magnetic materials and devices. It relies on the continuum theory of micromagnetism [1], which studies magnetization processes on a significant length scale. This scale is small enough to resolve magnetic domain walls and large enough to replace atomic spins with a continuous function of position. Whereas this intrinsic length scale is a few nanometers for most industry relevant magnetic materials, the design related length scales such as the grain size or magnet size are much larger. In this talk, I will discuss strategies towards large-sample-size micromagnetic simulations.

One approach is to rely on fast numerical algorithms. Key sub-tasks of a micromagnetic solver are the magnetostatic field computation and the efficient search for the next local minimum of the total energy. Hysteresis curves of synthetic microstructures that reflect realistic grain shapes and grain boundary phases of permanent magnets can effectively be treated using the finite element method. In a finite element framework, algebraic multigrid solvers are state-of-the-art for computing the magnetic scalar potential. For following the local minima along the hysteresis loop, energy minimization techniques can be applied [2]. We show that preconditioning can reduce time to solution by up to two orders of magnitude in a limited-memory quasi-Newton method [3]. Both methods have been implemented in mammosmag, an open-source finite element micromagnetic solver.

Despite effective algorithms, the total sample size of classical micromagnetics is limited by the available computational resources. To go further up in length scale, we developed a reduced order model [4]. This method is suitable for computing magnetization reversal process in granular permanent magnets with grain sizes of several micrometers. From local hysteresis models which are applied at representative points of the microstructure, the macroscopic demagnetization curve can be constructed. This method requires the magnetostatic interaction field of uniformly magnetized grains which can be effectively computed with an integral approach accelerated with hierarchical matrices. The sequence of grains which become reversed as the external field is decreased can be recorded and used for training a graph neural network that represents the granular structure of the magnet. Finally, the graph neural network, can be used to predict the demagnetization curve of large-scale granular microstructures.

Funded by the European Union through the MaMMoS project (Grant agreement ID: 101135546), the Austrian Federal Ministry of Labour and Economy, the National Foundation for Research, Technology and Development and the Christian Doppler Research Association.

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Invited

Mode filtering and projection in micromagnetics for studying magnon population dynamics

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Nonlinear spin wave phenomena are the subject of renewed focus due to potential applications in unconventional computing. In magnon reservoir computing, for example, three-magnon scattering can be exploited to perform pattern recognition [1]. From a computational perspective, it is therefore desirable to access the nonlinear dynamics of magnon modes directly in micromagnetics simulations.

In this talk, we will discuss a mode filtering and projection method developed for MuMax3 micromagnetics simulations, which allow the amplitude and population of magnon eigenmodes to be tracked on-the-fly. We illustrate this approach with a number of case studies, such as parallel pumping [2] and non-degenerate magnon scattering [3] in in-plane magnetized disks, magnon scattering in vortex-state eigenmodes, and magnon Floquet states [4]. These examples bring to light phenomena such as mode synchronization, off-resonant scattering, and complex transient processes (e.g., Fig. 1), which are difficult to access with conventional spectral analyses in the frequency domain.

This work is supported by the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101070290 (NIMFEIA).

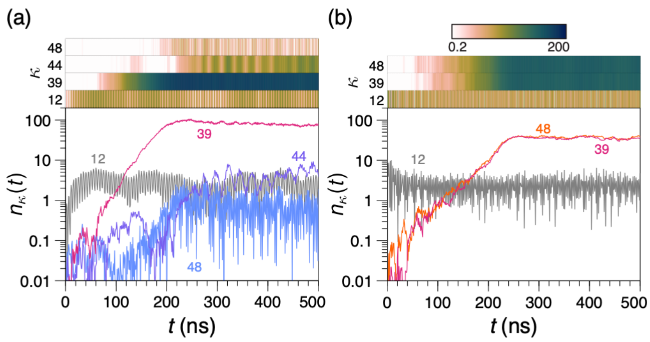

Figure 1: Mode population dynamics under high-power transverse field pumping of an in-plane magnetized YIG disk at (a) 6.90 GHz and (b) 7.32 GHz. After Ref. 3.

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Invited

Dynamics of coupled layers in magnetic tunnel junctions

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The magnetic tunnel junction (MTJ) are key elements in the development of spintronic devices and offers a large panel of advantages in terms of size, energy consumption and operation speed. Their non-volatility serves to store information in magnetic random access memories MRAM and the field-dependence of their resistance allows conceiving magnetic field sensors [1]. Beside to these well-known applications, new functionalities can be envisaged by adapting the composition of the magnetic stacks and the stimuli. One promising structure is an MTJ with two free layers (Fig.1a) capable of continuously switching their magnetization if a bias voltage is applied, thus generating trains of resistance spikes, signals similar to firing event in biologically inspired neurons. The interplay between the inter-layer coupling mechanisms and their individual parameters are responsible of various operating regimes. Modelling and experiments have been performed to identify the suitable condition for spiking and understand the impact of interlayer coupling on the device operation (Fig.1b-c). We confirmed that spike frequency is tunable in the MHz range by varying the voltage amplitude and depends on the MTJ lateral size [2]. The control of the spike generation as well as the downscaling of the MTJ are essential in developing artificial neurons CMOS compatible. Additionally, the device operating point at zero magnetic field is relevant for large scale integration point of view and hardware implementation of spiking neural networks (SNN) for energy efficient computation of spatio-temporal data.

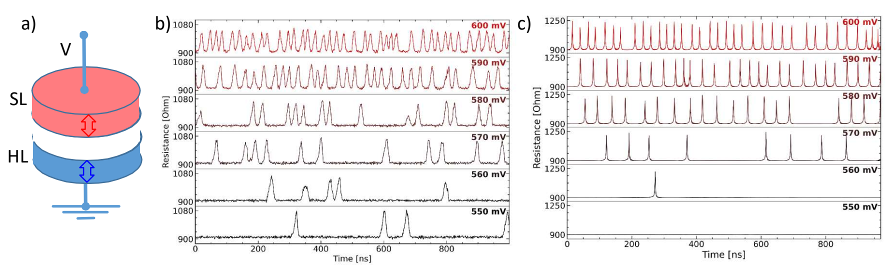

Figure 1: a) Schematics of the magnetic tunnel junction with a soft layer (SL) and a hard layer (HL). b) Filed free experimental and c) simulated time traces of the resistance upon varying the bias voltage.

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Micromagnetic modeling with tetmag: an open-source finite-element software with GPU acceleration

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The reliability, accuracy, and predictive power of micromagnetic simulations have been firmly established over the last decades. Simulations have become an indispensable tool in research in nanomagnetism and related fields, like spintronics or magnonics. The intensive computations required to solve micromagnetic problems can be significantly sped up by exploiting the inherently massively parallelized architecture of GPU processors [1,2]. The popular MuMax3 code [3], based on a finite-difference formulation, uses such GPU acceleration and has been used very successfully in the community. Novel problems in micromagnetism investigate the impact of three-dimensional geometric aspects in magnetic nanostructures [4], including samples with smoothly curved surfaces, arrays of interconnected magnetic nanowires, or gyroids [5]. In such cases, the geometric flexibility of finite-element methods is essential to obtain accurate geometric models. Here I will present our open-source micromagnetic finite-element software tetmag [6], which is particularly suited to simulate three-dimensional structures with irregular geometries.

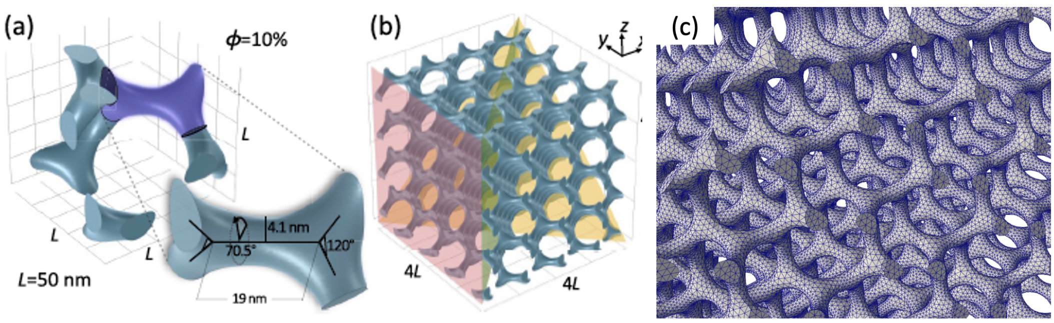

Figure 1: Complex three-dimensional geometries like gyroids [5] can be accurately modeled with the finite elements. By exploiting GPU acceleration, tetmag can simulate the micromagnetic properties of large magnetic systems with such shapes.

The software boasts GPU acceleration and efficient mathematical methods [7], allowing it to perform accurate simulations of large-scale problems while retaining a nearly linear O(N) scaling in computation resources. The code is made publicly available to provide a valuable addition to the existing collection of micromagnetic simulation software tools.

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Generation of topological spin textures using light-induced radially polarized magnetic field

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Laser-driven manipulation of magnetic skyrmions holds great promise for the development of next-generation information memory devices [1] due to its the flexibility of optical modulation. In this study, we use micromagnetic simulations to present a novel approach for generating and manipulating stable topological spin textures using light-induced radially polarized magnetic field [2], along with the ability to easily control quasiparticles by adjusting the intensity of the input beam. The generated topological spin textures can shrink into a stabilized quasiparticle with a size significantly smaller than the light-induced radially polarized magnetic field in few picoseconds, as observed on fig. 1. Through exploiting the relaxation mechanism of the spin texture at the center of the beam, we demonstrate the creation and stabilization of quasiparticles with higher ring numbers. Furthermore, we discover that the nπ quasiparticles (n > 1) exhibits significantly faster velocities compared to traditional skyrmion, with the 4π quasiparticle being the fastest. Our method offers a promising avenue for constructing various topological spin textures with multi-ring profiles in ultrafast and high-density data storage devices.

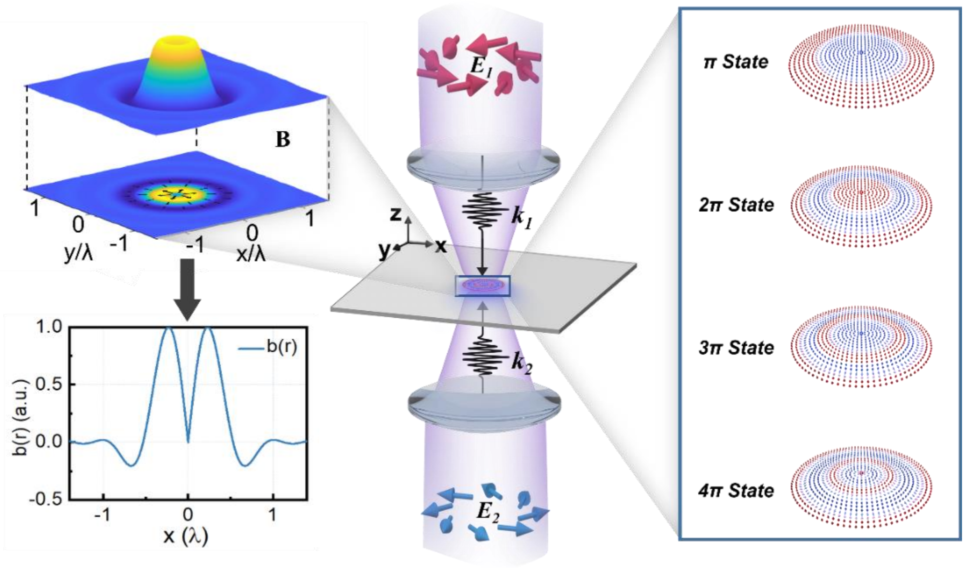

Figure 1: Creation of topological spin textures by a radially polarized magnetic field induced by the inverse Faraday effect. Two cylindrical vector beams with electric field $\mathbf{E}_1$ and $\mathbf{E}_2$ are tightly focused on the sample. Under different amplitude of the indiced field, four stable topological spin textures can be created (the right inset).

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Reduced order micromagnetics of permanent magnets

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We present our results on the development of a reduced order model for full micromagnetic simulations of permanent magnets in the presence of grain boundary phases or surface defects. Micromagnetic simulations get computationally infeasible for modelling real-world magnets, because their macroscopic behaviour depends sensitively on reversal mechanisms requiring a nanometer resolution of the computational grid. In our reduced-order model each hard magnetic grain is assigned a macrospin, which is switched, when the total field close to the grain surface exceeds the Stoner-Wohlfarth switching field [1]. However, for magnets with low anisotropy grain boundary phases, these local switching fields need to be computed with a model, which takes into account the width of the grain boundary phase and the relative alignment of the local anisotropy axes with respect to the external field. In [2] a numerical model for finite defect thickness and an analytical model for infinite defect thickness under the conditions $A_{hard} = A_{soft}$, $J_{hard} = J_{soft}$ and $K_{soft} = 0$ are presented.

We have run 1D micromagnetic simulations for NdFeB and MnAl and evaluated the distance of the simulation results to these models (Fig. 1a). This way we obtain a phase diagram (see Fig. 1b) with areas of validity for each model depending on the normalized

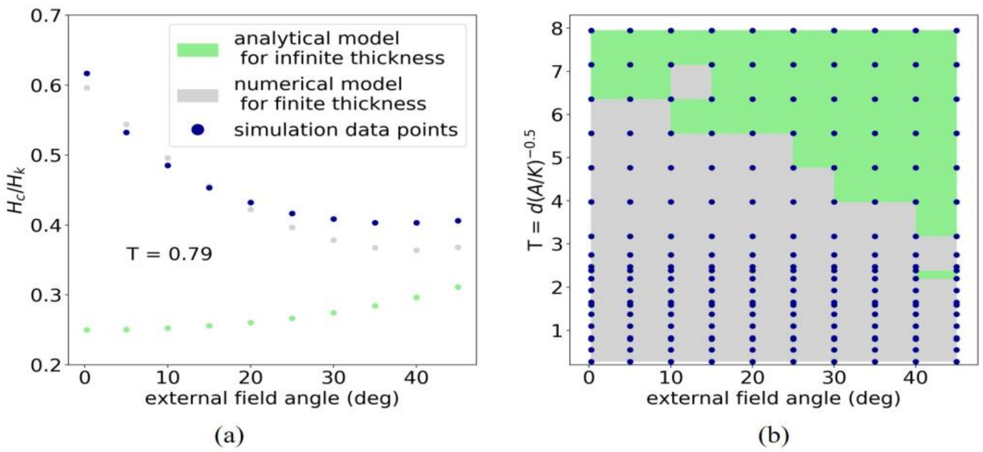

Figure 1: (a) simulation and model data (b) phase diagram for model selection in the reduced order model

thickness and the field angle. This phase diagram allows to select the appropriate model for fast computation of more realistic switching fields using the reduced order model.

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Magnetic MEMS micromirror with closed-loop control

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We present the study on the design and fabrication of a magnetic MEMS micromirror with closed-loop control. The device includes an array of permanent (micro)magnets, a system of copper micro coils lying on the suspended substrate and an array of magnetic sensors allocated on the moving part. The actuation mechanism is based on the Lorentz force raising from the interaction between the magnetic field generated by the permanent magnets and the electrical current flowing through the planar coil. The MEMS micromirror is designed via mechanical simulations performed with COMSOL and combined with electromagnetic simulations via the free Python package Magpylib v5. A systematic study was performed to determine the optimal magnet-coil topology configuration to achieve a field of view of 30° under specific general constraints (i.e., size, power losses, impedance). Additionally, a solution for close-loop control of the micromirror motion is proposed via the monolithic integration of a magnetoresistive sensor, optimized via micromagnetic simulations to achieve the operation range of interest.

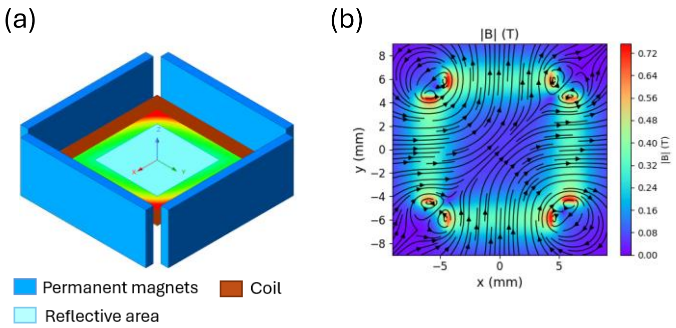

Figure 1: (a) Schematic representation of the magnetic micromirror. (b) Distribution of the magnetic field on the surface of the micromirror.

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Micromagnetic simulation of inertial magnetization dynamics in ferromagnets

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The investigation of ultra-fast magnetization processes is crucial in spin dynamics due to their potential use in future generations of nanomagnetic and spintronic devices[1]. Over the past few decades, the study of ultra-fast magnetization processes has attracted the attention of many research groups, leading to a considerable amount of research being produced, following the pioneering experiment[2] that revealed subpicosecond spin dynamics. Recently, experimental confirmation[3] of the presence of inertial effects in magnetization dynamics, which were theoretically predicted several years ago[4], was achieved by directly detecting spin nutation in ferromagnets in the terahertz range.

From a theoretical perspective, inertial magnetization dynamics can be modeled by augmenting classical Landau-Lifshitz-Gilbert (LLG) precessional dynamics with a torque term that considers angular momentum relaxation[3,4]. The torque term is proportional to the second time-derivative of magnetization, and transforms the classical LLG equation into a higher-order wave-like equation with hyperbolic mathematical nature, indicating that inertia results in wave propagation phenomena with finite speed and THz frequency.

In this paper, we first show that the inertial LLG (iLLG) equation significantly differs from the classical LLG equation, demanding twice the number of state variables[5]. However, despite increased complexity, it exhibits remarkable conservation properties for magnetization amplitude and projection, and a Lyapunov structure under constant external magnetic fields. Then, we propose two unconditionally-stable numerical schemes for time-integration of iLLG dynamics based on the implicit midpoint rule. The first one notably preserves all properties but doubles the number of unknowns, requiring extensive changes in numerical codes. A second one retains the same computational cost as midpoint-discretized LLG while preserving magnetization amplitude and projection. Implementing the implicit midpoint rule involves solving a system of nonlinear equations, addressed with a fast quasi-Newton iterative technique[5]. Validation is made computing broadband frequency response of a ferromagnetic thin film magnetized along the easy direction[3] and subject to out-of-plane AC fields from GHz to THz (see fig. 1).

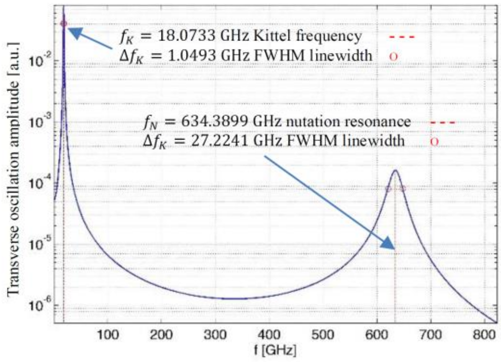

Fig. 1. Frequency response of magnetization oscillation transverse to the easy direction for an infinite ferromagnetic thin-film. The applied DC field bias is 0.35 T, the Gilbert damping constant is 0.023, the time scale of inertial effects is about 11 picoseconds[3]. Peaks and linewidths associated with usual GHz Kittel FMR frequency and ultra-fast nutation in the THz regime are visible.

The effectiveness of the second scheme is assessed by combining analytical theory and full micromagnetic simulations of iLLG dynamics to demonstrate the possibility to excite ultra-short inertial spin waves that propagate with finite speed in a confined ferromagnetic nanodot[6]. The nanodot is driven by terahertz fields with amplitude similar to those achievable with state-of-the art terahertz experimental setups.

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Skyrmions and Magnetic Textures

Invited

Metadynamics calculations of the effect of thermal spin fluctuations on skyrmion stability

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The stability of magnetic skyrmions has been studied previously, primarily without considering thermal fluctuations. However, thermal spin fluctuations alter the magnetic properties, such as exchange stiffness, Dzyaloshinskii–Moriya interaction (DMI), and anisotropy, which are crucial for skyrmion stability. Additionally, thermal magnons induce internal skyrmion dynamics, distorting their shape. Experimental evidence also indicates that entropy influences skyrmion lifetimes [1], a factor often neglected or simplified in earlier research. In this study, we employ metadynamics to calculate the free energy surface of a magnetic thin film using topological charge and magnetization as variables [2]. We identify the free energy minima associated with various spin textures (Fig. 1) and determine the lowest energy pathways between the ferromagnetic and single skyrmion states. Our results reveal that at low temperatures, skyrmion collapse is the process with the lowest free energy barrier. However, this barrier increases with temperature. Conversely, an alternative pathway, involving a singularity forming at the skyrmion edge, initially has a higher free energy barrier at low temperatures, but decreases as the temperature rises, eventually becoming the most favourable path.

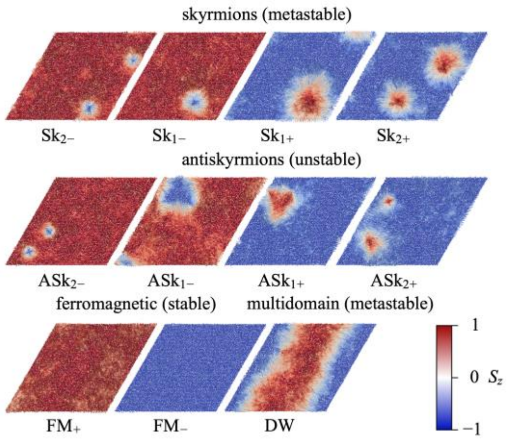

Figure 1: Snapshots of metastable spin states at different points of the free energy surface calculated using metadynamics.

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Invited

Magnetization dynamics of skyrmion lattice in cubic chiral magnets

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In materials that host skyrmions, cubic chiral magnets are of particular interest due to their ability to form periodically ordered skyrmion lattices over large, millimeter-sized single crystals, facilitated by the intrinsic bulk Dzyaloshinskii-Moriya interaction [1]. This study focuses on the magnetization dynamics of the skyrmion lattice in the low-damping chiral magnetic insulator Cu_2OSeO_3 [2]. To probe these dynamics, we employed broadband microwave spectroscopy, specifically investigating distinct magnetic modes associated with the low-temperature skyrmion lattice at 5 K.

Furthermore, we investigated the magnetization behavior in heterostructures composed of a Cu_2OSeO_3 single crystal and a polycrystalline NiFe (Py) thin film. Our findings revealed significant changes in the field dependence of the skyrmion phase within these heterostructures. Notably, we discovered that depositing Py onto Cu_2OSeO_3 promotes the formation of the skyrmion phase without the need for the static field cycling commonly used in the literature [3] to populate this phase. These results highlight the importance of combining cubic chiral magnets with suitable magnetic materials to effectively modify both the static and dynamic magnetization properties of skyrmions.

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Invited

Manipulation of magnetic skyrmions for memory and logic applications

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Skyrmions are topological spin textures which hold great promise as nanoscale bits of information in memory and logic devices [1]. Although room-temperature ferromagnetic skyrmions and their current-induced manipulation have been demonstrated [2,3], their velocity has been limited to about 100 meters per second [3,4]. In addition, their dynamics are perturbed by the skyrmion Hall effect, a motion transverse to the current direction caused by the skyrmion topological charge. Antiferromagnetic skyrmions allow these limitations to be lifted owing to their vanishing magnetization and net zero topological charge, promising fast dynamics without skyrmion Hall effect. In this talk, I will address the stabilization and current induced manipulation of skyrmions in compensated synthetic antiferromagnetic (SAF). I will first show that skyrmions can be stabilized at room temperature in Pt/Co/Ru based compensated SAFs and nucleated using local current injection and ultrafast laser pulses [5]. I will then show that SAF skyrmions can be moved by current at velocities over 900 m/s without skyrmion Hall effect [6]. Micromagnetic simulations and analytical models using experimental parameters show that this enhanced skyrmion velocity can be explained by the compensation of the gyrotropic force in the synthetic antiferromagnet. I will conclude the talk with recent results on the electrical nucleation and detection of a skyrmion in magnetic tunnel junctions, which is another important milestone for skyrmion based devices [7]. Our results open important paths toward the realization of logic and memory devices based on the fast manipulation of skyrmions.

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[2] O. Boulle et al., Nature Nano., **11**, 449 (2016)
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[4] R. Juge, S-G. Je et al., Phys. Rev. Appl. **12**, 044007 (2019)
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From magnetostatics to topology: antiferromagnetic vortex states in NiO-Fe nanostructures

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Magnetic vortices are topological spin structures frequently found in ferromagnets, yet novel to antiferromagnets. Using XMCD- and XMLD-PEEM we demonstrate [1] that in a nanostructured antiferromagnetic-ferromagnetic NiO(111)-Fe(110) bilayer as schematically shown in Fig. 1a, a magnetic vortex is naturally stabilized by magnetostatic interactions in the ferromagnet (Fig.1 b,d,f) and is imprinted onto the adjacent antiferromagnet (Fig.1 c,e,g) via interface exchange coupling. We use micromagnetic simulations to construct a corresponding phase diagram of the stability of the imprinted AFM vortex state. Our theoretical analysis reveals that the interplay between interface exchange coupling and the antiferromagnetic anisotropy plays a crucial role in locally reorienting the Néel vector out-of-plane in the prototypical in-plane antiferromagnet NiO and thereby stabilizing the vortices in the antiferromagnet.

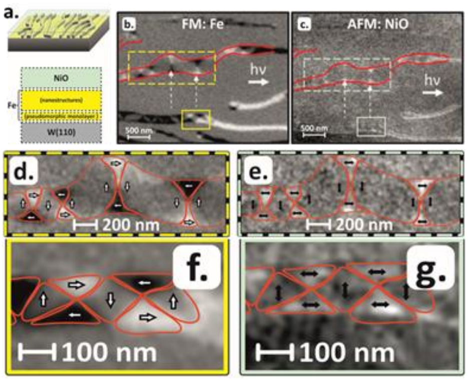

Figure 1: a) Schematic representation of the NiO-Fe bilayer structure. b,c) XMCD- and XMLD-PEEM images of the typical 4μm×2.5μm region covering several NiO-Fe nanostructures, that can be seen as black and white contrast atop the grey background of the Fe monolayer. The white dashed arrows indicate two of the magnetic vortices within the central nanostructure. Two yellow (b) and green (c) dashed and solid rectangles mark regions selected for magnification shown in d-g. White and black arrows schematically depict the local in-plane orientation of magnetic moments in Fe and double arrows for the Néel vector for NiO vortices, respectively.

[1] M. Ślęzak et al., Advanced Materials Interfaces (2024), accepted

Near-landauer pipelined voltage-propagated skyrmion logic

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Previous works have demonstrated the feasibility and efficiency of skyrmions in cascaded logic structures inspired by reversible computing, either by pipelining the skyrmions with inefficient electronic current [1-3] or moving them individually with the highly efficient voltage-controlled magnetic anisotropy (VCMA) effect [4]. However, previous works had yet to demonstrate the pipelining of cascaded logic structures using VMCA propagation. In this work, we perform the first demonstration of pipelining with VCMA propagation, illustrated for a full adder that simultaneously performs three distinct addition tasks. Further, we provide insight into the extrinsic causes of dissipation that can be improved to help skyrmion logic approach the limit predicted by the Landauer principle.

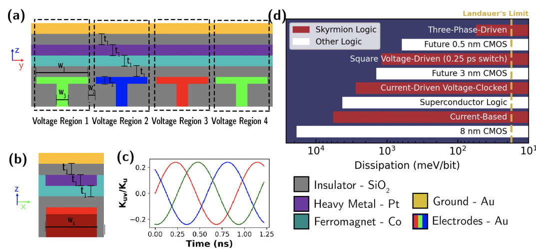

Figure 1. Three-phase VCMA propagated skyrmion logic operation. (a) YZ Cross Section. An electric field is applied across a Co/Pt interface (teal/purple) via electrodes (red/green/blue) separated by SiO2 (grey). The skyrmion exists in the ferromagnet layer. (b) XZ Cross Section (w1=19 nm, w2=1 nm, w3=11 nm, w4=20 nm, t1=0.8 nm, t2=0.5 nm) (c) VCMA anisotropy waveform applied to electrodes of corresponding color. (d) Comparison of total dissipation per bit processed for skyrmion logic technologies (red) and other logic technologies (white) relative to the room temperature Landauer limit (gold line).

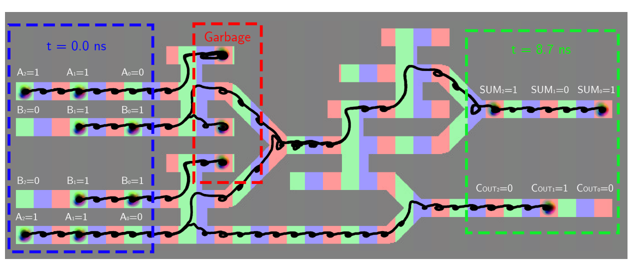

Figure 2. Micromagnetic simulation of pipelined full adder. Skyrmions are pipelined into the full adder form the left, encoding inputs (A_0=0, B_0=1; A_0=0, B_0=1; A_1=1, B_2=1; A_3=1, B_3=0). Black lines represent their trajectories, and skyrmions are propagated according to the respective VCMA regions (light red/green/blue) using the VCMA waveform shown in Fig. 1(c). At t=0 ns (blue), the skyrmions are initialized and propagated rightward to the correct logical outputs at t=8.7 ns (green).

[1]: M. Chauwin et al., Physical Review Applied 12 (2019) 064053
[2]: B. W. Walker et al., Applied Physics Letters 118 (2021) 192404
[3]: X. Hu et al., IEEE Magnetics Letters 13 (2022) 4503805
[4]: B. W. Walker et al., ArXiv Preprint, (2023), doi:10.48550/arXiv.2301.1070

Dynamically stabilized synthetic antiferromagnetic skyrmions

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Skyrmions, as topological spin textures, have garnered significant attention for their potential as efficient information carriers in spintronic devices. While skyrmions have been primarily studied in ferromagnets (FMs), they have also been observed in various other magnetic materials, including ferrimagnets (FiM), antiferromagnets (AFM), and synthetic antiferromagnets (SAFs). Most research has concentrated on the formation and manipulation of static skyrmions. Recently, dynamic skyrmions has been observed in nanocontact spin torque nano oscillators (NC-STNOs) with a FM free layer, which highlight their promising applications in microwave electronics. In this work, we demonstrate that SAF-based NC-STNOs can host and stabilize dynamic SAF skyrmions and skyrmioniums (see Fig. 1). By applying varying current densities (spin transfer torque) into the perpendicular SAF free layers —comprising two (top and bottom) antiferromagnetically coupled FM layers and a nanmangetic spacer —we observe and simulate five distinct dynamic states: magnetic droplet, single dynamic skyrmion, double dynamic skyrmion, dynamic SAF skyrmionium, and dynamic SAF skyrmion (see Fig. 1). Through a systematic study of the effects of dipolar and Oersted fields, Dzyaloshinskii-Moriya interaction (DMI), and RKKY interactions, we find that dipolar and Oersted fields are crucial for the nucleation and dynamics of SAF skyrmions and skyrmioniums. Notably, the frequency of dynamic SAF skyrmions can reach up to 10 GHz and is highly tunable by currents, even in the absence of Dzyaloshinskii-Moriya interaction and applied fields. Our research extends the understanding of dynamic spin textures to SAF skyrmions and skyrmionium, presenting significant potential for high-frequency field-free nano-oscillators.

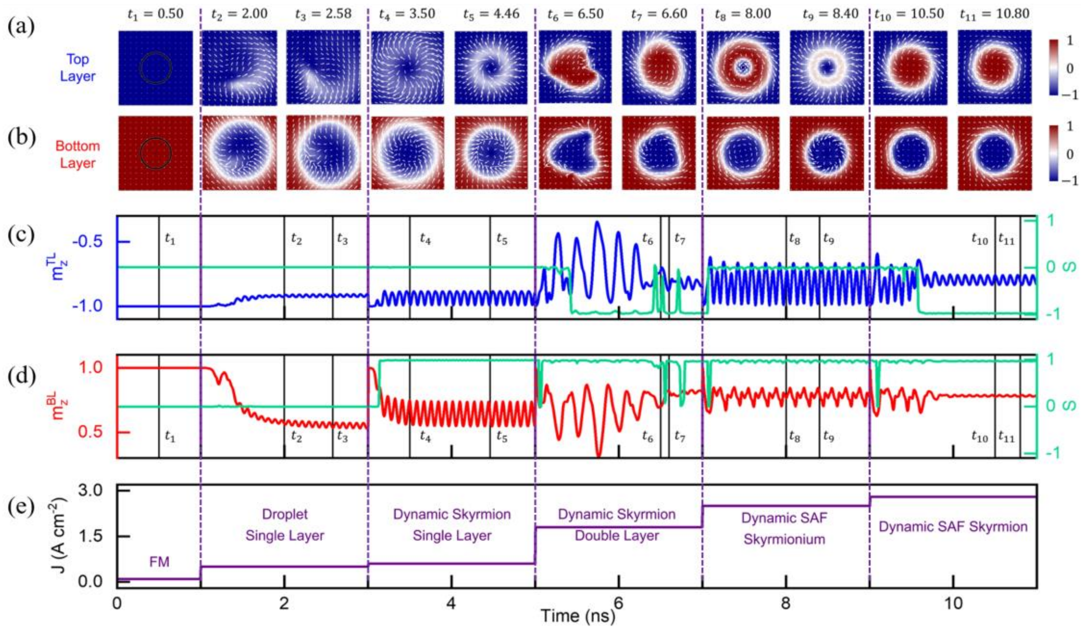

Figure 1: (a) and (b) are the snapshots of m_z components of the top and bottom FM layers. The black circle indicates NC with a 16-nm radius. (c) and (d) are the time trajectories of the m_z components and the skyrmion numbers. The vertical black line corresponds to the snapshot above. (e) the current density applied and corresponding dynamical states.

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[3] **Jiang, S.**, *et al*. Nat. Comm., **15** (2025), 2118

Magnetic nanopatterning of skyrmion lattices via direct laser writing

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Spin textures in magnetic materials, such as magnetic domains, domain walls, and skyrmions, show significant potential for data storage and processing devices due to their nanoscale size, resistance to external perturbations, and high tunability [1]. Effective manipulation of these textures is crucial for developing spintronic devices with selected properties and functionalities. Magnetic skyrmions, in particular, have gained attention for their unique properties, including stability and nanoscale dimensions, making them promising building blocks for information processing at the nanoscale [2]. However, controlling their nucleation and arrangement in magnetic films remains challenging.

In this work, we introduce phase-nanoengineering [3], specifically Direct Laser Writing (DLW), as an effective method for creating reconfigurable spin textures on CoFeB/Ta/Ru/IrMn and IrMn/NiFe/Co magnetic multilayers. These stacks are ideal for stabilizing skyrmions at room temperature and zero field, although stabilization occurs randomly [4]. By using a highly localized energy source to selectively heat the material in presence of a magnetic field, we achieve localized magnetization pinning and create arbitrarily shaped and reconfigurable spin textures. As shown in Figure 1a, magnetic patterning with an external field allows fine-tuning of the film exchange bias with laser power, demonstrating DLW's potential for greyscale patterning. Figure 1b illustrates the successful patterning of a skyrmion lattice with arbitrary arrangement and a minimum feature size of around 250 nm using DLW, with skyrmion size increasing with laser power. The patterned spin textures remain stable at remanence and resist erasure by magnetic fields.

These findings highlight DLW as a promising technique for precise, reconfigurable spin texture engineering, offering significant potential for nanoscale data storage and processing applications.

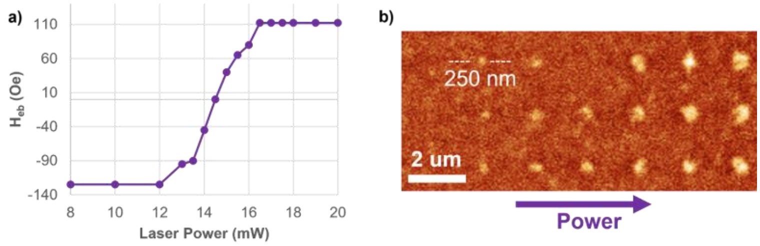

Figure 1: **a)** Dependence of the exchange bias shift of patterned regions on the laser power.
b) Patterned skyrmion lattice with increasing skyrmion size as a function of laser power

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Topological spin-torque diode effect in skyrmion-based magnetic tunnel junctions

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Magnetic skyrmions have reached a great success as information carriers in next-generation of data storage (racetrack memory), and unconventional computing[1]. The recent room-temperature observation of skyrmions in magnetic tunnel junctions (MTJs)[2] has opened the way to the combination of Spintronics and Topology to expand the possible applications of skyrmions.

Here, we design MTJ devices hosting magnetic skyrmions at room temperature with a diameter of less than 300nm[3]. We perform experimental spin-torque diode measurements, by which we identify three modes as a function of frequency and applied external field (Fig. 1): 1 mode at frequency of 4 GHz and low field, which we refer to the skyrmion breathing mode; 1 mode at frequency of 5 GHz at high field with red-shift we associate to the reference layer (RL) dynamics of the MTJ; and 1 mode at frequency of 8 GHz at high field with blue shift we relate to the uniform dynamics of the free layer (FL). To confirm the origin of these modes (i), we use two strategies. One is to grow an MTJ without the skyrmion-hosting layer. The second is to perform state-of-the art micromagnetic simulations of the whole device magnetic stack with layer dependent parameters and direct and forward spin-transfer torque in the free and reference layer of the MTJ respectively. By engineering the material properties of the MTJ free layer and of the skyrmionic layer, the simulations confirm, both qualitatively and quantitatively, the different origin of the three modes.

Work supported by the projects PRIN 2020LWPKH7, PRIN 20222N9A73 funded by the Italian Ministry of Research, PE0000021, "Network 4 Energy Sustainable Transition – NEST", funded by the European Union – NextGenerationEU, Mission 4 Component 2 Investment 1.3 - Call for tender No. 1561 of 11.10.2022 of Ministero dell'Università e della Ricerca (MUR) (CUP C93C22005230007), and by PETASPIN association (www.petaspin.com).

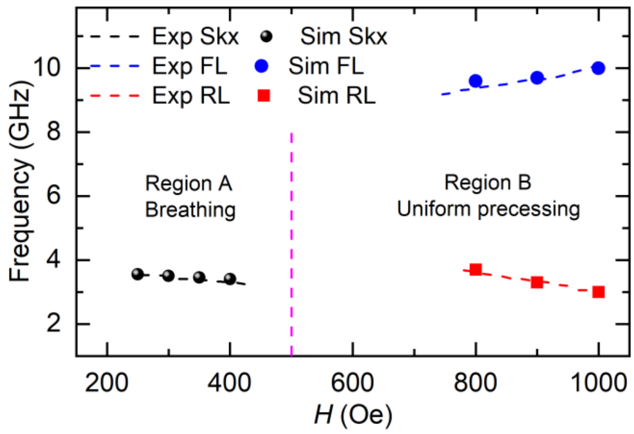

Figure 1: Frequency of the excited modes as a function of the applied field H for tilted of θ = 30° with the respect to the positive out-of-plane axis. Solid symbols represent the results of the micromagnetic simulations, dashed lines correspond to the experimental results.

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Visualization of skyrmion-superconducting vortex pairs in a chiral magnet-superconductor heterostructure

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Magnetic skyrmions, the topological states possessing chiral magnetic structure with non-trivial topology, have been widely investigated as a promising candidate for spintronic devices. They can also couple with superconducting vortices to form skyrmion-vortex pairs, hosting Majorana zero mode which is a potential candidate for topological quantum computing. A lot of theoretical proposals have been put forward on constructing skyrmion-vortex pairs in heterostructures of chiral magnet and superconductor. Nevertheless, how to generate skyrmion-vortex pairs in a controllable way experimentally remains a significant challenge. We have designed a heterostructure of chiral magnet and superconductor [Ta/Ir/CoFeB/MgO]$_7$/Nb in which zero field Néel-type skyrmions can be stabilized and the superconducting vortices can couple with the skyrmions when Nb is in the superconducting state. We have directly observed the formation of skyrmion-superconducting vortex pairs which is dependent on the direction of the applied magnetic field. Our results provide an effective method to manipulate the quantum states of skyrmions with the help of superconducting vortices, which can be used to explore new routines to control the skyrmions for spintronics devices. [1]

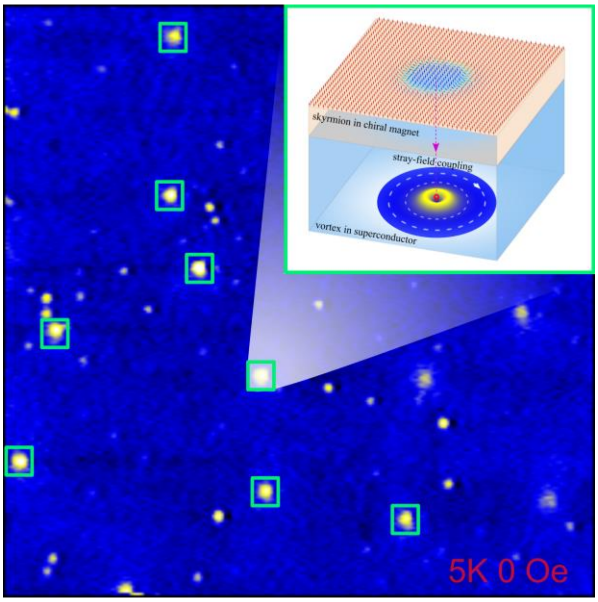

Figure 1: The stray field of a skyrmion generates a superconducting vortex and they couple together to form a bounded topological pair, which provides an alternative approach to search for Majorana zero modes.

[1] Y.J. Xie et al, Physical Review Letters, 2024, Accpeted, editor’s suggestion article

Spin Waves and Magnonics

IEEE Italy Section
Politecnico di Bari
IOM Istituto Officina dei Materiali
PetaSpin
IEEE Magnetics Italy Chapter
IEEE NANO Nanotechnology Council - Italy Chapter -
MetroSpin
AIMagn Associazione Italiana di Magnetismo
IEEE young professionals Italy Section
IAS IEEE Industry Applications Society Linking Research to Practice
PELS IEEE Power Electronics Society Powering a Sustainable Future
Italy Joint Chapter C&S
ZABRE Nanometer magnetic fields made visible.

Invited

Controlling and imaging spin waves in 3D

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Three-dimensional (3D) control of spin-wave dynamics is a groundbreaking advancement in magnonics [1], enabling new functionalities for nanoscale computing and signal processing. In this context, this presentation shows how spin waves can be controlled and imaged in three dimension using two novel approaches.

First, we employed focused UV laser irradiation on Yttrium Iron Garnet (YIG) thin films [2], achieving stable and giant modification of the perpendicular magnetic anisotropy, while preserving the crystalline quality. The modification is highly confined at the nanoscale both in the lateral and vertical dimensions, enabling precise modulation of spin-wave properties, including band structure and non-reciprocity. Finally, we utilized this approach to fabricate a single-step three-dimensional magnonic crystal.

Additionally, using magnetic X-ray laminography, we provided the first 3D imaging of propagating spin-wave modes within synthetic antiferromagnets (SAF) [3]. This technique captures with temporal and nanoscale resolution the 3D dynamics, the complex localization and interference of spin waves, revealing unexpected depth-dependent profiles originated from the interlayer dipolar interaction. These features can be tuned by controlling the composition and structure of the magnetic system.

Together, these works enable new possibilities for 3D devices with tailored magnetic properties and complex magnonic functionalities.

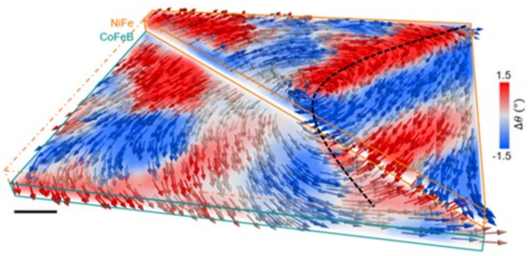

Figure 1: Reconstruction of the three-dimensional magnetization dynamics (arrows) in NiFe and CoFeB. The blue/red colour-code refers to the in-plane dynamics. Scale bar: 200 nm.

[1] G. Gubbiotti, Three-Dimensional Magnonics. Jenny Stanford Publishing (2019)

[2] V. Levati et al., submitted

[3] D. Girardi et al., *Nat Commun* **15**, 3057 (2024).

Invited

Spin waves in curved magnetic shells

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Modifications to the topology, symmetry, or, more generally, geometry induced by surface curvature can lead to various emergent phenomena in condensed matter systems. For example, electronic bands can acquire Landau levels when bending graphene, nematic crystals experience geometric frustration, or curved superconductors bear correlated vortex tubes [1-3]. In magnetically ordered systems, such geometrical effects can play a fundamental role because magnetization is a pseudo-vector order parameter. This can lead to emergent anisotropies or chiral symmetry breaking, among other consequences [4,5]. Even the recently discovered altermagnets have been predicted to exhibit curvature-induced magnetization [6]. Geometrical effects in magnetism are not restricted to static phenomena but are also found ubiquitously in magnetization dynamics. Magnetic domain walls have been experimentally shown to exhibit geometry-driven automotion in three-dimensional helices or on curved nanostrips. Similarly, the curvature and topology of magnetic nanotubes were predicted to induce chiral symmetry breaking of domain-wall motion. They can even suppress the Walker breakdown, which ultimately led to the prediction of the spin Cherenkov effect.

In this talk, I aim to explore the consequences of topology, symmetry, and curvature on the fundamental low-energy dynamics of ferromagnets, called spin waves. These consequences can often involve different magnetic interactions. For example, the curvature of magnetic shells can modify the dynamic magnetic pseudo charges. As a result, magneto-chiral symmetry breaking of dipolar origin can lead to asymmetric spin-wave dispersion [7], nonreciprocal spatial mode profiles, and strongly modify nonlinear magnetization dynamics. Moreover, a nontrivial topology of three-dimensional magnetic specimens can induce a topological Berry phase that is dominated by exchange and behaves as a curvature-induced Dzyaloshinskii-Moriya interaction, lifting degeneracies in the spin-wave spectrum or resulting in heterosymmetric modes [8]. Topology may also impose selection rules on the possible dynamics of magnetic textures, such as domain walls on Möbius ribbons. Lastly, achiral symmetry breaking, induced, for example, by lowering rotational symmetries, can lead to symmetry-governed splitting of degenerate modes. Aside from several of the aforementioned geometrical effects on magnetization dynamics, I will briefly discuss numerical techniques to study spin waves in curved magnetic shells [9].

[1] Nigge et al., Sci. Adv. 5, eaaw5593 (2019)

[2] Lopez-Leon et al, Nat. Phys. 7, 391 (2011).

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[8] Körber et al., Phys. Rev. B **110**, 134428 (2024)

[9] www.tetrax.software

Invited

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Dynamical renormalization of the magnon spectrum via nonlinear coherent spin dynamics

A major research trend of modern condensed matter physics aims at optically manipulating magnetic materials at fundamental timescale, i.e. the inherent timescales of the eigenfrequencies and lifetimes of collective vibrational, electronic and magnetic excitations in solids. The full dynamical response of a magnetic solid, at all possible time- and length-scales, is encoded in the dispersion relation of magnons. The optical activation of coherent magnons, which enables to imprint a well-defined phase on a macroscopic ensemble without requiring any laser-induced heating, has been widely reported. Coherent collective excitations have been driven into nonlinear regimes, displaying coupling among different modes and between light and collective modes not allowed in a linear dynamical regime. Despite the massive volume of research in this direction, an arbitrary optical control of the spectrum (frequency, amplitude and lifetime) of the eigenmodes appearing in the dispersion relation of magnets is lacking. In my talk I will discuss several strategies pursued by my group to achieve such a high-level of control on magnons. First, we realize a manipulation of the magnetic resonance frequency in quasi 2D ultrathin crystals via different mechanisms. These pathways are identified and quantified in terms of their fingerprints on the spin dynamics, as they appear at different timescales. Second, I will discuss a different approach, based on a resonant drive of high-energy magnons, with wavevectors near the edges of the Brillouin zone. The transient spin dynamics reveals the activation and a surprising amplification of coherent low-energy zone-centre magnons, which are not directly driven. Strikingly, the spectrum of these low-energy magnons differs from the one observed in thermal equilibrium. The light-spin interaction thus results in a room-temperature renormalisation of the magnon spectra, as five-fold and three-fold increases of the amplitudes and 4% frequency shifts of their ground-state values were measured. We rationalise the observation in terms of a novel resonant scattering mechanism, in which zone-edge magnons couple nonlinearly to the zone-centre modes. A quantum mechanical model and numerical simulations (atomistic spin dynamics) reveal that the observed corrections to the spectrum are due to both the photoinduced magnon population and the subsequently triggered channels of magnon-magnon scattering channels. Our results present a milestone on the path towards an arbitrary tuning of the quasiparticles eigenfrequencies.

Terahertz charge and spin transport in metallic ferromagnets: The role of crystalline and magnetic order

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We study the charge and spin dependent scattering in a set of CoFeB thin films whose crystalline order is systematically enhanced and controlled by annealing at increasingly higher temperatures. Terahertz conductivity measurements reveal that charge transport closely follows the development of the crystalline phase, with the increasing structural order leading to higher conductivity. The terahertz-induced ultrafast demagnetization, driven by spin-flip scattering mediated by the spin–orbit interaction, is measurable in the pristine amorphous sample and much reduced in the sample with the highest crystalline order. Surprisingly, the largest demagnetization is observed at intermediate annealing temperatures, where the enhancement in spin-flip probability is not associated with an increased charge scattering. We are able to correlate the demagnetization amplitude with the magnitude of the in-plane magnetic anisotropy, which we characterize independently, suggesting a magnetoresistance-like description of the phenomenon.

Fully-integrated self-biased magnonic phase-shifter

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Advancements in tunable magnonic systems can lead to significant improvements in RF signal processing technology [1]. However, a primary challenge for magnonic devices is the requirement for a tunable local magnetic field, capable of both tuning the signal and allowing spin wave propagation, which is usually provided by external electromagnets.

This study, conducted within the M&MEMS European project [2] framework, presents a fully integrated device fabricated on silicon. The device comprises a CoFeB waveguide, two SmCo permanent magnets, and two T-shaped NiFe magnetic flux concentrators (MFCs), arranged as depicted in Figure 1a. The permanent magnets provide an on-chip magnetic field source, while the MFCs focus the magnetic flux generated by the SmCo magnets into a confined space, thereby enhancing the uniformity and intensity of the magnetic field within the region between the concentrators, and providing the field required to bias the CoFeB conduit along its short axis. The magnetic field intensity achieved in the area of interest is 25 mT, as predicted by simulations and confirmed by micro-MOKE and thermal Brillouin Light Scattering experiments.

We investigated the propagation of spin waves using a Vector Network Analyzer system. Our findings indicate that spin wave propagation is sustained in the conduit without externally applied magnetic fields, unlike reference samples that lacked nearby magnets and therefore did not exhibit any SW signal without an external field. Additionally, we studied devices with varying distances *d* between the concentrators and the micromagnets. We observed that the position of the magnets strongly affects the SW frequency window and the phase accumulated at the output antenna. A future outlook involves implementing a dynamic variation of *d* by placing micromagnets on top of micro-actuators to realize a reconfigurable phase shifter.

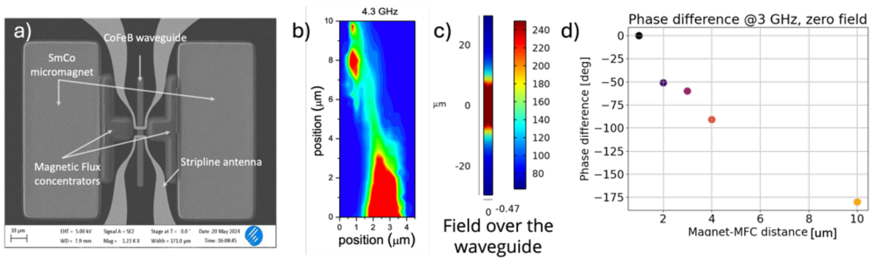

Figure: a) Device layout; b) Micro-focused BLS and intensity mapping recorded at zero external field, showing SW propagation; c) Comsol-Multiphysics simulation of the field generated over the waveguide; d) Phase variation at the output antenna of the SW signal as a function of the magnet-MFC distance *d*.

[1] P. Pirro, V. Vasyuchka, A. Serga, and B. Hillebrands, Nat. Rev. Mater. 6, 1114 (2021).

[2] https://mandmems.eu/ (EU Project 101070536 — MandMEMS)

Three dimensional, nanoscale control of magnetism in crystalline yttrium iron garnet for magnonics

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The goal of magnonics is to exploit Spin Waves (SWs) for data transmission and processing, with application in next generation low-energy consumption devices. Yttrium Iron Garnet (YIG) is currently the most promising material in the field, thanks to the lowest Gilbert damping ever recorded, which allows for the longest coherent propagation of SWs [1]. Still, YIG nanostructuring via conventional lithographic processes and crafting the properties of YIG with ion irradiation are challenging tasks, and are solely limited to 2D geometries. In this work, we employed UV laser irradiation to pattern a single crystal 1-µm thick YIG film, achieving an effective 3D grayscale tuning of its magnetic properties, via phase-nanoengineering [2]. In particular, the irradiation of arbitrarily shaped patterns induces a stable enhancement of the magnetic perpendicular anisotropy in a three-dimensional region whose depth can be controlled. MFM images of irradiated areas show a significant reduction of the magnetic stripe domains periodicity (inset of Fig. 1a), along with a rise of the saturating field. The crystalline quality of the pristine YIG is maintained upon irradiation, while the red shift of some peaks in Raman spectra acquired on patterned areas (Fig. 1a) indicates presence of local strain which results in an enhancement of the magnetoelastic contribution to perpendicular magnetic anisotropy [3]. Finally, the patterning technique was used for altering the magnetization dynamics of irradiated areas and fabricating proof of concept magnonic crystals, obtaining peculiar SWs band structure, non-reciprocity, and controlling the SWs localization and propagation, as revealed by micro-Brillouin Light Scattering experiments (Fig. 1b).

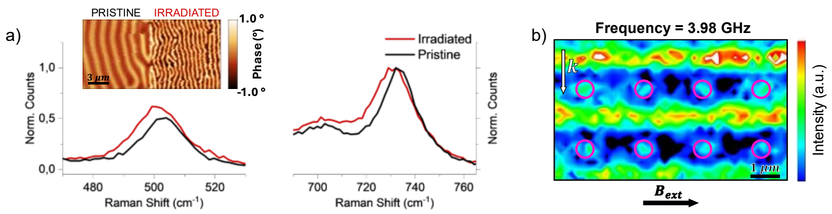

Figure 1: a) Raman spectra of the patterned film shows a left side broadening compared to the one of the pristine film. The inset shows an MFM image of the pristine and irradiated regions. b) µ-BLS measurement of a magnonic crystal made by an array of patterned nanodots (purple circles) revealing the spatial localization of the spin-waves.

[1] P. Pirro et al., Nat. Rev. Mater. **6** (2021), 1114–1135

[2] V. Levati et al., Adv. Mater. Technol. **8** (2023), 2300166

[3] Y. Meng et al., Small **20** (2024), 2308724

Unraveling spin-wave dynamics in ferro- and antiferro-magnetic insulators

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Spin waves offer several attractive properties such as scalability owing to their short wavelength in the microwave range, frequency tunability by an applied magnetic field, non-reciprocity and non-linear effects, notably for the development of innovative microwave devices. In this perspective, new approaches are required to electrically characterize spin-wave dynamics for device optimization but also to unravel unexplored magnonic phenomena.

In this talk, I will first evidence how time of flight spin wave spectroscopy [1] enables an unprecedented access to the spin-wave physics of (i) conventional garnets and their interfaces, which is key to optimize spin-wave devices, and to unexplored (ii) canted antiferromagnetic materials which can host ultra-fast and non-degenerated spin-waves [2]. I will then present a complementary detection technique relying on spin-orbitronic phenomena (such as spin-pumping and spin-Hall magnetoresistance) and demonstrate that one can achieve spin-rectification of antiferromagnetic dynamics [3] in both the linear (see Fig. 1) and nonlinear regime. These two electrical detection techniques hold promising opportunities for the development of novel magnonic devices.

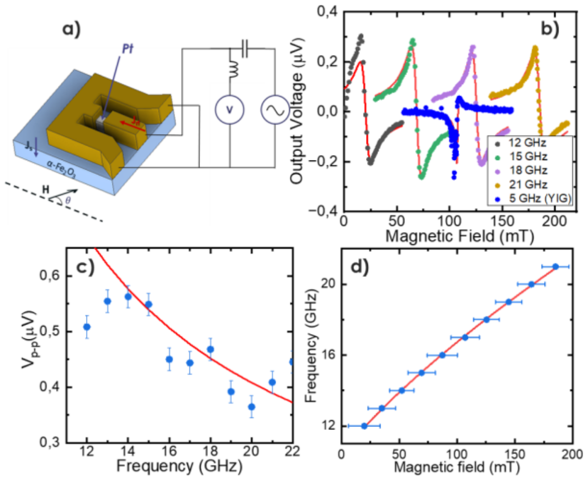

Figure 1: Spin-rectification in bilayers of the canted antiferromagnet hematite capped with 5 nm of platinum. (a) Sketch of the experimental devices. (b) Spin-rectification for different frequencies. (c) Peak-to-peak voltage amplitude V_{P-P} as a function of frequency. (d) Frequency dependency with the applied magnetic field.

[1] T. Devolder et al., Phys. Rev. B 103, 214431 (2021)

[2] A. El Kanj et al., Sci. Adv.9, eadh1601(2023)

[3] A. El Kanj, S. Mantion et al., in preparation.

Anomalous hardening of spin waves in cobalt/molecular-semiconductor heterostructures implying strongly anisotropic spinterface magnetism: a time-resolved MOKE investigation

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We investigated influence of metal/organic-molecules interfaces on the magnetic dynamics in thin polycrystalline Co thin films grown by electron-beam evaporation. To assess the dynamics we measured temperature and magnetic field dependence of the femtosecond-laser induced coherent spin waves by means of the time-resolved magneto-optical Kerr effect (MOKE) spectroscopy [1]. We compare the effects of interfacing the Co films to a nonmagnetic metal (Al), metalorganic complexes tris(8-ydroxyquinoline)gallium (Gaq_3) and M-phthalocyanines (M=Cu, Co) as well as Buckminster-fullerene (C_{60}) molecules.

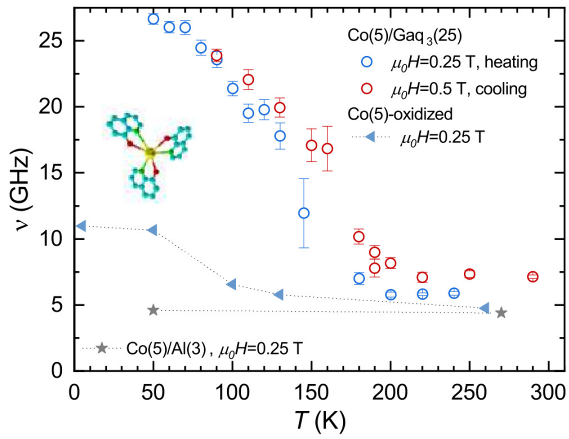

Figure 1: The spin-wave frequency as a function of temperature at a constant external magnetic field in the Co(5 nm)Gaq_3(25 nm) sample compared to the reference Co(5 nm)/Al(3 nm) sample and oxidized Co(5 nm) film.

In general, the transient MOKE signals were found to exhibit damped coherent spin wave oscillations (CSWO) with frequencies up to several tens of GHz. Detailed analysis of the spin-wave temperature and magnetic field dependences allowed us to compare the influence of different molecular interfaces. We found that the thin Co films interfaced with molecular layers display strong hardening of the CSWO frequency at low T with a rather sharp transition in the 170 K - 200 K range. Surprisingly, the behavior is found to be very similar for different molecular species/shapes and can be attributed to the presence of a strongly-anisotropic magnetic ordering at the hybridized interface (spinterface) that is not directly related to the bulk Co-film magnetism and sets in below T~170 K.

[1] M. van Kampen et al., Phys. Rev. Lett. 88 (2002) 227201.

[2] T. Moorsom et al., Phys. Rev. B. 101 (2020) 060408.

Magnonic convolutional neural networks

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Convolutional Neural Networks (CNNs) are a class of deep learning models particularly well-suited for processing many different types of data, such as text, spectra, and images. By leveraging convolutional layers, CNNs automatically and hierarchically extract and learn spatial features, enabling efficient pattern recognition and image classification. Unlike traditional fully connected networks, CNNs maintain spatial relationships between pixels, significantly reducing the number of parameters and computational cost. Their widespread application extends beyond computer vision, including natural language processing, medical image analysis, and autonomous systems, making CNNs a foundational tool in modern AI-driven research and technology.

In this paper, we experimentally demonstrate magnonic convolutional neural networks (CNNs) composed of yttrium iron garnet (YIG) waveguide networks, which utilize routed spin-wave propagation and interference for direct convolutional processing. Spin waves within the network are excited via microwave antennas at the inputs, while their transport and interference are imaged using super-Nyquist sampling magneto-optical Kerr effect (SNS-MOKE) microscopy. As a conceptual demonstration, we employ magnonic convolutional processing for various classification tasks, achieving 100% accuracy in identifying 3×3 digit letters (Figure 1), 90.8% accuracy in classifying gait signals from ten patients with Parkinson's disease, 92.9% accuracy on the Modified National Institute of Standards and Technology (MNIST) image dataset, and 91.0% accuracy in distinguishing brain tumors from Magnetic Resonance Imaging (MRI) images. These findings highlight the transformative potential of magnonics for advanced AI applications.

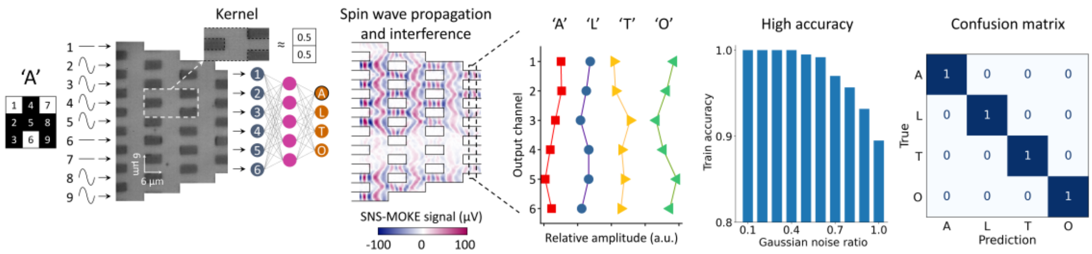

Figure 1: A magnonic CNN composed of a network of YIG waveguides with 9 inputs and 6 outputs. The CNN employs a 2×1 kernel and three convolutional layers to process images of the letters 'A', 'L', 'T', and 'O'. The system achieves 100% classification accuracy, even with a Gaussian noise ratio of up to 0.4.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101070347-MANNGA.

Floquet magnons in a periodically-driven magnetic vortex

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Magnetic vortices are prominent examples for topology in magnetism with a rich set of dynamic properties. They exhibit an intricate magnon spectrum and show an eigen-resonance of the vortex texture itself, the gyration of the vortex core. While there have been studies about magnon-assisted reversal of the vortex core polarity [1], the impact of the vortex core gyration on the magnon spectrum has not been addressed so far.

The fundamental modes of both excitation types are clearly separated in their resonance frequencies. While the vortex typically gyrates at a few hundred MHz, the magnon modes typically have frequencies in the lower GHz range. This separation allows for studying the temporal evolution of the magnon spectrum when the gyration of the vortex core is driven by an external drive. Under the influence of such a periodic driving field, Floquet states emerge due to a temporal periodicity imposed on the system's ground state, much like the formation of Bloch states in the periodic potential of a crystal lattice. While Bloch states are shifted in momentum space, Floquet states are shifted in energy by multiples of the drive frequency, facilitating the design of novel properties and functionalities in condensed matter systems.

This talk delivers experimental results how the regular magnon modes in a magnetic vortex transform into novel Floquet bands, when the vortex ground state is modulated in time by driving the vortex core gyration simultaneously. The observed magnon Floquet states are both distinct from the well-known regular magnon modes as well as from the vortex gyration and represent truly unique excitations providing new opportunities to study and control nonlinear magnon dynamics.

This work has received funding from the EU Research and Innovation Programme Horizon Europe under grant agreement no. 101070290 (NIMFEIA).

[1] M. Kammerer, et al. Nature Communications **2**, 279 (2011)

The toroidal moment in nanomagnets and its connection with nonreciprocal magnonics

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Nonreciprocal magnonics focuses on manipulating magnons in magnetic materials to achieve nonreciprocal behaviour, where spin wave propagation differs in opposite directions. Over the past decade, several nonreciprocal magnonic systems have been theoretically predicted, and some have been experimentally demonstrated [1], showing frequency shifts of a few GHz. However, for complex magnonic systems or nonuniform magnetization, numerical methods are needed to estimate frequency shifts for counterpropagating spin waves. Given the importance of nonreciprocal wave propagation for magnon-based devices, new approaches to predict spin-wave nonreciprocity are crucial. One approach involves the toroidal moment $\boldsymbol{\tau}$, first proposed from multipole expansions of the vector potential [2]. It can be understood by considering an electric current moving along the meridians of a toroid, generating a magnetic field and a circular magnetization through the center of the toroid. In ferromagnetic systems lacking external electric or polarization currents, the volume-bound current (the curl of the magnetization) can generate a toroidal moment. However, there are a few definitions of $\boldsymbol{\tau}$ [3], and their interrelation is investigated theoretically [4]. It is found that the term that links them corresponds to a surface toroidal moment originated by surface-bound currents. The surface and volume toroidal moments for different well-known magnetic textures, such as conical-helix and skyrmionic/vortex classes, are calculated, and the relevance of each contribution is discussed [4]. The surface toroidal moment is generally parallel in direction to the volume toroidal moment but may differ in magnitude and sign. Considering the surface term can broaden the discussion around the toroidal moment and emphasize surface phenomena when examining magnetic materials.

The significance of the toroidal moment in nonreciprocal magnonics is also discussed in various scenarios, such as current-induced spin-wave Doppler shift in thin films, different magnetic textures, magnetization-graded films, magnetic bilayers, and films with interfacial and bulk DMI. The toroidal moment breaks spatial symmetry, allowing nonreciprocal spin-wave propagation if the wave vector $\boldsymbol{k}$ has a nonzero projection along it ($\boldsymbol{\tau} \cdot \boldsymbol{k} \neq 0$) [5]. We illustrate the relationship between $\boldsymbol{\tau}$ and nonreciprocity in various magnetic systems, suggesting a strategy for anticipating a nonreciprocal behaviour. This research shows that straightforward calculations can predict the presence of nonreciprocity by considering geometry and static equilibrium magnetization. These findings can be validated through magnetization dynamics calculations and micromagnetic simulations.

[1] B. Flebus et al., J. Phys.: Condens. Matter **36,** 363501 (2024).

[2] V. Dubovik and V. Tugushev, Phys. Rep. **187,** 145 (1990).

[3] N. A. Spaldin, M. Fiebig, and M. Mostovoy, J. Phys.: Condens. Matter **20**, 434203 (2008).

[4] F. Brevis, L. Körber, R. A. Gallardo, A. Kákay, and P. Landeros, in preparation.

[5] L. Körber et al., Phys. Rev. B **106,** 014405 (2022).

Vortex gyrotropic mode excited by surface acoustic waves

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One particularly interesting example of magnetization dynamics in found in magnetic vortices.These structures are an inhomogeneous magnetic texture that can be formed in magnetic nanosdisks, featuring in-plane magnetization curling along the disk's perimeter and out-of-plane magnetization at the center, which defines the vortex core [1]. At remanence the vortex core is localized at the center of the disk. Resonant excitation by a microwave field induces gyrotropic dynamics of the vortex core [2]. Recently, it has been proposed by simulations that surface acoustic waves (SAWs) can excite the gyrotropic mode of the vortex state in a magnetic disk [3].

Here we report on experiments utilizing a magnetic resonance force microscope to investigate magnetization dynamics in CoFeB sub-micrometer disks in the vortex state, grown on a Z-cut $LiNbO_3$ substrate [4]. Our device design enables excitation of the gyrotropic mode either inductively, using an antenna on top of the disks, or acoustically via SAWs launched from an interdigital transducer (IDT) (figure, left). These experiments demonstrate the clear excitation of the vortex gyrotropic mode by magneto-acoustic excitation. Our modelling indicates that the lattice rotation ω_{xz} generates a localized magneto-acousticfield that displaces the vortex from the disk center (figure, right). Combined with the other non-vanishing strain terms (ε_{xx} and ε_{zz}) that results in an additional magneto-acoustic excitation field that allows driving the vortex gyrotropic mode.

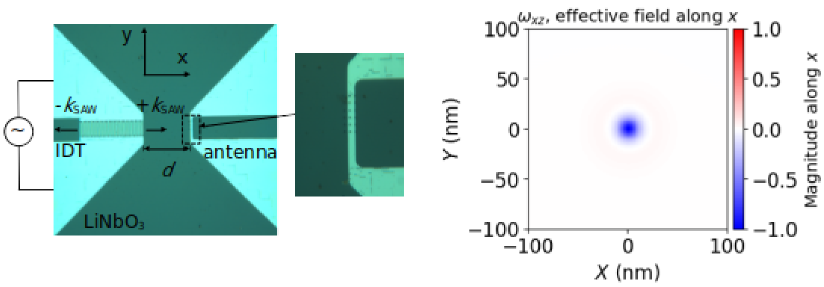

Figure 1: Left: Optical image of the sample employed for the experiments. Right: Magneto-acoustic field distribution in the absence of and applied magnetic field.

[1] R. P. Cowburn *et al*, Phys. Rev. Lett. **83**, 1042 (1999).

[2] V. Novosad *et al*, Phys. Rev. B **72**, 024455 (2005).

[3] A. Koujok *et al*, Applied Physics Letters **123**, 32403 (2023).

[4] R. L. Seeger *et al*, in preparation.

Mutual nonlinear interactions between parametrically excited spin-wave modes in a YIG microdisk

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Hardware based neuromorphic computing (HNC) has been proposed as a potential solution for the exponential increase in energy cost of training deep neural networks. Recently, HNC leveraging in nonlinear magnetization dynamics has been successfully implemented in magnon reservoirs [1,2]. In magnetic microstructures, all the spin-wave eigenmodes (SWM) excited non-linearly are mutually coupled. Thus, by defining the neural network in the k-space, the result is a fully interconnected and tunable network of neurons (SWM) and synapses (mutual couplings) – with minimal nanofabrication required.

We have previously demonstrated that parallel parametric pumping allows the efficient excitation of a large number of SWM in YIG microdisks with a microwave stripline [3]. Here, we use frequency multiplexing to parametrically excite several SWM and study their mutual interactions by magnetic resonance force spectroscopy. The total SWM magnon count as a function of two delayed tone frequencies f_A and f_B is obtained. Clear signatures of nonlinear interactions between SWM are observed: at the eigenmode frequency crossings, the total magnon count is not the sum of the respective single tone experiments. Nonlinear frequency shifts (Fig.1a) and non-commutativity (Fig.1b) are seen, with the final dynamic state depending on the pulse sequence. These phenomena are explained by a normal mode model [4], where the key ingredients are the self and mutual nonlinear frequency shifts of the SWMs. Multiplexing three excitations with variable relative delays leads to a large amount of distinct dynamic states with little change in experimental conditions. These results open up exciting new avenues to exploit mutual interactions of parametrically excited SWM for fundamental magnetism, neuromorphic computing and beyond.

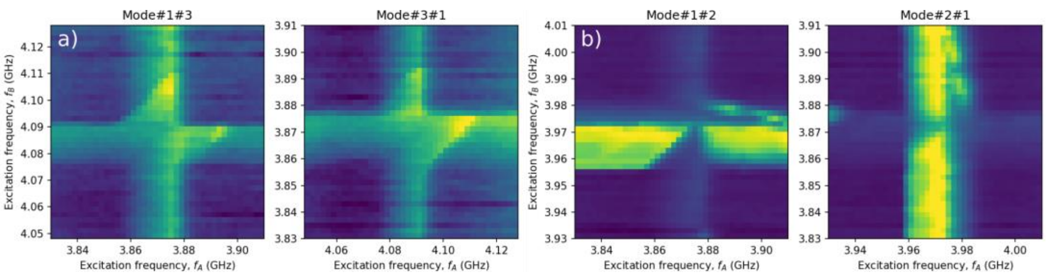

Figure 1: Delayed two-tone parametric spectroscopy maps with nonlinear frequency shifts (a) and non-commutativity (b).

[1] A. Papp, W. Porod, and G. Csaba, Nature Commun. 12, 6422 (2021)
[2] L. Körber, et al., Nature Commun. 14, 3954 (2023)
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[4] S. Perna et al., J. Magn. Magn. Mater. 546, 168683 (2022)

Nonlinear spin waves processes in a 500nm Bismuth Yttrium Iron Garnet disk

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One of the interesting properties of spin waves, the elementary excitations of magnetic material, is their nonlinearity, which can be reached with moderate radio frequency RF excitation fields. The nonlinear interactions between spin waves attract increasing attention in neuromorphic computing and magnonic logic devices. This study presents micro-focused Brillouin light spectroscopy (uBLS) of nonlinear processes in a 500 nm Bismuth Yttrium Iron Garnet (BiYIG) disk [1]. Such material is a soft ferrimagnet with moderate cubic anisotropy and has one of the lowest dampings among all the magnetic materials. The spin waves are excited with out-of-plane RF excitation generated by the omega-shaped antenna. An in-plane static magnetic field is applied, resulting in an in-plane magnetized disk with some nonuniformity at low static field strengths. We vary three parameters to investigate the nonlinear dynamics: the in-plane static field, the rf power (ranging from -15 dBm to 10 dBm), and the rf frequency. We focus on three magnon splitting, where one magnon at f_0 splits into two magnons around $f_0/2$. Fig. 1.a. shows the thermal spectra for a 14 mT in plane static field. By sweeping the rf frequency between 2.1 and 2.7 GHz at 5 dBm power, we observe that when the excitation frequency is in resonance with the thermal mode f_0, a doublet appear around $f_0/2$ (denoted f_A and f_B) indicating the occurrence of three magnon splitting as shown in Fig. 1.b. Time-resolved BLS measurements show that the signal of f_A and f_B appears after f_0, with the intensity of f_0 reaching a minimum when f_A and f_B reach their maximum values. We also investigated the power threshold by sweeping the excitation power and its found to be -2.5dBm for the observed process [2].

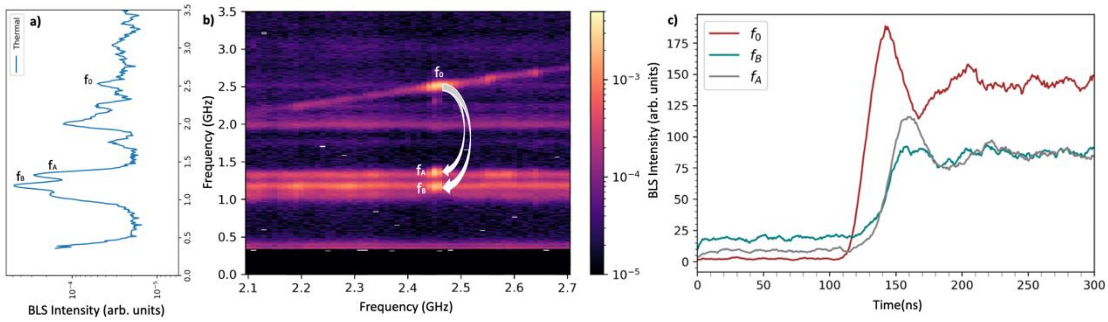

Figure 1: a) Thermal BLS spectra for 14mT in plane static field. b) BLS spectra measured for excitation frequency ranging from 2.1 to 2.7 GHz at 5 dBm power. c) Temporal dependence of the modes f_0, f_A and f_B.

This work was supported by the French National Research Agency (ANR) [under a public grant overseen as part of the Investissements d'Avenir program (Labex NanoSaclay, reference: ANR-10- LABX-0035), SPICY, and a research contract No. ANR-20-CE24-0012 (MARIN)].

[1] A. Serga, A. Chumak, and B. Hillebrands, J. Phys. D: Appl. Phys. 43, 264002 (2010).
[2] H. Merbouche, et al., Phys. Rev. Appl. 21, 064041 (2024).

Spin-Orbit Torque and Spin-Currents

Invited

Spin and orbital torques in Cu-based ferromagnetic heterostructures

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Current-induced torques originating from earth-abundant 3*d* elements offer a promising avenue for low-cost and sustainable spintronic memory and logic applications. Recently, orbital currents -transverse orbital angular momentum flow in response to an electric field- have been in the spotlight since they allow current-induced torque generation from 3*d* transition metals [1-3]. In this talk, we will report a comprehensive study of the current-induced spin and orbital torques in Cu-based magnetic heterostructures. We will show that large torque efficiencies can be achieved in engineered $Ni_{80}Fe_{20}$/Cu bilayers where Cu is naturally oxidized, exceeding the ones found in the archetypical Co/Pt. Furthermore, we will demonstrate sign and amplitude control of the damping-like torque by manipulating the oxidation state of Cu via solid-state gating. Our findings provide insights into the interplay between charge, spin, and orbital transport in Cu-based heterostructures and open the door for developing gate-tunable spin-orbitronic devices.

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[2] G. Sala & P. Gambardella, *Phys. Rev. Research* **4**, 033037 (2022).

[3] Q. Huang et al., *Nano Letters* **23**, 11323 (2023)

Invited

Spin, orbital, and magnetotransport in oxide interfaces

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At perovskite oxide interfaces, two-dimensional electron gases (2DEGs) with compelling properties, such as high mobilities, ferroelectricity, and superconductivity, can occur [1]. They are particularly promising from an spin-orbitronic perspective, since they provide efficient spin- and orbital-charge interconversion, and their properties can be tuned by gating and strain [2,3]. Importantly, not only spin transport has been found in these materials, but also pronounced transport of orbital angular momentum has been predicted and experimentally observed [4,5].

In this talk, I will discuss the theory of spin and orbital transport phenomena in oxide interfaces, in particular $SrTiO_3$- and $KTaO_3$- based 2DEGs. These systems have been demonstrated to provide efficient and tunable spin- and orbital-charge interconversion via the Edelstein effect, as sketched in Fig. 1 [2-4]. Using a semiclassical Boltzmann approach and effective tight-binding models, I will examine spin- and orbital-charge interconversion and discuss strategies to manipulate, control, and optimize this conversion [2-4].

Spin and orbital transport is closely related to magnetotransport phenomena. In particular, a bilinear magnetorestistance has been observed in oxide interfaces, resulting from a nonequilibrium spin and orbital polarization due to the Edelstein effect. Hence, magnetotransport measurements can be used to indirectly detect charge to spin and orbital angular momentum conversion [6]. I will discuss the general concepts of the bilinear magnetoresistance as well as challenges related to its calculation in complex systems.

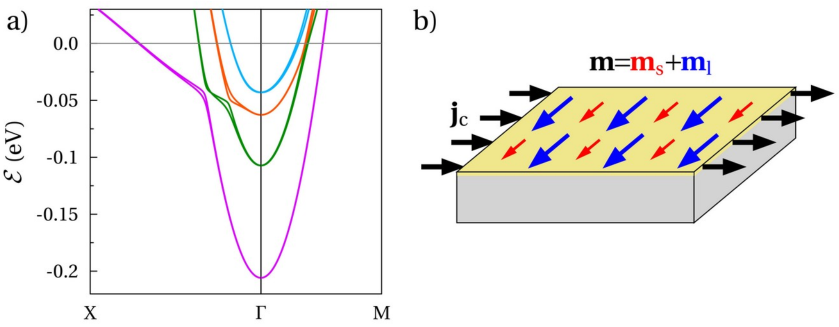

Figure 1: a) Model band structure of the 2DEG at the $SrTiO_3/AlO_x$ (001) interface. b) Charge to spin/orbital conversion by the Edelstein effect: A charge current $\mathbf{j}_c$ generates a magnetic moment **m** with spin ($\mathbf{m}_s$) and orbital ($\mathbf{m}_s$) contributions. Figures adapted from [4].

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Invited

Spin or orbital?

Torques for efficient manipulation of the magnetization

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In the last decades, spin currents and spin torques have occupied the center stage in spintronics research. The recent discovery of orbital currents and associated orbital torques opens a new chapter in the description of nonequilibrium angular momentum transport in condensed matter systems, raising fundamental questions about the underlying transport and conversion mechanisms, offering improvements in torque efficiency and magnetic damping, and expanding material options for future spintronic technologies. Here I will report evidence of spin-orbital torques originating from electric fields applied to 3d and 5d nonmagnetic layers, emphasizing strategies and material systems designed to enhance the orbital-to-spin conversion ratio.

Ultrafast spin dynamics across metal/semiconductor interfaces: all-optical injection of spin currents in silicon

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Integrating magnetic properties in the current semiconductor technology is the aim of Spintronics. The increased ability to tailor hybrid metal-semiconductor heterostructures made possible to use them as building blocks for spintronic devices based on current semiconductor technology. Furthermore, these systems still allow to gain intriguing insights from the complex interplay of different mechanisms, both from the fundamental and applied physics point of view. However, a viable Spintronic technology requires the effective generation, transport, manipulation, and detection of spins in solid-states devices. A path towards the generation and transport of spin currents in silicon will be proposed via the propagation of a superdiffusive spin current (SDSC) triggered by the ultrafast demagnetization of a magnetic film [1]. The system under study - a nickel thin film grown on a passivated silicon substrate [2] - offers a benchmark for investigating the interaction between optical, magnetic, and electric properties in a simple device.

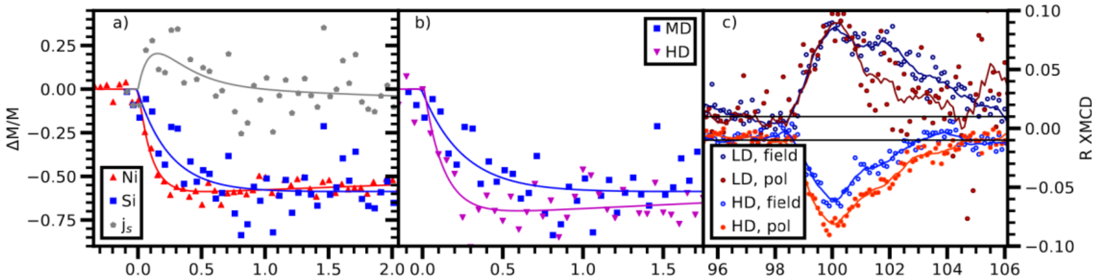

Figure 1: a) RMOKE magnetic dynamics [3,4] at the Ni $M_{2,3}$ and Si $L_{2,3}$ edges (red and blue). The solid lines represent the fitting from which the characteristic demagnetization times are extracted. The difference $(\Delta M/M)_{js}$ is also shown (gray). b) RMOKE magnetic dynamics at the Si $L_{2,3}$ edge on two samples varying only for the doping of the Si substrate (medium and high-doped in blue and magenta respectively). c) Reflectivity XMCD both at opposite fields and helicities on the low and high-doped samples at the Si $L_{2,3}$ edge [5].

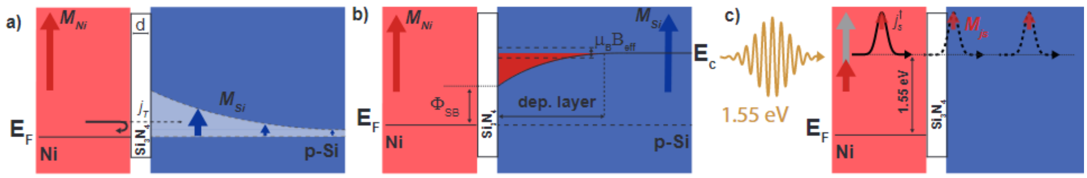

Figure 2: Magnetism in Si can be explained both by spin-polarized diffusion of thermal electrons through the barrier (a) and by the chemical potential splitting due to the proximity effect caused by the interface with a ferromagnet (b). The dynamics triggered by the optical pulse arrival causes contemporary a quenching of the magnetization in Ni and thus in Si, and the generation and propagation of a SDSC in Si (c). The overall observed dynamics is a competition between the demagnetization and the transient SDSC.

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Optimal magnetization switching via spin-orbit torque in ferromagnet/topological insulator heterostructures

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Controlled switching via an external stimulus, such as an external magnetic field, light, or even current pulses, is among the basic operating principles of several devices for data storage, transmission, and processing. One way to achieve this is through the so-called spin-orbit torque (SOT), which involves the conversion between charge and spin currents via spin-orbit coupling (SOC). In this case, the switching can be achieved by, for example, applying a current to a high-SOC host material, onto which a ferromagnetic (FM) sample is placed. Instead of conventional heavy-metal systems, topological insulators (TIs) [1] - characterized by an insulating bulk but conducting surface states - present a promising alternative in this context [2]; the spin-momentum locking of Dirac electrons at the surface of a TI allows for a large charge-to-spin conversion [3], thereby enabling a correspondingly large SOT on the FM element. Moreover, TIs offer the advantage that intrinsic properties, such as Fermi energy or velocity, can be modified by strain [4] or the application of external gate voltages [5].

When it comes to magnetization switching in FM/TI heterostructures, a key challenge is minimizing the energy cost of this process to make it energy-efficient. Here, we discuss the development and implementation of energy-efficient magnetization switching control in FM/TI systems via current pulses, based on optimal control theory. We show that particularly efficient switching can be achieved by vanishing damping-like torque. In addition, although the optimal current pulse is rather complex, it can be largely simplified in some realistic situations, making the protocol sufficiently easy and robust for experimental verification.

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Spin-orbit-torque switching in α-W-based magnetic tunnel junction

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Spin-orbit-torque (SOT) provides an efficient way to induce magnetization dynamics and switching of nanomagnets using electrical currents [1]. In this study, we present a SOT-induced magnetization switching in low-resistive α-W-based magnetic tunnel junction (MTJ) with an effective in-plane magnetic anisotropy. We use harmonic Hall voltages to determine damping-like and field-like components of SOT in the W/FeCoB bilayers [2]. Next, based on the same bottom structure we fabricated MTJ W(6)/ FeCoB(1.7)/ MgO(1.35)/ CoFe(3)/ SAF. The MTJ pillars with dimensions ranging from 100 × 200 to 300 × 600 nm were fabricated on the top of a 1-μm-wide W-channel using electron-beam lithography and ion-beam etching. Both the bottom free and top reference layers are in-plane magnetized, however, due to the FeCoB/MgO interface there is a significant perpendicular component to the effective magnetic anisotropy. To determine it, we measured ferromagnetic resonance spectra using the full MTJ stack and simulated resonance frequency vs. magnetic field dependence of two FMR peaks corresponding to the free and reference layers using *cmtj* software [3].

In a small in-plane magnetic field below 20 kA/m, the free layer magnetization is tilted from the plane resulting in the resistance state between fully parallel and antiparallel. The TMR ratio reaches 110 %, an example of resistance vs. magnetic field loop is presented in Fig. 1. To verify SOT-induced switching in our MTJ, 5 ms-long pulses of increasing amplitude were applied to the W-channel, while MTJ's resistance was measured after each pulse. At the current density of around +/- 7×10^{11} A/m^2 we measured a switching between parallel and antiparallel states, depending on the current polarity.

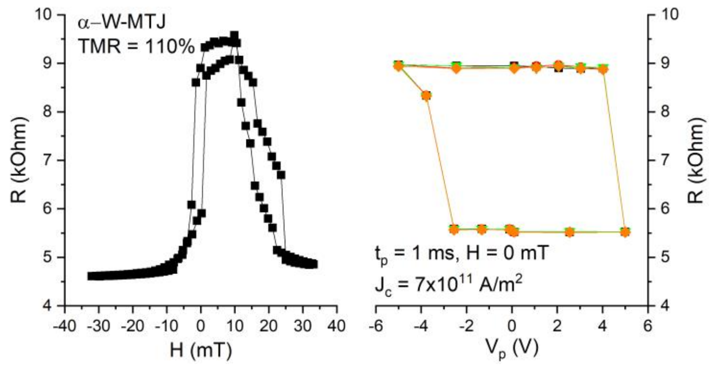

Figure 1: (left) TMR loop in the in-plane magnetic field and (right) SOT-switching loop.

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Interfaces with Graphene: an amazing playground for SpinOrbitronics

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The introduction of giant spin-orbit coupling (SOC) in the electronic bands of graphene via proximity with intercalated layers potentially allows the realization of highly efficient, electrically tunable, nonvolatile memories as well as opens up new pathways towards the realization of spintronic devices exploiting novel exotic electronic and magnetic states.

In this work, we will examine the properties of Gr epitaxial layer interfaced with different materials [1]. In particular, in epitaxial Gr/FM grown on heavy metal/insulating oxide supports, element dependent and averaged surface/interface sensitive measurements provide evidence of a strong orbital hybridization leading to an enhancement of the PMA driven by the 3d Co orbital moment anisotropy [1,2,3], and an energy splitting of in-plane spin polarized Gr π bands, consistent with an Rashba-SOC at the Gr/Co interface [4,5].

By resorting to the additional intercalation of rare-earth materials, e.g. via 4f europium doping, we demonstrate the possibility to generate single-spin polarized bands [6]. The doping is controlled by Eu positioning, allowing for the formation of a localized single spin-polarized low-dispersive parabolic band if Eu is on top, and a π* flat band with single spin character when Eu is intercalated underneath graphene.

Finally, by spin pumping experiments [7] we demonstrate the possibility to control the spin-charge conversion, anisotropy and damping, by building a highly epitaxial, clean, double Rashba interface Graphene-based system, i.e. Pt/Gr/FM (with FM=Co, Fe) [8].

All this is then translated in a measurable induced magnetic moment in Gr, in the generation of competing effects for charge, orbital and spin conversion, in driving the appearance of non-trivial, exotic topological spin textures and emerging symmetry-broken phases, and enables the electrical control of the SOC driven properties even by the interface with ferroelectric layers [9].

Financial support AEI/MICINN PID2021-122980OB-C52 (ECLIPSE-ECoSOx), CNS2022-136143 (SPINCODE), CEX2020-001039-S, and from the "(MAD2D-CM)-UAM" is acknowledged.

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Artificial Spin Ice Physics and Applications

Invited

Architecting emergence in nanomagnets: artificial spin ice

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Theoretical condensed matter physics typically distills relevant interactions and symmetries into simplified models, describing the complexity of real materials through emergent degrees of freedom, such as excitations [1]. But what if we inverted this approach? Rather than serendipitously discovering a material with interesting properties and modeling it with a simplified Hamiltonian, we could start from the model and deliberately architect exotic emergent behaviors into an artificial material [2]. This concept has guided our research for nearly two decades, leading to various realizations using nanomagnets [2,3], magnetic colloids [4], skyrmions and disclinations in liquid crystals [5], macroscopic magnets [6], quantum annealers [7], and even mechanical metamaterials [8]. In this talk, I will outline the history of this field and then present recent results: from the LANL-Princeton on entropy-driven order [9], topological transitions in string states [10], fractional magnetic charges trapped by disclinations [11], and new spin noise methodologies [12]; the LANL-Dwave collaboration on quantum annealer realizations [7]; the LANL- University of Colorado Boulder collaboration on liquid crystal realizations; the LANL- University of Tel Aviv collaboration on mechanical metamaterials [8]. This talk will highlight the potential and outcomes of this approach, avoiding overly technical details—though I will be happy to delve into those during Q&A or personal discussions at the conference.

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Invited

3D Artificial spin-ice

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In this talk, I will start by providing a brief overview of work carried out at Cardiff, whereby two-photon lithography (TPL) has been used to realise and study 3D artificial spin-ice systems [1-3]. Monte-Carlo simulations of such structures, predict a rich phase diagram with a number of charge-ordered phases including a single and double charged monopole crystal [3]. By using magnetic force microscopy, I will show that the vertex states in experimental systems can be determined, and monopole transport upon the lattice surface can be directly visualised [2]. More recent strategies in the measurement of 3DASI systems will then be discussed, including the use of transmission x-ray microscopy [4] and Brillouin Light Scattering (BLS). The spin-wave modes associated with different vertex types as determined by micromagnetic simulations will be described. BLS measurements performed upon as-deposited samples and those subject to an in-plane demagnetizing protocol exhibit distinct spectra, with the latter harbouring a strong peak associated with type III, monopole vertices. Such results are consistent with magnetic imaging experiments which demonstrate as-deposited samples are largely composed of type II tiling and demagnetized samples exhibit large patches of magnetic charge crystallite. The work suggests that BLS spectra can be exploited, even in complex 3DASI samples, to infer characteristics of the sample microstate.

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Invited

Topological boundaries and geometric constraints in artificial colloidal ice

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In this talk, I will show recent results obtained using experiments and numerical simulations on the effect of boundaries [1] and geometry [2,3] on a colloidal ice system. The colloidal ice is a soft matter analogue of spin-ice system, where interacting particles are confined within a lattice of double wells that display a collective frustration [4,5]. In the first part of the talk, I will show how boundaries can be engineered to control the bulk behaviour in such system. In particular, an antiferromagnetic frontier can be used to force the system to rapidly reach the ground state (GS), as opposed to the commonly implemented open or periodic boundary conditions. I will also show that strategically placing defects at the corners generates novel bistable states, or topological strings, which result from competing GS regions in the bulk [1].

For lattices with single coordination as the square one, the colloidal ice behaves similarly to the artificial spin ice following the ice selection rules [6]. However, in mixed coordination geometries, negative monopoles spontaneously appear at a density determined by the vertex-mixture ratio and accumulate at sublattice locations, breaking the ice rules. Thus, I will show that a geometric transformation between two mixed coordination geometries, from Shakti to Cairo, leads to a breakdown of the ice rule in all but one specific geometry. The result is a transfer of the topological charge among sublattices which can be controlled in sign and intensity, vanishing at the ice-rule point [2,3].

All these results could be generalized to other frustrated micro- and nanostructures where boundary conditions may be engineered with lithographic techniques.

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Impacts of multipolar corrections, boundary conditions and cutoff radius on the ground state of artificial kagome spin ice

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Arrays of nanoscale bar magnets have been largely used to realize a multitude of spin models [1]. In general, the long-range character of the magnetostatic interaction between the nanomagnets is not negligible. This is particularly evident in the so-called artificial kagome spin ice [2], where long-range couplings correlate the system ultimately into an ordered ground state (GS) within a dipolar model [3,4]. This picture holds considering both periodic boundary conditions (PBC) and open boundary conditions (OBC) [5] for finite lattices having the size of experimental arrays, which might leave the impression that these conditions do not play an important role in this type of system.

In this work, we show that the GS of kagome spin ice is much more sensitive to the boundary conditions when small but non-null multipolar corrections are added to the pure dipolar Hamiltonian. These extra terms take into account the finite size of the nanomagnets, and are considered up to the sixth neighbors, in contrast to many studies in which such corrections are usually neglected above nearest-neighbors [2,5].

When assuming PBC, the GS greatly depends on the cutoff radius R. Certain R values happen to single out different ordered spin configurations exhibiting unit cells of linear size ~ R, which are always larger than the dipolar GS's unit cell. The dipolar GS is fully recovered only for $R > \sim 12\, r_{nn}$ (r_{nn} is the nearest-neighbor distance), whereas a cutoff radius as small as $R = 2\, r_{nn}$ is already enough in the dipolar model [6]. On the other hand, when assuming OBC, the multipolar corrections have no significant effect and this more realistic description ends up reproducing the dipolar physics.

The novel GSs predicted by the multipolar model are not expected to be seen experimentally since they only occur in the unnatural scenario of PBC with finite cutoffs. However, many works on artificial spin systems interpret their experiments in light of dipolar models under exactly these assumptions. While the physics of dipolar kagome spin ice is the same for PBC and OBC, our results make it clear the potentially overlooked fact that this equivalence is incidental, and that it should not be taken as granted in general.

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Controlling phase transitions and magnetic order in a ruby artificial spin ice

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Artificial spin ices are arrangements of dipolar-coupled nanomagnets with magnetic moments that behave like Ising spins due to shape anisotropy. Their frustration was originally envisaged as an analogue to the frustration observed in rare-earth pyrochlores. However, they have proven an excellent platform to realize interesting phase transitions, non-equilibrium phenomena, and collective dynamics such as monopole motion.

The ruby lattice is a 2D geometry that has not yet been realized in an artificial spin ice context. It consists of a network of edge-sharing triangles, rectangles and hexagons, as depicted in Figure 1. Using electron beam lithography, we fabricated artificial spin ices based on the ruby lattice and probed them experimentally using magnetic force microscopy (MFM) and x-ray photoemission electron microscopy (X-PEEM), as well as via computational techniques, including micromagnetic and Monte Carlo simulations.

A unique feature of the ruby artificial spin ice is that it is possible to tune the couplings between nanomagnets using two lattice parameters, a and b, while maintaining the same symmetry group and ground state. In sweeping independently the two lattice parameters, we control the energy hierarchy in the system and, as a consequence, how ordering proceeds.

When the two lattice constants are of similar size ($a \approx b$), the interactions between nanomagnets in triangles and hexagons are approximately balanced, so that the system orders in a single step.

When one lattice constant is much greater than the other ($a >> b$ or $a << b$), the system orders in two steps. These steps correspond to head-to-tail loop of nanomagnet moments associated with the individual hexagonal and triangular shapes. The nanomagnets in the shape with the strongest coupling will form a moment loop first.

Since the coupling is controlled by the lattice parameters, we can choose which shape will flux close first or have them flux close together in a single phase transition. This was directly observed on thermal annealing of the structures using X-PEEM.

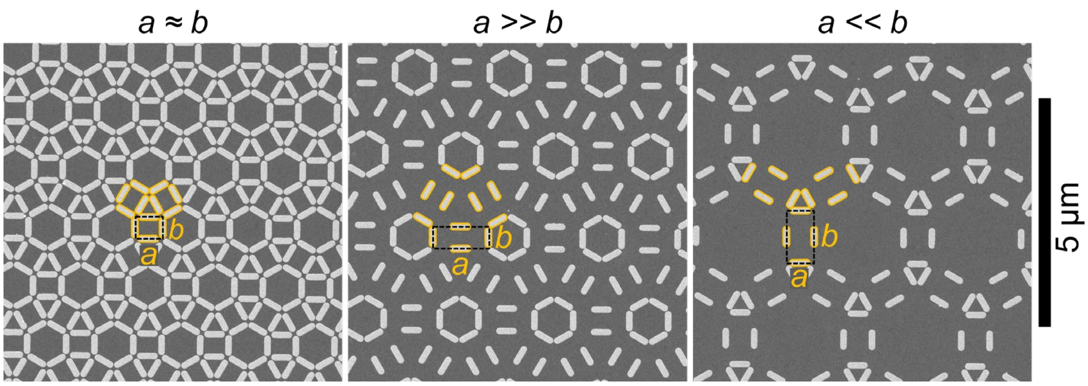

Figure 1: The ruby artificial spin ice for three representative lattice parameters: $a \approx b$, $a >> b$ and $a << b$. Shown in yellow is a unit cell with lattice parameters a and b.

Effective interaction strengthening and absence of spin fragmentation in connected artificial kagome ice

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Assemblies of interacting nanomagnets patterned by lithography have become a fruitful playground for investigating frustrated magnetism through a lab-on-chip approach [1]. In particular, the artificial kagome ice features a rich phase diagram including a two-step melting process [2,3]. In samples with physically disconnected magnetic elements, field-driven demagnetization protocols are known to equilibrate the system into a conventional spin liquid [4], and one of the challenges is to access very low effective temperatures to reach the exotic fragmented spin liquid [1,5,6]. Previous works suggest that this regime could be attained in artificial kagome ice systems in which the magnetic elements are physically connected at the vertices [7,8]. However, no comprehensive study has been conducted so far.

Our investigations reveal that connected artificial kagome ice is actually left out-of-equilibrium after being subjected to typical field protocols that equilibrate other systems. More specifically, certain spin correlations are systematically larger than the ones expected from the equilibrated dipolar model. This strongly suggests that the standard field protocol induces domain wall motion in such a way that sizeable kinetic effects impede proper equilibration.

Remarkably, the configurations we image after demagnetization are well accounted for by a modified, effective model at equilibrium characterized by strengthened interactions between specific neighbors. This effective model exhibits a distinct low temperature physics, notably lacking the fragmented spin liquid phase and presenting a polarized ground state.

An interesting prospect from our work is the possibility of tuning the effective neighbor coupling by controlling the degree of connection at the vertices. This might be a promising route to realize other models as well to access spin fragmentation [9].

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Strategies for degeneracy and monopole mobility in two-dimensional artificial spin ices

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In this work, we present strategies investigated by our group to achieve degeneracy in planar Artificial Spin Ice (ASI), thereby enhancing monopole mobility in response to applied external fields. Our objective was to integrate theory and experiments to develop compatible systems for potential applications in magnetricity devices. We began by expanding on previous investigations of the dipole-dipole model in stretched ASI [1]. Through the Dumbbell-model approach and magnetic spin factor (MSF) analysis [2], we demonstrated how the dimensions of nanomagnets within the lattice influence degeneracy, as illustrated in Figure 1. Subsequently, we conducted experiments based on these predictions. Both magnetic force microscopy and magneto-resistive measurements provided evidence of degeneracy. We observed that in specific geometries, magnetic monopoles flow freely without constraints [3]. Additionally, we explore alternative strategies to control monopole mobility. For instance, we investigate leveraging proximity effects with metals or employing reversible methods such as the all-optical devices approach. Our findings aim to contribute to the advancement of magnetricity technologies with practical implications for future device applications.

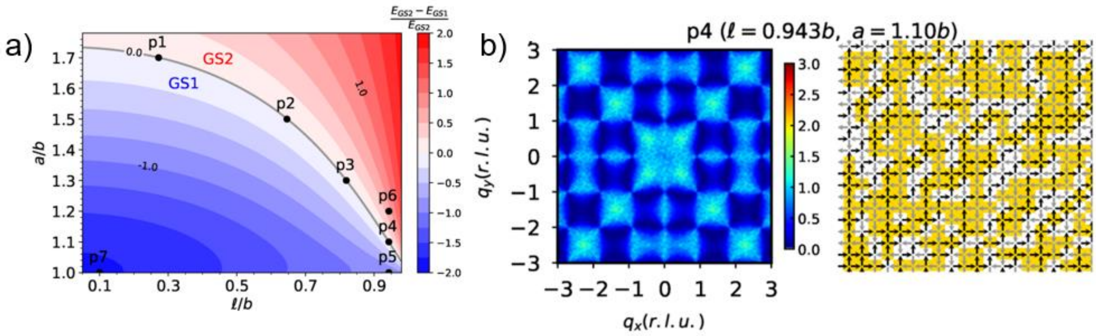

Figure 1 – a) Phase diagram: Favourable ground state as a function of geometric lattice ratio and island size to separation ratio. b) Average MSF of low-energy states of the 100 samples simulated using the dumbbell model and one representative sample of the spin configuration.

[1] NASCIMENTO, F. S. et al. New Journal of Physics, v. 14, n. 11, p. 115019, 2012.

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Spatially ultra-selective all-optical magnetic switching and vortex writing in nanomagnets

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The realisation of high-fidelity and spatially selective control of nanomagnets, specifically through all-optical magnetic switching, promises ultrafast magnetisation control while circumventing the requirement for an external magnetic field, and addressing a longstanding goal in data storage and computational technologies. Traditional state-control approaches, utilising magnetic field and thermal protocols, access only a limited fraction of magnetic microstates, while alternative techniques, such as scanning magnetic tips [1], are impeded by slow setups and susceptibility to tip damage. Furthermore, existing methodologies relying on complex magnetic materials [2] underscore the need for a rapid and localised microstate control method across extensive nanomagnetic networks.

Building upon our prior breakthrough in nanomagnetic writing within dense arrays[3], we present a spatially selective technique, in which we can effectively target magnetic writing to single NiFe nanomagnets as small as a few hundred nanometres long, despite being in a densely packed array. In nanomagnets with vortex/macrospin bistability, such as in Artificial Spin-Vortex Ice [4] we demonstrate than we can controllably convert macrospins to vortices. Moreover, our approach enables reproducible intricate microstate engineering of complex patterns to create magnetic images, a functionality that significantly expands the potential applications in data storage and computational technologies.

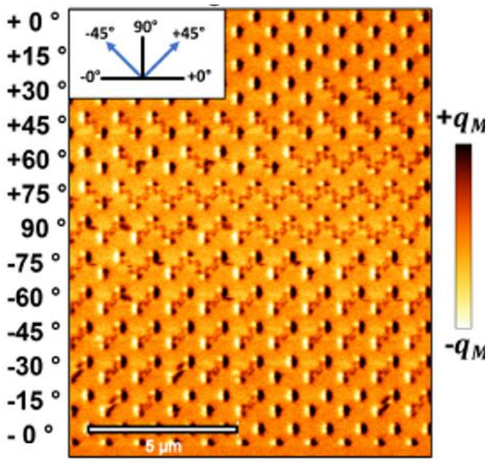

Figure 1: MFM image of Artificial Spin-Vortex Ice Array after row illuminations at laser polarisations at angle indicated to left of row (as defined in inset).

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Controlling Dzyaloshinskii-Moriya Interaction

Invited

Controlling and tuning the interfacial Dzyaloshinskii-Moriya interaction: Chiral domain walls, Skyrmions and Merons

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The control and understanding of the interfacial Dzyaloshinskii-Moriya Interaction (iDMI) at heavy metal/3d ferromagnet interfaces have enabled the realization of various chiral magnetization textures in two dimensions, such as chiral domain walls, skyrmions, and merons, and more recently, in three dimensions; hopfions [1].

In this contribution I will elaborate on how we approached the extraction of the iDMI using in-situ scanning electron microscopy with polarization analysis (SEMPA). Here, specifically applied to chiral domain walls generated in multilayered samples where the competition between dipole field intensity (via layer thickness) and iDMI sets the chirality of domain walls as shown in Figure 1a [2,3]. I will then shortly discuss how we control and inject skyrmions in these systems using current, light and assist this with ion irradiation [4,5].

Finally, I will elaborate on recent observation of imprinted merons in the top layer of a multilayer stack (see Figure 1b). These results are corroborated by micromagnetic simulations indicating that the iDMI induces a homochirality in the merons, and elongate anti-merons [6].

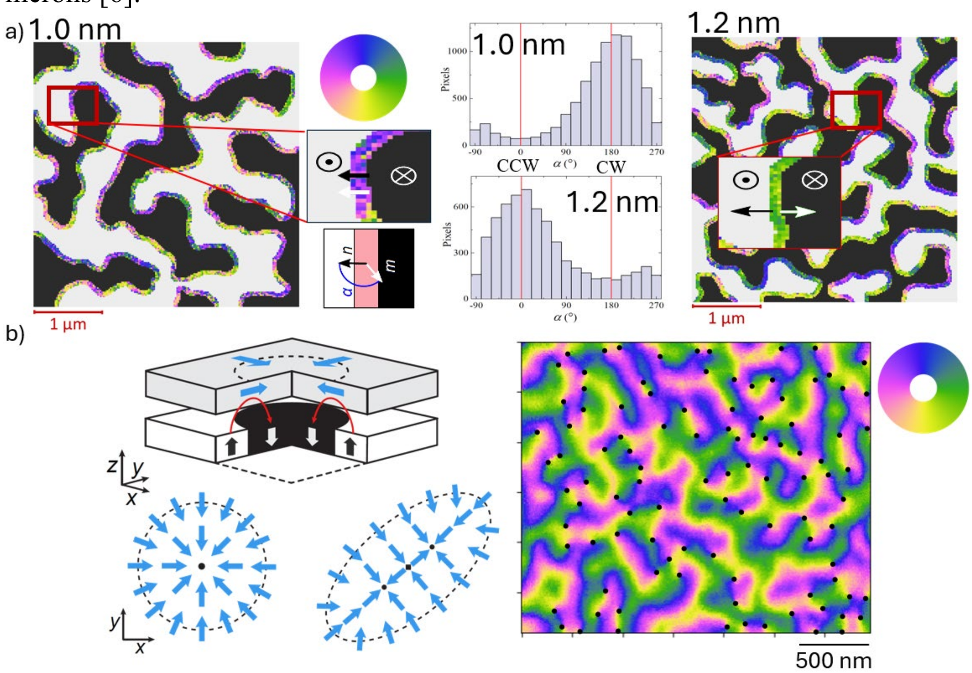

Figure 1: SEMPA results of dipole - iDMI competing systems (a) extracting the chiral nature (CW = clockwise, CCW = counter clock wise) of domain walls as a function of top ferromagnetic layer thickness (b) merons and anti-merons (black dots) as detected using SEMPA on a 2.4 nm thick Co top layer.

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[2] Meijer *et al.*, PRL 124, 207203, (2020)
[3] Lucassen *et al*, PRL 102 014451 (2020)
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Invited

Measurement of Dzyaloshinskii-Moriya interaction and its modification by magneto-ionic effects

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Several experimental methods are available to measure the strength of the Dzyaloshinskii-Moriya interaction (DMI) in magnetic thin films with perpendicular magnetic anisotropy. One of the most popular is based on the measurement of the domain wall (DW) velocity driven by an out-of-plane magnetic field, as a function of a continuous in-plane field [1,2]. I will discuss the use of this method for DW velocities in the creep and flow regime, and give some examples of how the DMI values compare with the values obtained with the Brillouin Light Scattering method.

I will then show that in Pt/FM/MOx trilayers (FM=ferromagnet, MOx=metallic oxide) the DMI value can be tuned with the oxidation degree of the FM/MOx interface and that an electric field gating can be used to change the degree of oxidation of the ferromagnetic layer, and therefore the DMI, by magneto-ionic effects. These effects are reversible and reproducible, allowing a local control of the DW velocity, that can even be inverted with a gate voltage [3,4].

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[2] "Study of the velocity plateau of Dzyaloshinskii domain walls" V. Krizakova et al. Phys. Rev. B **100**, 214404 (2019)
[3] "Tuning the dynamics of chiral domain walls of ferrimagnetic films with the magneto-ionic effect" C. Balan et al. Physical Review Applied **18**, 034065 (2023)
[4] "Gate-controlled skyrmion and domain wall chirality" J.E. Fillon, Nature Communications **13**, 5257 (2022)

Invited

Measuring the Dzyaloshinskii-Moriya interaction and the METROSPIN project

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In the rapidly growing research field of chiral magnetism, accurate measurement of the interfacial Dzyaloshinskii-Moriya interaction (DMI) in ultrathin magnetic films in contact with heavy-metal under- or over-layer, is attracting a lot of interest, not only for fundamental reasons, but also for the opportunity of designing new spintronic devices. However, it has been pointed out that substantial and systematic discrepancies can emerge when comparing the results relative to the DMI constant D obtained by different state-of-the-art methods. [1] In particular, it has been recently found, in Co/Pt and CoFeB/Pt ultrathin films, that the values of D obtained by Brillouin light scattering (BLS), looking at the non-reciprocity of spin waves propagating in opposite directions, are systematically larger than the values derived from asymmetric bubble domain expansion imaged by the magneto-optical Kerr effect (MOKE). [2] Both methods are currently exploited within the framework of the METROSPIN Italian national project whose aim is to analyse the measurement statistics, also in relation to sample inhomogeneities and defects, and to adopt a machine-learning approach to evaluate the DMI from magnetic domain patterns. In this talk, I will first focus on the capabilities of BLS to quantify the DMI constant, discussing in details the proper choice of experimental parameters, as well as the reproducibility and repeatability of the BLS measurements. Subsequently, I will review the comparison between the values of D obtained by BLS and MOKE in various systems, suggesting possible reasons for the observed discrepancies, focusing attention on both the characteristics of the theoretical models used to extract the value of D from the experimental data and the chosen regime for the bubble expansion measurements.

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Invited

Spin textures in synthetic antiferromagnetic multilayers

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Synthetic antiferromagnet (SAF) multilayers make use of indirect exchange coupling across spacer layers to achieve an antiferromagnetic ground state. SAFs are predicted to [1], and show [2] reduced skyrmion Hall angle [3] and fast skyrmion [4] and DW motion [5].

Here we study spin-textures generated during the field-induced transition [6] from the SAF to saturated state. We report on studies of SAFs based on the repeat unit [Pt(8)/ CoB(16)/ Ru(7)/ Pt(8)/ CoFeB(10)/ Ru(7)], with layer thicknesses in Å. Our chosen multilayer stack has ultrathin CoB layers so properties are dominated by interfaces, indirect AF exchange coupling across Ru spacers, and Pt layers to induce perpendicular anisotropy (PMA) and Dzyaloshinskii-Moriya interaction (DMI). The CoB and CoFeB layer thicknesses were chosen to give equal moments that cancel, forming the sublattices of a SAF structure.

We report the evolution of spin textures in perpendicularly magnetised synthetic antiferromagnet (SAF) Ta/Ru/{Pt/CoFeB/Ru/Pt/CoB/Ru}×5}Ta multilayers as observed by Lorentz microscopy, soft x-ray resonant magnetic scattering, and magnetic force microscopy. As we reduce the field from saturation we observe a variety of spin textures during the transition to the SAF ground state: conventional skyrmions with core opposed to field direction; stripe domain states; and skyrmions with a core in the field direction that exist in only one superlattice and hence present a 3D character.

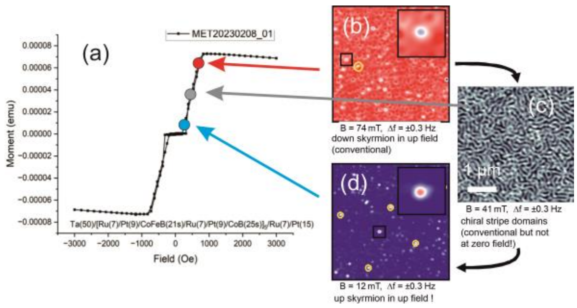

Figure 1: SAF behaviour under field. (a) Hysteresis loop measured by SQUID-VSM. MFM images at (b) 74 mT; (c) 41 mT; and (d) 12 mT. The reversal of the skyrmion core polarity is evident in panels (b) and (d).

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Domain wall curvature effects on the measurement of the Dzyaloshinskii-Moriya interaction strength in the creep regime

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The measurement of the interfacial Dzyaloshinskii Moriya interaction (DMI) strength D via domain wall (DW) velocity in the creep regime is a versatile technique that allows access to this important quantity through magneto-optical experiments [1]. The downside of this method is that it sometimes lacks agreement in the value of D with other measurement methods such as the Brillouin light scattering (BLS) technique [2]. A possible cause and important factor in accurately determining the DMI strength in the creep regime is the radius dependence of magnetic domain wall velocity in bubbles, but up to now few works have analysed this aspect [3]. In this work we address the radius dependence of the DW velocity in thin film Pt(3)/Co(0.8)/Ir(1) samples. We measure (see Fig. 1) a significant radius dependence of the DW velocity and discuss how this could be due to the pinning characteristics of the considered sample. We support our findings by using an adapted version of the analytical model by Je et al. [1] for DW motion in the creep regime in the presence of IP fields and DMI. We emphasise the effect of this radius dependence of the velocity on the experimentally measured values of the DMI strength, demonstrating how disregarding the bubble radius can cause a systematic measurement underestimation (up to 30% - See Fig. 2).

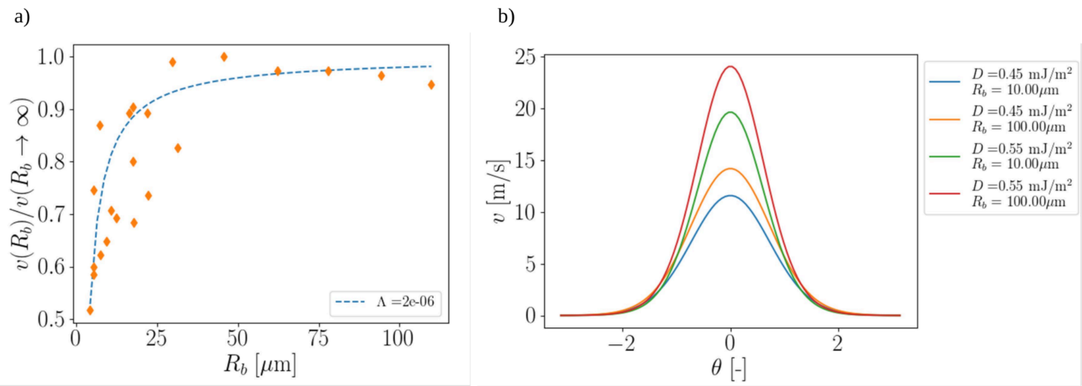

Fig1-a) Value of the ratio between the velocity of a bubble of radius R and the velocity in the limit of an infinite-size bubble, as a function of the bubble radius R . Best fit obtained with our model. b) Effect of the initial radius on the curve shapes of the domain wall velocity

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[1] S.-G. Je, D.-H. Kim, and S.-C. Yoo, Physical Review B, vol. 88, p. 214401 (2013).

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Recent progress in studies of interlayer Dzyaloshinskii-Moriya interactions

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In this talk, an overview of recent progress in the study of the interlayer Dzyaloshinskii-Moriya interaction (IL-DMI) will be presented. This interlayer DMI induces a unique chirality of magnetization not only within a layer plane, as the interfacial (IF)-DMI does, but also across the multilayers [1,2] and its strength can be comparable to that of the IF-DMI (0.1-0.2 mJ/m^2). In particular, it will be shown that IL-DMI can occur not only in layered heavy metal/ferromagnet interfaces, but also in multilayers with spacers made of rather light metals. An example of such a system give Co/Ag/Co trilayers, which were recently studied with the aid of surface-sensitive magneto-optical measurements that take advantage of the light penetration depth [3] and confirmed by first-principle calculations [4]. The symmetries of interfacial and interlayer exchange interactions are different, although they both arise from pairwise exchange interactions between magnetic sites mediated by nonmagnetic atoms. Unlike IF-DMI, which does not contribute to the FMR frequencies, IL-DMI alters the frequencies of fundamental FMR modes and can be separated from other contributions by an FMR experiment.

It will also be shown how the IL-DMI changes the magnetic order within the magnetic planes [5]. The combination of the described phenomena opens up new avenues for the design of three-dimensional chiral spin structures combining IF- and IL-DMI and paves the way for enhancements of the DMI strength.

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Ferroelectric control of the magnetic properties in the layered multiferroic Co/$Hf_{0.5}Zr_{0.5}O_2$

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Magnetoelectric multiferroics are promising candidates for energy-efficient in-memory computing in single-phase and composites ferroelectric/ferromagnetic coupled films. Among others, doped hafnia stands out for its compatibility with industrial CMOS processes [1].

Here, we present the magneto-electric properties of heterostructures made by perpendicularly magnetized cobalt thin films grown on ferroelectric Zr-doped hafnia ($Hf_{0.5}Zr_{0.5}O_2$ - HZO). The polarization-dependent magnetic properties of Co are studied by magneto-optical Kerr microscopy (Fig. 1a). The similarity of dc and remanence measurements suggests a purely ferroelectric control of coercivity, with a negligible role of voltage-controlled magnetic anisotropy (VCMA), at variance with previous reports on similar systems [2].

The effects of polarization switching on Dzyaloshinskii-Moriya interaction (DMI) and domains-wall propagation are also investigated through the study of the anisotropic expansion of bubble domains [3] as well as by Brillouin light scattering (BLS). Some insights on the ferroelectric control of DMI will be given and interpreted by calculations on the interfaces.

These results suggest that the artificial multiferroic Co/HZO may represent a promising candidate for voltage-controlled spin-based computing.

C.R. acknowledges the PRIN project SORBET (grant no. 2022ZY8HJY) funded by MUR.

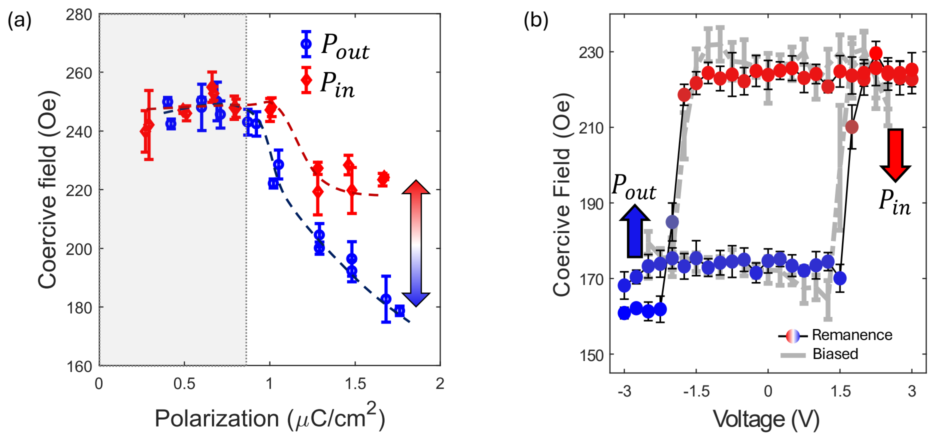

Figure 1: (a) Magnetic coercive field of cobalt versus ferroelectric polarization strength in HZO for the two remanent polarization states. (b) Magnetic coercivity as a function of the amplitude of the voltage pulse used to set the polarization state.

[1] T. Zakusylo *et al.*, Materials Horizons **11**, 2388 (2024).

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Amplitude modulation and sign inversion of the Dzyaloshinskii-Moriya interaction by work function engineering in Co based metallic multilayers.

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In the last decade there has been extensive research on the Dzyaloshinskii-Moriya interaction (DMI), which in thin films and multilayers (MML) plays a key role in the stabilization of chiral spin textures such as chiral domain walls, magnetic 2D skyrmions or 3D cocoons [1]. Our objective in the present study is to unravel the different contributions at the origin of amplitude of the DMI beyond the Fert-Levy 3-site model.
We observe in [2, 3] that D_s has been related to various intrinsic material properties such as the atomic number, the electronegativity and the work function difference ($\Delta\phi$) between Co and top metal layer [Fig.1(a)], finding the best (linear) correlation with the latter. We go one step further to check if the linear correlation is universal, we have grown asymmetric trilayers and MML with a moderate number of repetitions (n = 3, 4, 5 and 6) with Pt|Co|*M* and Pd|Co|*M* structures. The strength of D_s has been determined by analytical (lambda-delta-psi) [4] model and MuMax3 simulations. We can conclude that the DMI amplitude is found to be constant in MML with number of repetitions up to n = 6. Moreover, the linearity vs $\Delta\phi$ is preserved regardless of the bottom layer (Pt or Pd) [Fig.1(b)]. Finally, we would like to modify the DMI sign by varying the surface potential with the orientation of the film. Replacing Pt by W, the total DMI amplitude will be much smaller. Moreover, if we complete the trilayer with Cu, $\Delta\phi$=0, we can assume that all the contribution due to the interfacial potential gradient will come from the W|Co bottom interface. Therefore, by varying the W growth orientation from 110 (ϕ = 5.22 eV) to 100 (ϕ = 4.66 eV) we can invert $\Delta\phi$ and thus the sign of the DMI [Fig.1(c)].

[1] Grelier et al., Nat. Comm. **13**, 6843 (2022).
[2] Park et al. NPG Asia Materials (2018) 10: 995–1001
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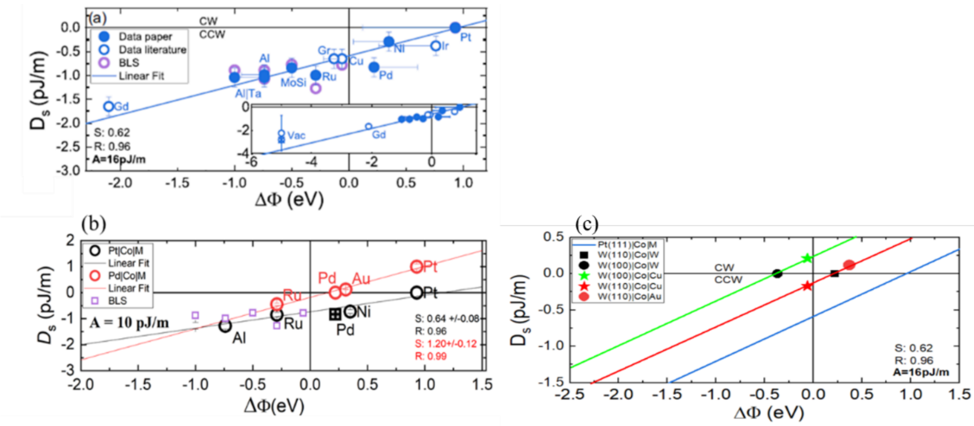

Figure 1 (a) D_s vs $\Delta\phi$ of Pt|Co|M trilyers (b) D_s vs $\Delta\phi$ of Pt|Co|M and Pd|Co|M multilayers with n=3 to 6. (c) D_s vs $\Delta\phi$ of W|Co|M with W 100 (green) and 110 (red)

Computational studies of novel Dzyaloshinsky-Moriya interactions

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The exploration of magnetic phases in chiral magnets has gathered significant interest due to the unique physics and potential applications of these materials. A key factor in these systems is the Dzyaloshinsky-Moriya Interaction (DMI) [1, 2], which arises from the asymmetric environment of interacting magnetic spins and is linked to non-centrosymmetric crystallographic point groups. While a few point groups have had their DMI extensively studied, many remain unexplored [3].

In this talk, we present results which start to address this gap by computationally investigating these relatively unexplored DMI terms. These novel terms have been integrated into micromagnetic simulation tools, and made available as open-source resources. We systematically explore the multidimensional parameter space of these new DMI terms to identify magnetic phases and classify new ones By leveraging Machine learning algorithms, such as clustering and autoencoders, have been using to automate this process, rapidly identifying and cluster similar magnetic phases across vast parameter spaces. As a result, we have generated detailed phase diagrams for select crystallographic point groups and obtained novel and complex magnetic structures such as Figure 1.

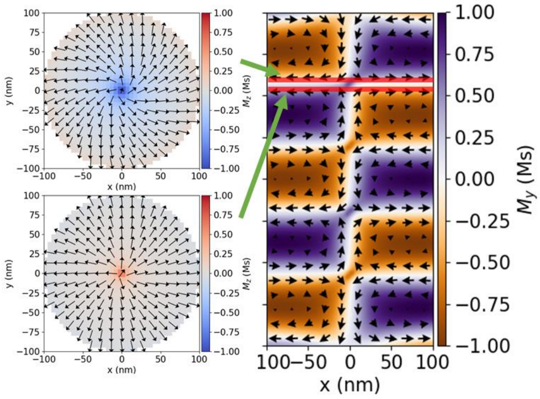

Figure 1 Micromagnetic simulation for D_n ($n \geq 3$) crystallographic point group showing a stacked vortex structure with stable Bloch points. The images on the left represent cross-sections at the positions of the red lines shown on the right.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101152613 and MaMMoS No 101135546.

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Tailoring magnetic anisotropy and interfacial Dzyaloshinskii-Moriya interaction in a ferromagnetic layer by contact with antiferromagnetic NiO

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The interfacial Dzyaloshinskii-Moriya interaction (iDMI) and perpendicular magnetic anisotropy (PMA) are two critical phenomena in the field of spintronics and magnetism. They play crucial roles in determining the behavior and control of magnetic materials' properties, leading to numerous technological advancements, particularly in data storage, memory devices, and sensors.

We have shown that a NiO layer can be a source of iDMI and strong PMA when it surrounds a ferromagnetic (FM) layer. We demonstrated that NiO layer induced strong surface anisotropy in NiO/Co/Au, which favors PMA of the Co layer over a wide range of its thickness [1]. We also found that this type of magnetic anisotropy can be achieved in a Co layer surrounded on both sides by NiO layers [1], thus showing the important role of antiferromagnetic oxide (AFO) layers in controlling magnetic anisotropy by the presence of the exchange-bias interaction at the FM/AFO interface. This is also corroborated by the results obtained for Au/Co/Ni layered system after plasma oxidation, where strong PMA is supported by the formation of the NiO layer on top of the ferromagnetic Co/Ni layer [2,3].

Additionally, we have shown that the presence of FM/NiO interface is responsible for the strong iDMI (D). In the case of the Au/Co/NiO right-handed chirality within the Néel domain walls is present (D=-1.1pJ/m) while for NiO/Co/Pt left-handed chirality was documented (D=2.0 pJ/m) [4]. Based on the obtained results and literature analysis, we found a correlation between the composition of nickel oxide layers and the values of D, where the highest value was measured for stoichiometric NiO layers. Moreover, the stoichiometric NiO layers stabilize right-handed chirality in Au/Co/Ni after plasma oxidation, similarly to what was found for the Au/Co/NiO layered system. This all shows that NiO layer plays a significant role in inducing PMA and the iDMI.

Acknowledgments: This work was supported by the National Science Centre, Poland under OPUS 17 funding (Grant No. 2019/33/B/ST5/02013).

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Curvilinear and 3D Magnetism

Invited

Controlling superconductivity with curvilinear magnetism

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In order to combine resistance-free superconducting currents with the benefits of spin-based manipulation and computation, the last decades have focused on using magnetic multilayers to convert conventional spin-singlet superconductivity into spin-polarized triplet correlations. This is severely restrictive in terms of material choice and control, and has hampered the technology's large-scale implementation. In the last few years, we have shown that the effective spin-orbit coupling of curvilinear magnets can simplify the manipulation of superconductivity, while also enabling a host of new control mechanisms and probable systems [1-4]. We use the quasiclassical framework to investigate spin transport phenomena in diffusive proximity-coupled superconducting structures, and show how curvilinear ferro- and antiferromagnets control the superconducting correlations. We separate and explain the different roles of geometric curvature and curvature-induced strain, and compare the roles of torsion and in-plane curvature.

In this presentation, I will give a pedagogical introduction to combining the typically competing phases of superconductivity and magnetism, and show how it is facilitated by curvilinear magnets. I will present examples of insights and new functionalities enabled by the curvilinear geometry, including using a piezoelectric substrate to control the torsion in a ferromagnetic wire to create an electrically controlled superconducting spin valve (Fig.1a) [2]. I will also compare Josephson current-switching in devices with equal or opposite chirality at different interfaces (Fig.1b,c) [1,3], and indicate how density-of-states measurements under torsion control can give information about the quality of buried antiferromagnetic interfaces [4].

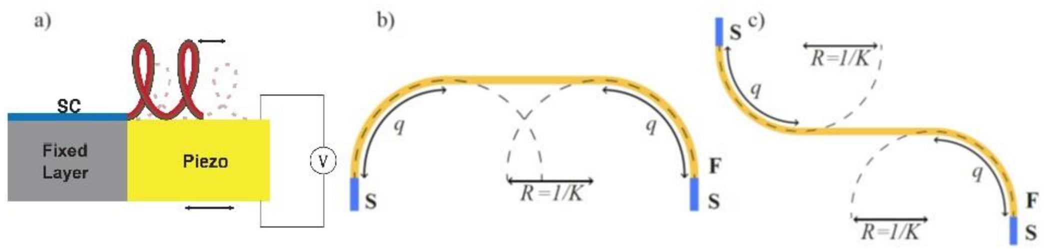

Figure 1: (a) Piezoelectric control of a superconducting spin valve using a ferromagnetic helix [1]. (b,c) Superconductor-ferromagnet-superconductor junctions with opposite (b) and equal (c) chirality at the interfaces [2].

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Invited

Magnetically guided small-scale robots for biomedical applications

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We are increasingly surrounded by robots, including robotic surgical systems, drones, autonomous rovers, and robotic household tools. A growing category of robots consists of magnetically guided small-scale devices developed specifically for biomedical applications. These miniature devices can be precisely navigated within biological environments using external energy sources, such as magnetic fields and gradients. One of the ultimate goals of biomedical robotics is to create tethered or untethered machines capable of delivering therapeutic agents to targeted regions or performing other medical tasks within the confined spaces of the human body [1]. While tethered continuum robots can be maneuvered over long distances, untethered magnetic devices offer the advantage of wireless navigation and the ability to perform therapeutic tasks in confined spaces. However, the initial deployment of untethered magnetic devices, such as microrobots, is a critical yet often overlooked challenge in their clinical applications. The delivery of these devices into the dynamic environment of the human body poses significant challenges due to long travel distances and dispersion caused by circulatory physiological flows. Moreover, despite the promising applications demonstrated for small-scale magnetic robots, further research is needed to address issues such as complex locomotion, shape transformation, multifunctionality, biocompatibility, and biodegradability, which are essential for the successful transition of these devices into real-world applications. To overcome these challenges, new deployment strategies and innovative fabrication techniques are urgently needed.

In this talk, we will present several approaches for effectively fabricating and delivering small-scale magnetic robots. These strategies involve using magnetically navigated tethered robotic tools to assist in delivering untethered magnetic devices to target sites [2]. This method successfully concentrates magnetic devices carrying therapeutic agents at the desired location, hence offering a promising solution for the controlled deployment of untethered magnetic devices within the complex circulatory systems of the human body. Moreover, we will introduce novel fabrication techniques for creating highly integrated small-scale soft devices that closely mimic the complex motion and morphing behaviors of living organisms. By leveraging microfluidic control to regulate reaction-diffusion (RD) processes, we can fabricate multifunctional and compartmentalized magnetic soft continuum robots (mSCRs) [3]. Under controlled RD conditions, these mSCRs can be tailored in terms of geometry, stiffness, and magnetic responsiveness. Additionally, chemically cleavable regions within the mSCRs enable disassembly into smaller robotic units or roll-up structures when exposed to a rotating magnetic field, after being deployed with the aid of tethered magnetic devices. These findings highlight the importance of new deployment methods and versatile fabrication techniques in the development of highly integrated small-scale magnetic devices, bringing these technologies closer to real-world biomedical applications.

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Invited

Progress and challenges in the measurement of three-dimensional magnetization textures using transmission electron microscopy

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The transmission electron microscope is a powerful tool for measuring not only local variations in microstructure and composition, but also functional properties in materials. In this talk, I will describe how electron optical phase images that have been recorded using techniques such as electron holography and ptychography can be interpreted to reconstruct magnetization textures in materials quantitatively with nm spatial resolution. Our approach is based on model-based iterative reconstruction, and specifically on the optimized implementation of a forward model and regularization techniques to find best-fitting solutions for reconstructed magnetization distributions, either in projection or in three dimensions. The algorithm benefits from the incorporation of a micromagnetic energy term in the loss function. I will present examples taken from studies of magnetic textures in confined sample geometries, magnetic superstructures and topological magnetic states that have mixed Bloch-type and Néel-type character. Figure 1 shows an example of an electron optical phase image of a magnetic "skyrmion braid" in a focused ion beam milled lamella of FeGe recorded using off-axis electron holography at 300 kV in aberration-corrected Lorentz mode [1]. I will highlight the key experimental challenges that need to be considered when recording and interpreting such images, including the influence of sample preparation, dynamical diffraction and electron-beam-induced specimen charging. I will also discuss the influence of noise and choice of magnetic constants on the reconstructed magnetization. I will conclude with a discussion of future improvements to the approach, as well as possibilities for developments in instrumentation and techniques in transmission electron microscopy that may allow such measurements to be made with greater reliability, precision and accuracy [2].

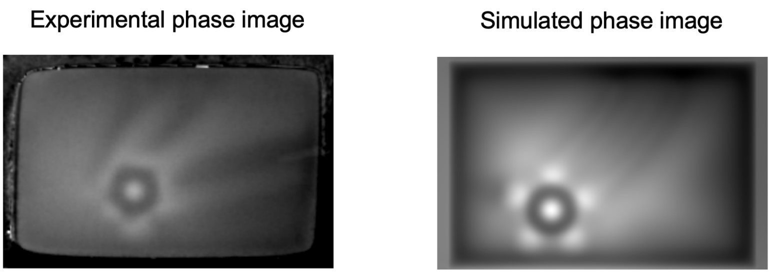

Figure 2. Experimental and simulated phase images of a 6-skyrmion braid in a lamella of FeGe of size 800 nm x 540 nm and thickness 180 nm recorded at 95 K in a 187 mT field.

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Invited

Controlling Bloch point singularities in magnetic systems

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Topology and magnetism are closely related as the topological properties of magnetic configurations have a strong impact on their characteristics [1,2]. They affect for instance the stability of magnetic textures and their behaviour under external stimuli. Thus, the study and understanding of the topological properties of magnetic textures is of paramount importance for technological applications.

We analyse Bloch point magnetic singularities: points where the magnetization vector field vanishes and which present an ideally integer three-dimensional topological charge of Q = ±1 [3]. Bloch points are naturally formed within stripe domain configurations in systems with perpendicular magnetic anisotropy (PMA), among many others, and play a key role in the in-plane reversal processes of weak PMA materials [4]. We characterize them by using Magnetic Soft X-ray Vector Tomography, allowing to volume resolve the three-dimensional magnetization vector with tens on nanometers in resolution, and study their interactions by the computation of the magnetic emergent field [5].

In this talk we will present the Bloch points formed within different heterostructures and microstructures with weak PMA [5,6], showing the importance of these singularities and their topology within the full magnetization configuration context, allowing to understand from a topological perspective the reason for their presence and their impact on magnetization transformations. Finally, we show how it is possible to engineer Bloch points by the accurate design of magnetic systems, modifying the inner magnetic configuration surrounding the singularity thanks to the fine tuning of competing interactions at the interface of ferrimagnetic/ferromagnetic heterostructures [7].

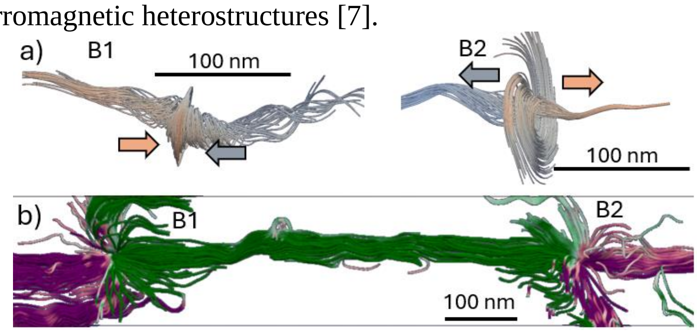

Figure: a) Different circulating Bloch point magnetizations with head-to-head (B1) and tail-to-tail (B2) core configurations. b) Magnetic emergent field streamlines for the same singularities (B1 and B2) showing their topological connection within the magnetization framework.

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Invited

Spin-Wave Edge and Cavity Modes in a Moiré Magnonic Crystals

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Moiré superlattices, which consist of twisted layers of van der Waals materials [1] exhibit extraordinary electronic behaviors such as superconductivity and correlated topological states. Moiré physics has recently been applied in photonics to reconstruct photonic band structures that enable novel functionalities such as magic-angle lasers. So far, moiré physics in magnonic systems has only been studied from a theoretical point of view [2].

In this work, we use micromagnetic simulations to report magnon flat-band formation in twisted bilayer magnonic crystals at the optimal "magic angle" and interlayer exchange coupling combination. At the flat-band frequency, magnons undergo a strong two-dimensional confinement with a lateral scale of about 185 nm. The magic-angle magnonic nanocavity occurs at the *AB* stacking region of a moiré unit cell, unlike its photonic counterpart which is at the *AA* region, due to the exchange-induced magnon spin torque. The magnon flat band originates from band structure reformation induced by interlayer magnon-magnon coupling.[3]

We also investigate the confinement of spin waves in a nano magnonic waveguide integrated on top of a magnetic moiré superlattice. Our numerical analysis reveals a magnonic flat-band at the centre of the Brillouin zone, created by a 3.5-degree twist in the moiré superlattice. The flat band, characterized by a high magnon density of states and a zero-group velocity, allows for the confinement of magnons within the *AB* stacking region. From the experimental point of view, we have fabricated nanostructured moiré magnonic crystals based on low-damping yttrium iron garnet thin films. We report the experimental observation of spin-wave moiré edge and cavity modes using Brillouin light scattering spectro-microscopy in a nanostructured magnetic moiré lattice consisting of two triangular antidot lattices based on a yttrium iron garnet thin film. Spin-wave moiré edge modes are detected at an optimal twist angle and with a selective excitation frequency. At a given twist angle, the magnetic field acts as an additional degree of freedom for tuning the chiral behavior of the magnon edge modes. Micromagnetic simulations indicate that the edge modes emerge within the original magnonic band gap and at the intersection between a mini-flat band and a propagation magnon branch. [5]

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Invited

Nonchiral topologically protected antiferro-(alter)-magnetic textures stabilized by magnetoelastic interactions

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Antiferromagnets are considered as promising materials for spintronic applications due to their fast internal magnetic dynamics and robustness with respect to the external magnetic field. Those antiferromagnets that are suitable for practical applications due to high ordering temperature and high, terahertz, frequencies are also known for pronounced magnetoelastic coupling, which can play an important role in the formation, manipulation and control of antiferromagnetic textures. Recently, we [1-4] developed an approach to describe the magnetoelastic effects in the finite-size antiferromagnets based on the concept of magnetoelastic charges and applied it to the formation of the domain structure in thin films. We found that because of the mathematical similarity between the equations of magnetostatics and magnetoelasticity, magnetoelastic charges produce effects similar to dipole-dipole fields in ferromagnets. In particular, such long-range interactions can favour the formation and stabilisation of topologically non-trivial magnetic textures. In this talk we discuss the formation of vortices and concentric nonchiral structures in an easy plane antiferromagnet and a weak ferromagnet (altermagnet). We also consider the lattice distortions caused by the strain mismatch in such magnetic textures. We discuss possible effects arising from the distortion gradients, such as curvature-induced Dzyaloshinskii-Morya interactions and additional magnetisation induced by the altermagnetic stiffness [5]. Finally, we discuss ways to detect these effects and use them to manipulate the magnetic textures.

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Magnetic textures in curvilinear spin chains of constant torsion

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Geometrical curvature and shape of ferro- (FM) and antiferromagnetic (AFM) systems provide a possibility to tailor their magnetic responses via geometry-driven anisotropy and Dzyaloshinskii-Moriya interaction (DMI) [1,2]. In particular, curvilinear spin chains represent convenient objects to study as they capture the hallmarks of more complex systems. Their properties are determined by two geometric quantities: curvature κ and torsion τ. There are intensive studies of systems with constant κ and τ, such as rings and helices, for which the ground states, linear excitations and domain wall dynamics are analyzed [1]. Here, we present a study of closed FM, AFM and frustrated chains (FRU, odd number of spins with AFM exchange coupling) with a constant torsion: low-symmetry ferrotoroidal systems with magnetic ordering and absence of the inversion center. We show that such systems can support frustrated magnetic textures, where the presence or absence of frusrtation can be governed by geometric symmetry.

An exemplary curve of a constant torsion (spherical epicycle) can be obtained by the Bäcklund transformation of a spherical curve with N knots [3]. The resulting spin chain possesses the same N-fold symmetry axis of the N-knotted spherical curve and, as such, its curvature is periodically distributed along the chain. The chain's curvature spans a considerable sets of values, ranging from values much smaller than the critical curvature of the helimagetic phase transition to values, which are much above that one. The magnetic state of the chain with a small enough τ is primarily determined by whether the magnetic anisotropy along the tangential direction $\boldsymbol{e}_T$ is of easy-axis or hard-axis types. In the easy-axis chains (FM and AFM), the ground state remains almost tangential, with a small deflection from $\boldsymbol{e}_T$ in both, rectifying and osculating planes near the knots. If the magnetostatic interaction is sizeable in comparison with the single-ion anisotropy, the segments of the chain interact with dipolar fields enhancing the difference with $\boldsymbol{e}_T$.

For the hard-axis systems with constant geometric parameters and small τ the ground state is expected to be along the binormal direction $\boldsymbol{e}_B$ [1]. In contrast, the AFM and FRU epicycles try to develop the helimagnetic state as the ground one. The reason is that the torsion-induced DMI dominates over the long distance of the sample and the regions with high curvature near knots provide strong pinning potentials for the spatially inhomogeneous textures. We found an interplay between the (anti)periodic boundary conditions and number of knots N in (FRU) AFM chains: the purely helimagnetic ground state is developed in both, AFM chains with even amount of knots N or FRU chains with odd N. Otherwise, AFM chains with odd N and FRU chains with even N necessarily develop a segment in the binormal state of their order parameter to fit the boundary conditions. The toroidal domains are developed where the helimagnetic ordering is broken.

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Hopfion rings

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Magnetic skyrmions are well-studied examples of two-dimensional topological solitons. They resemble vortex-like strings in a magnetization field. Typically, skyrmions extend through the entire sample from one surface to the other, meaning they are effectively localized in two dimensions only. Hopfions, on the other hand, are three-dimensional topological structures, appearing as closed loops of skyrmion strings. In their simplest form, hopfions look like a ring. Although hopfions were theoretically predicted in frustrated magnets [1], observing them in these systems remains challenging, as materials satisfying the model criteria are not yet known.

We found an alternative approach for hopfion stabilization in magnetic crystals. Specifically, our recent experiments showed that in crystals of cubic chiral magnets, hopfions become stable when linked with skyrmion strings [2]. These structures resemble a group of skyrmion strings enclosed by a hopfion ring. In this presentation, I will show direct observations of such hopfions in B20-type FeGe plates using Lorentz transmission electron microscopy and electron holography. I will cover various aspects of hopfion rings, including a reliable method for their nucleation, a comparison between theory and experiment, and an exploration of their extraordinary mobility. I will also present the homotopy group of these topological textures that distinguishes them from ordinary isolated hopfions and isolated skyrmion strings.

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Current-induced nucleation, propagation and pinning of Bloch-point domain walls in cylindrical nanowires

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Cylindrical magnetic nanowires are considered as candidates for building blocks of future 3D technologies. They offer multifunctional responses to magnetic fields, electric currents, and thermal gradients, enabling the conversion between different functionalities. Cylindrical geometry ensures the existence of complex chiral 3D domain walls such as the Bloch point, vortex-antivortex (transverse vortex) or double vortex-antivortex domain walls. Among them, the Bloch point domain wall (BPDW) is topologically non-trivial and has been predicted to potentially reach very high velocity [1]. Thus, understanding how to manipulate BP DWs is important for future applications. At the same time, the use of electrical current as an external stimulus provides energy-efficient domain wall manipulation.

Our joint theoretical and experimental work sheds light into different scenarios of complex dynamics of BP DW under external current, due o simultaneous action of spin-transfer torque, Oersted field, Joule heating and temperature gradient. Indeed, 1) Theory shows that spin-transfer torque should move BP DW against the current direction while experimentally this is the case of low current densities only [2,3] 2) Oersted field may produce BPDW chirality switching [4] or BPDW transformation into another domain wall type and its stopping [2]. 3) The Oersted field may be also responsible for BP DW pinning by creating an opposite chirality, for example, at notches 4) At high temperatures Joule heating is responsible for DW nucleation [3] 5) The action of temperature gradient competes with the STT effect moving DW to nanowire center 6) High temperature together with temperature gradient produces BP DW bouncing from the nanowire ends.

Using the XMCD/PEEEM measurements in ALBA synchrotron we report experimental observation of several of the above phenomenon in Ni cylindrical nanowire [3]. Particularly, we measured BP DW nucleation, propagation with velocities up to 1 km/s, pinning by Oersted field and bouncing from the ends due to thermal gradients.

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[2] J.A.Fernández-Roldán and O.Chubykalo-Fesenko, APL Materials **10** (2022) 111101.

[3] C. Bran et al Nanoscale, **15**, (2023) 8387.

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Modeling of the micro-focused Brillouin light scattering signal

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Advances in Brillouin light scattering (BLS) spectroscopy and microscopy allowed us to study and develop the first generation of magnon devices and is one of the main reasons why magnonics became one of the most promising candidates for “beyond CMOS” technology. The scattering in conventional BLS is guided by the conversation of momentum law: $k_\mathrm{i} = k_\mathrm{r} + k_\mathrm{m}$, where k_i (k_r) is the wavevector of the incident (reflected) light and k_m is wavevector of the magnon [1]. Thus, in the back-scattering geometry, the maximal wavenumber of spin waves, which can be detected, equals twice the incident light wavenumber. However, the micro-focused BLS situation is even more complicated and requires precise modeling.

We tackle this challenge by calculating induced polarization using a semi-analytical model for driving the Gaussian field developed by Richard and Wolf [2] and an analytical model for spin waves developed by Kalinikos and Slavin [3]. The transition from induced polarization to the far field and, thus, the resulting intensity is calculated using dyadic Green function formalism developed by Sommerfeld and Weyl [4]. A similar model enriched by Maxwell equation simulation can also be used to model more complicated scenarios, such as, e.g., Mie resonator for enhancing the maximal detectable k-vectors [5,6].

The presented theoretical treatment can be used to model previously inaccessible situations [7]. For example, we can model, e.g., the dependency of the BLS signal on the thickness of the magnetic layer, see Fig. 1. This model can be used to fit more parameters from the acquired enabling precise characterization of the BLS setup and measured spin-wave system. Such capabilities can then be used to characterize 3D magnetic structures and textures.

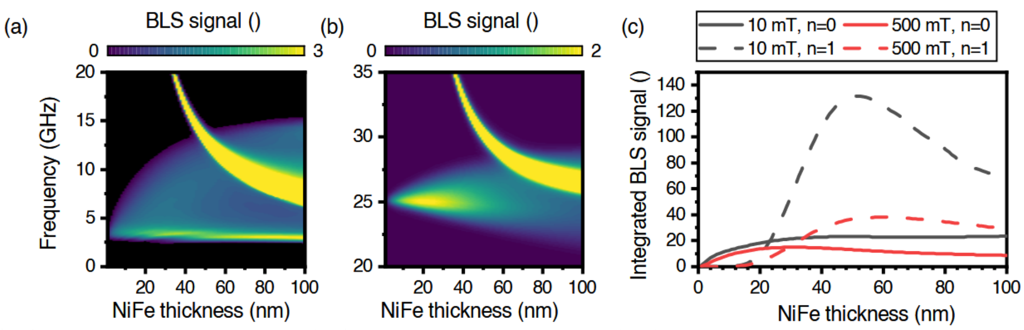

Figure 1: BLS spectra of NiFe with different thicknesses. a, b Calculated BLS spectra of NiFe using Eq. 1.30 in 10 mT (a), and 500 mT (b) of thicknesses ranging from from 1 nm to 100 nm. We used parameters for NiFe and calculated the signal for fundamental and first thickness modes c, Integrated signal of all four shown peaks.

[1] Sebastian, T., et al., *Front. Phys.* **3**:35 (2015).

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Magnetic solitons in hierarchical 3D magnetic nanoflower shaped architectures

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Progress in fabrication of curvilinear magnetic nanoarchitectures is enabled by a variety of methods oriented on *single* free-standing objects like focused electron/ion beam induced deposition or glancing-angle deposition. Effects of interest are mostly related to anisotropic and chiral responses originating in exchange interactions [1]. Recently, is has been shown that the magnetostatic interaction offers another possibility of non-local symmetry breaking in 3D samples [2]. Asymmetries in geometric shapes lead to magnetic symmetry breaking and even lifting degeneracy between magnetic vortices of opposite chiralities [3].

Here, we report recent advances of scalable fabrication of large arrays of magnetic nanostructures and the observation of magnetostatic effects in curvilinear shells. Periodic structures over several cm scales consisting of 50 nm thin Permalloy objects were fabricated with nanoflower shapes separated by deep valleys with small curvatures at characteristic spatial scales of about 400 nm (Fig. 1a). The shell keeps periodicity over cm-large scales. We were able to transfer the shell from Aluminium template to a TEM grid, to allow for characterization of magnetic textures by MOKE, MTXM and holography. On a microscale, due to the interaction between the uniformly magnetized valleys, one can observe the interaction domains with additional 4-fold symmetry, formed due to the corresponding geometrical symmetry of the valleys. This happens because each valley is magnetized almost uniformly following its surface. The nanoflowers support a variety of magnetic textures. The ground state of the nanoflower is the magnetic vortex with four edge states. The vortex line is shifted from the origin and is bent with zero torsion and curvature of about 0.027 nm^{-1} (Fig. 1b). This asymmetric state is formed due to the interaction of surface and volume magnetostatic charges. High-energy states include the so-called flower state, several vortices bounded within single nanoflower and purely symmetric configuration with a vortex in the center of the nanoflower. In conclusion, these ordered arrays of magnetic architectures of complex shape enable further research in nonlinear magnetization dynamics, 3D magnonics and curvilinear spintronics.

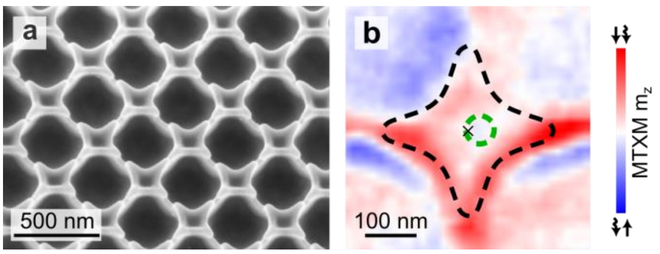

Figure 1. (a) tilted view scanning electron microscopy (SEM) image of 50-nm-thick Permalloy ($Fe_{80}Ni_{20}$) nanoflowers; (b) magnetic vortex shifted from the center (lowest energy state)

[1] D. Makarov and D. D. Sheka, Ed., Springer International Publishing (2022)

[2] D. D. Sheka et al., *Communications Physics*, 3(1), 128 (2020)

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Three-dimensional magnetic imaging with soft X-ray ptychographic laminography

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The complete understanding of magnetic systems often requires insight into the three-dimensional structure of the magnetisation that can only be provided by direct visualisation. Imaging methods involving X-rays from synchrotrons benefit from both chemical and magnetic sensitivities by elemental and dichroic contrasts, respectively. The method of hard X-ray ptychography has been successfully employed to image the three-dimensional magnetic structure of intermetallic compounds at the Gd L_3-edge in both the tomography [1] and laminography [2] geometries. The latter involves the rotation of the tilted sample so that the axis of rotation is no longer perpendicular to the incident X-ray beam. This is particularly valuable in the case of extended planar samples that may completely attenuate the beam due to excessive thickness under certain angles in what is known as the "missing wedge" artefact.

Although the attenuation of X-rays in the hard X-ray energy range makes the method suitable for micrometre thick samples, the magnetic contrast from X-ray magnetic circular dichroism (XMCD) is minute for elements other than the rare earths. This limitation can be overcome by imaging with soft X-rays that can probe the L-edges of magnetic transition metals and the M-edges of the rare earths that exhibit prominent XMCD. However, the absorption of X-rays also becomes several orders of magnitude higher with soft X-rays. This lends further importance to laminography, with the first three-dimensional magnetic soft X-ray imaging having been carried out with scanning transmission X-ray microscopy (STXM) [3]. Yet two drawbacks remain: besides the high absorption that limits the maximum thickness of samples, the spatial resolution of a STXM measurement is dictated by the spot size achievable with the Fresnel zone plate used to focus the X-ray beam. This is around 25 nm for routine measurements. As a coherent diffractive imaging method, ptychography does not depend on the focusing optics and can achieve higher spatial resolutions. Furthermore, it is possible to image the magnetisation in thicker samples by ptychographic phase contrast imaging with the XMCD at energies of the pre-edge [4].

In this presentation, the first results of three-dimensional ptychographic imaging in the laminographic geometry will be presented. These were obtained with the SOPHIE (Soft X-ray Ptychography Highly Integrated Endstation) endstation, which is currently hosted by the SoftiMAX beamline at MAX IV (Lund, Sweden).

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[2] C. Donnelly *et al.*, Nat. Nanotechnol. **15**, 356–360 (2020).

[3] K. Witte *et al.*, Nano Lett. **20**, 2, 1305–1314 (2020)

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Energy Landscape and Pinning Fields of Bloch-Point Domain Walls in Curved Nanowires

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Soft-magnetic nanowires can promote the formation of stable Bloch-point domain walls depending on their material parameters and size. Motivated by experimentally measured pinning fields in curved nanowires [1], we investigate the energy landscape and pinning by means of micromagnetic simulations. In the context of numerical micromagnetics, the singular nature of the Bloch point requires special care since it violates the prerequisite of a smooth magnetization distribution that is assumed in the micromagnetic theory. Depending on the discretization strategy this has various implications that have to be handled carefully. In the case of finite-difference micromagnetics, simulations are based on a regular mesh with a mesh size usually chosen in the dimension of the matierial's exchange length. This discretization underestimates the magnetization gradient of the Bloch point and thus its energy. As a consequence, this modeling approach also underestimates pinning effects at the atomic lattice [2]. In the case of finite-element micromagnetics, simulations are based on an irregular mesh. This allows for the accurate modeling of curved surfaces as required by the investigated nanowires. However, due to varying cell sizes of the mesh, the energy of the Bloch point strongly fluctuates depending on its position leading to spurious pinning sites. In this work, we combine finite-difference simulations with finite-element simulations to obtain a complete picture of domain wall pinning effects in curved nanowires due to curvature, see Fig. 1(a), and lattice pinning, see Fig. 1(b). Our simulations match the experimental findings obtained on Cobalt nanowires with varying curvature and deliver a deep understanding for the origin of the different contributions that act as pinning sources.

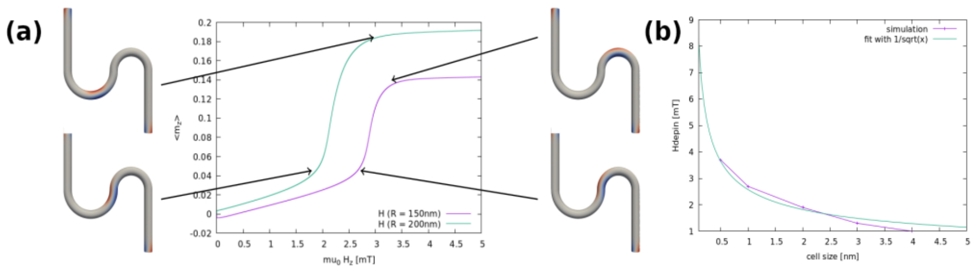

Figure 1: Depinning of Bloch-point domain walls in curved nanowires. (a) Pinning due to curvature (b) Lattice pinning of Bloch point.

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Topological magnetic textures with extreme combinatorial diversity

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Recent experimental and theoretical studies have revealed many new topological micromagnetic textures such as skyrmion braids [1] and hopfion rings [2]. Classification of such states using homotopy theory shows that the corresponding algebra of their topological invariants is more complex than the group of integers, $\mathbb{Z}$, and is rather described by the free abelian group $\mathbb{Z}\times\mathbb{Z}$ [2]. This result indicates a rich combinatorial diversity. We will consider these important combinatorial aspects and discuss in detail why systems classified by non-abelian homotopy groups may be of further interest [3].

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[3] F.N. Rybakov & O. Eriksson, arXiv:2205.15264 (2022).

Estimation of exchange parameters in system deformed by a strain-gradient

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There is a recent and growing interest in magnetic materials with non-trivial geometries. Indeed, whether obtained through direct deformation or clever engeniering, these materials are found to show non-trivial magnetic ground-states [1,2,3] and transport properties [4]; and require theoretical understanding.

Micromagentic simulations of such materials have been done [5], but they are limited in their ability to study these systems in a material-specific approach. We usually describe the magnetic properties of a material with the following microscopic spin Hamiltonian:

$$H = -\sum_{ij} S_i \cdot J_{ij} \cdot S_j - \sum_i S_i \cdot A_i \cdot S_i \quad (1)$$

where $S_{i,j}, J_{ij}, A_i$ are respectively the spin operator, the exchange tensor, and the anisotropy tensor. However, there is no reliable way to parametrize the microscopic model (1) for such systems. Usually, one uses density functional theory (DFT) approaches to parametrize (1), but to account for the non-trivial geometry (in particular the deformation accessible experimentally), the cell used in the simulations will quickly become so big that the numerical calculations will become prohibitively expensive.

In this talk, I will present our method to parametrize eq. (1) for any deformation expressable as a deformation field using density functional theory (DFT), in a material-specific way and without using very big supercells.

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[2] A. Fernández-Pacheco et al, Nat Commun 8, 15756 (2017)

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Oscillatory dynamics of strongly coupled magnetic domain walls in three-dimensional chiral nanostructures

I. Pamela Morales Fernández[1,2], Iason K. Douevas[3], Claas Abert[3], Sandra Ruiz-Gómez[4], Elina Zhakina[1], Sebastian Wintz[5], Markus König[1], Aurelio Hierro Rodríguez[6], Simone Finizio[7], Luke Turnbull[1,9], Naëmi Leo[8], Dieter Suess[3], Amalio Fernández-Pacheco[2], Claire Donnelly[1,9]

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The expansion of nanomagnetism into three-dimensional systems offers exciting opportunities beyond the physics of planar systems, which allows the exploration of new topological textures, curvilinear effects, and in particular, exotic magnetization dynamics. Among these, the ultra-fast propagation of three-dimensional magnetic domain walls—surpassing the Walker limit and entering the magnonic regime—and the emergence of non-reciprocal effects are of particular interest for the scientific community [1]. While these dynamic effects have been experimentally studied in straight nanowires [2,3], the influence of curvature and topology on the behaviour of non-trivial spin textures in three-dimensional nanosystems remains a rich area for further investigation.

Here, we experimentally investigate the magnetization dynamics of a specific magnetic spin texture featuring pairs of strongly coupled domain walls within three-dimensional double-helix nanostructures. These bound domain wall pairs arise from the interplay of intrinsic properties, such as shape anisotropy and chirality, and magnetostatic inter-helix interactions, leading to unique topological textures in the magnetic field induction [4].

We utilize direct 3D nanofabrication techniques [5] to create cobalt nano double helices integrated with microwave antennas and subject them to GHz magnetic field excitations. Time-resolved scanning transmission X-ray microscopy is employed to map the magnetization dynamics in real space [6]. Our findings reveal enhanced dynamics at the locations of the coupled domain walls, dependent on the nanostructure's geometry and excitation frequency. These results provide insight into the tunning capabilities for controlling the dynamic behaviour of complex three-dimensional magnetic field nanotextures, opening the door to understanding and harnessing nanomagnetism for future technological applications with increased dimensionality.

[1] A. Fernández Pacheco, et al. Nat. Commun. 8, 15756 (2017).

[2] M. Schöbitz, et al. Phys. Rev. Lett. 123, 217201 (2019)

[3] K. Ogawa, et al. Phys. Rev. Research 5, 033151 (2023).

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Robustness of magnetic skin upon touch assessed with TMR-based magnetic tactile sensors

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Touch is a crucial sense for advanced living organisms, particularly for humans, providing valuable information about the shape, size, temperature and texture of our surroundings. Robotics and automation have seen impressive development, taking advantage of nanotechnologies for smart systems integration [1]. In this work, we focus on magnetic–based soft sensors [2][3] and use a biomimetic, skin-inspired magnetic tactile sensor (Figure 1), comprising a 4×4 matrix of tunnel junction TMR sensors [4] integrated below a skin made of Ecoflex 00-30 impregnated with 5 µm NdFeB hard magnetic particles (40:60 mass ratio).

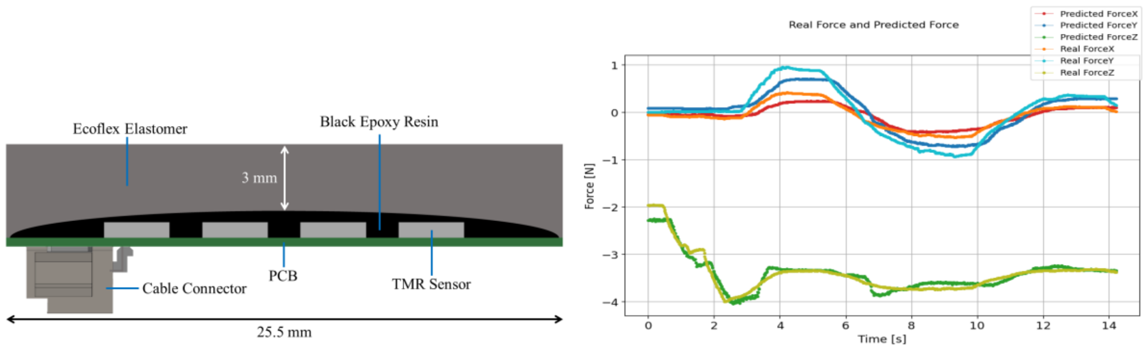

Figure 1 (a) Schematics of the tactile sensor module, including 16 magnetoresistive sensor chips encapsulated with epoxy, and buried under a 3 mm thick Ecoflex skin; (b) Force predictions from the neural network model and real force in the x, y and z.

The device robustness for harsh tasks (i.e., strong forces and shear stresses) was evaluated using a 3D-stage for control of an indenting tip mounted at a ATI nano 17 force sensor. The tactile sensor module was probed using this setup, together with the force sensor. This data was then used to train artificial neural network models that could predict the aforementioned parameters of the applied force. Additionally, structural integrity tests were made to quantify the mechanical stability and plasticity limit of the epoxy-encased wire bonding connections.

The force sensing neural network was trained using 31260 data points, where the tangential component was [0,2.75] N and the normal component was [0,17] N. The applied force was consistently quantified in every direction with a minimum mean absolute error of 0.07 N and a maximum of 0.17 N. One particular instance of the result of this prediction can be seen in Figure 2. The structural tests revealed that the device could withstand forces above 98 N for an epoxy distribution of 0.12 mL per sensor chip. This is very good news for a practical integration in unsupervised environments.

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Magnetic Levitation and Bearings and Electrical Machine Modeling

IEEE Italy Section
Politecnico di Bari
iOM Istituto Officina dei Materiali
PetaSpin
IEEE Magnetics Italy Chapter
IEEE NANO Nanotechnology Council Italy Chapter
MetroSpin
AIMagn Associazione Italiana di Magnetismo
IEEE young professionals Italy Section
IAS IEEE Industry Applications Society / PELS IEEE Power Electronics Society — Italy Joint Chapter C&S
ZABRE Nanometer magnetic fields made visible.

Invited

Magnetic Bearings for Space Cryogenic Applications

Efren Díez-Jimenez [a], Ignacio Valiente-Blanco [a], Miguel Fernandez-Munoz[a], Diego Lopez-Pascual [b], Hugo Rodríguez-Bodoque [a], Óscar Manzano-Narro [a], Jesús del Olmo-Anguix [a]

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[b] Electrical Engineering Area, Universidad de Alcalá, Spain.

The space and aerospace industries are increasingly demanding mechanisms able to work in cryogenic environments (T<100 K). As signal-to-noise ratios in sensors increase as temperature decreases, cryogenic environments are very desirable for accurate and precise measurements such as those required by far infrared interferometer spectroscopy. At very low temperatures, conventional mechanisms present severe tribological problems in bearings and teeth like cold spots, fatigue, and wear. Only solid lubricants such as PFTE or Molybdenum disulfide have been tried as a solution at low temperatures. However, for long life-time operation, solid lubricants turn out not to be a very reliable solution and the decrease of the efficiency in the mechanism is very significant. Magnetic bearings have demonstrated to be a good solution for reliability in space mechanism as they present lack of contact, no-wear, silent operation, reduced vibration, no need of lubrication, reduced maintenance, and improved reliability. Furthermore, they provide intrinsic overload protection and have no connection between the parts. Different types of magnetic bearings can be chosen depending on the complete list of requirements, specially depending on the satellite thermal environments. Active Magnetic Bearings (AMB) [1] applied in reaction wheels, Passive Magnetic Bearings (PMB) [2] applied in structural suspension systems and/or Superconducting Magnetic Bearings (SMB) [3][4] applied in thermal disconnects and linear mechanism for sensors have shown excellent performance under these harsh thermal conditions. In this work, we present recent examples of space application cases, developed within our research team, where AMB, PMB and SMB provides solutions to space applications in cryogenic environments.

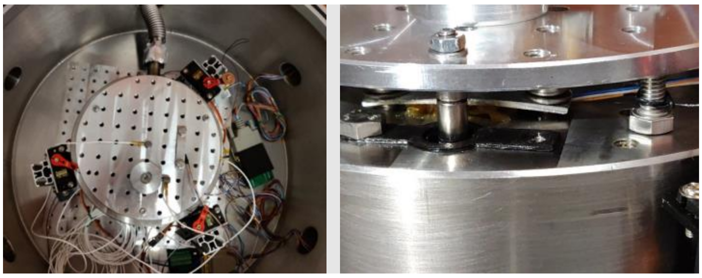

Figure 1: Example of Superconducting Magnetic Bearings supporting a levitating sensor baseplate operating at 77 K.

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Invited

Thermal management study of switched reluctance drive motor and power converter for electric heavy-duty trucks

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[c] Antonino Musolino is with the Department of Energy, System, Territory and Construction Engineering (DESTEC), University of Pisa, 56122 Pisa, Italy

Switched reluctance motors (SRMs) have shown significant advantages in electric heavy truck applications due to their simple structure, high temperature resistance, and high reliability. However, SRM systems face issues such as high power density, thermal management challenges, and system efficiency in electric heavy trucks. The power converter is responsible for converting the DC power supplied by the battery to the AC power required by the motor in an SRM system, thereby optimising the motor performance. Effective thermal management of the power converter can significantly improve its efficiency and overall system stability, mitigate failures due to overheating, and thus improve the overall operational performance of electric heavy trucks.

The switched reluctance motor asymmetric half-bridge power converter is taken as the research object to simulate the temperature field of the power converter and analyse the factors affecting heat dissipation, so as to carry out a reliability study and improve the stability of the system.

Firstly, the asymmetric half-bridge power converter is analysed to determine the main internal heat source, and the heat generation and distribution characteristics are analysed for the components such as power semiconductor devices and inductor coils. Excessive loss will cause the temperature to rise, which in turn affects the reliability of the power converter, therefore, solving the switching loss calculation and the reverse recovery loss calculation of the power diode is the basis of the temperature field modelling.

After that, according to the relevant theory of heat transfer, the calculated electrical loss of the power device is approximated as the heating power, and the temperature field simulation model is established. Thermal simulation software (ANSYS) is used to establish the thermal model, simulate the thermal behaviour under different operating conditions, evaluate the heat flow density of each part inside the power converter, and identify the critical paths of heat transfer and potential hot spot areas. The thermal resistance from the heat source to the heat sink is calculated and analysed, including the interface thermal resistance and material thermal resistance, in order to optimise the heat transfer path.

Finally, the simulation model is used to analyse the heat distribution, temperature change and heat dissipation effect for three typical working conditions of the power converter in order to improve the thermal management accuracy and efficiency of the power converter.

Study on 3 pole radial Active Magnetic Bearing virtual prototype

Adam Krzysztof Piłat

AGH University of Kraków

The model of the 3 pole radial Active Magnetic Bearing (AMB) was realised in 2D space using COMSOL Multiphysics (Fig. 2) to provide stationary and transient simulations. The numerical model is reflecting the laboratory prototype (Fig. 1). Properties are summarised in Table 1.

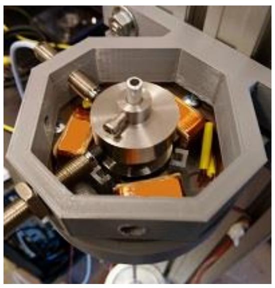

Fig. 1. Laboratory prototype

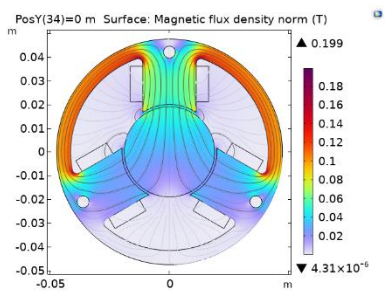

Fig. 2. Virtual Prototype

External diameter	95	mm
Internal radius	40	mm
Rotor external diameter	38	mm
Rotor internal diameter	34	mm
Thickness	10	mm
No of Turns	60	-
Wire diameter	0.6	mm

Table 1. AMB properties

The point of interest is to determine the nonlinear force characteristic f_1 and f_2 with respect to the rotor position and current driven coils.

$$F_X = f_1(x_0, y_0, i_1, i_2, i_3) \tag{1}$$

$$F_Y = f_2(x_0, y_0, i_1, i_2, i_3) \tag{2}$$

Therefore, the model was parameterized and then solved for different rotor positions using the cylindrical domain and coil currents. The data set was analysed to obtain the required characteristics. Depending on the rotor position and coil currents, the force nonlinearities are clearly visible throughout the domain with respect to the configuration of the supplied coils.

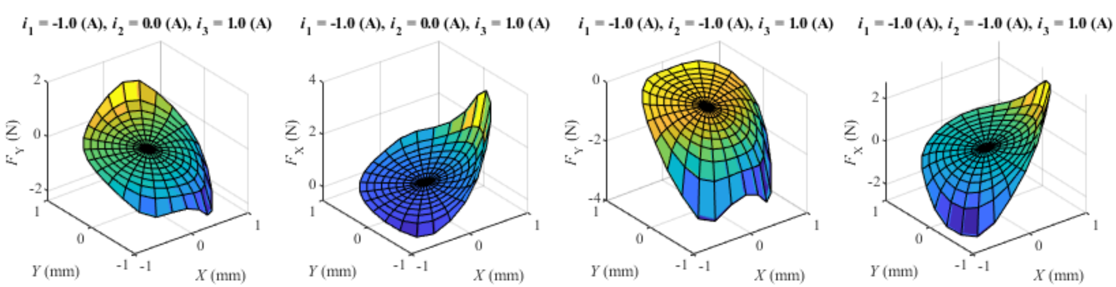

Fig. 3. Electromagnetic force components diagrams for a selected currents configurations.

Finally, the FEA model was extended to include ODE equations representing rotor motion. The coils were excited to obtain rotor motion and prepare the model for embedding the proposed controller.

S. L. Chen and C. T. Hsu, Optimal design of a three-pole active magnetic bearing, IEEE Trans. Magn., vol. 38, no. 5, pp. 3458-3466, Sep. 2002.

Meeker D.C., Maslen E.H., Analysis and Control of a Three Pole Radial Magnetic Bearing, Tenth International Symposium on Magnetic BearingsAt: Martiny, Switzerland, August 2006

Design of an axial rotary transformer for wound rotor synchronous machines excitation winding feeding

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In recent years, the use of permanent magnet (PM) machines has spread in industrial applications at the expense of wound rotor synchronous machines, since PM motors have a higher efficiency, guaranteed by the absence of rotor copper losses. Nowadays, the high cost and low availability of the rare earths used to realize the PMs make the interest in wound rotor synchronous machines grow again. The main issue connected to their use is the employment of a brushes-slip ring system to feed the rotating excitation winding. Since the slip rings rub the brushes, the system has to be frequently replaced. In this framework, a wireless power transmission between the fixed source and the spinning winding is proposed to remove the brushes-slip ring system. The use of a rotary transformer was proposed many years ago [1], but only recently, it has become possible to effectively use it thanks to the improvements in the switching frequency of power inverters that allow the increase in the working frequency and the reduction of the transformer size. In this case, the whole excitation system is composed of a DC-power supply, an inverter, the transformer and a rectifier (see Figure 1).

The considered geometry is composed of two cup-shaped ferromagnetic cores axially aligned, with an airgap between them: one core is fixed while the other spins with the synchronous machine's rotor. In each core, a winding is realised (see Figure 1), and the inverter feeds the primary one, arranged in the fixed core. The magnetic field produced by the current in the primary winding induces a voltage in the spinning secondary coil, realised in the rotary core. Such a voltage is rectified and applied to the synchronous machine's excitation winding. With respect to a power transformer, the rotary one has a higher leakage inductance and a smaller magnetising inductance due to the airgap.

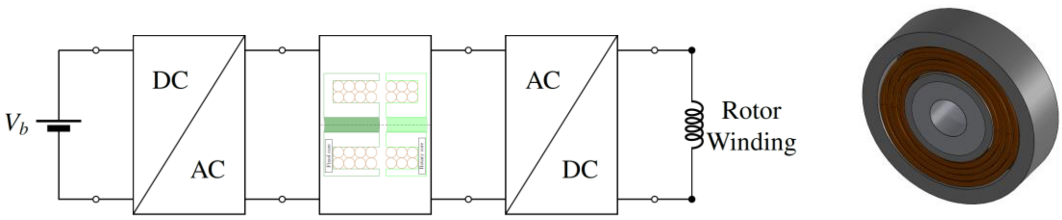

Figure 1. a) Excitation system with the rotary transformer. b) Single core of the axial transformer.

[1] E. E. Landsman, "Rotary transformer design," *1970 IEEE Power Electronics Specialists Conference*, Greenbelt, MD, USA, 1970, pp. 139-152, doi: 10.1109/PECS.1970.7066249.

[2] R. Manko, S. Čorović and D. Miljavec, "Analysis and Design of Rotary Transformer for Wireless Power Transmission," *2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*, Kremenchuk, Ukraine, 2020, pp. 1-6, doi: 10.1109/PAEP49887.2020.9240870.

Equivalent Network modelling of an Axial Flux Air-Core Compulsator

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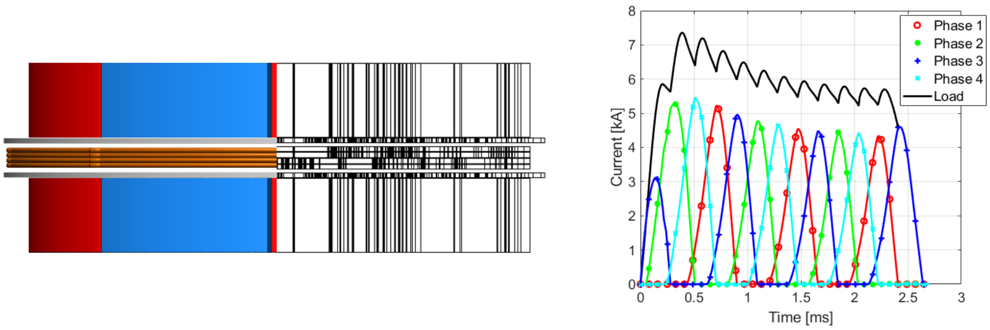
The analysis of electromagnetic launchers requires the solution of strongly coupled electrical and mechanical equations since the high speeds involved cause a fast electromechanical transient. Electromagnetic launchers need extremely high currents characterized by impulsive behavior to be effectively fed. In this framework, air-core compensated pulsed alternators could be a promising choice [1].

Further improvements could be achieved considering an axial flux air-core compensated pulsed alternator. Although some examples are present in the literature [2-3], their potential has not yet been extensively studied. In general, compared to radial flux devices, axial flux ones show high torque/power density and smaller axial length, reaching the requested performances with a compact and light device. However, their design inherently requires full-3D electromagnetic simulations, and consequently, their analysis is associated with intensive computational burden.

Most of the studies about air-core compensated pulsed alternators are based on the standard mathematical approach used in electrical rotating devices. However, these formulations cannot take into account all the physical aspects involved and need extensive simplifications. Moreover, given the inherent time-varying nature of the launchers and compulsators, identifying the parameters for the lumped equivalent circuit of these devices can be challenging.

In this contribution, the feasibility of an axial flux air-core pulsed alternator will be investigated. In particular, the numerical analysis of the device will be performed using a research numerical code based on an integral formulation.



(a) (b)

Figure 1. Analysed model (a) and currents waveforms in the compulsator and on the load (b).

[1] S. Wu, W. Zhao, S. Wang and S. Cui, "Overview of Pulsed Alternators," in IEEE Transactions on Plasma Science, vol. 45, no. 7, pp. 1078-1085, July 2017.

[2] C. Ye, X. Liang, J. Yang, Y. Xiang and Y. Li, "Feasibility Analysis of a Multidisk Axial Flux Compensated Pulsed Alternator," in IEEE Transactions on Plasma Science, vol. 47, no. 5, pp. 2412-2418, May 2019.

[3] X. Liang et al., "Research of a Novel Multidisk Axial Flux Compensated Pulsed Alternator," in IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, pp. 1-6, April 2018, Art no. 0601306.

Magnetic Wireless Power Transfer: Innovations in Materials, Control Algorithms and Modelling

Invited

Power Regulation in Inductive Wireless Power Transfer Systems Using a Controlled Variable Inductor

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Magnetic control through variable inductors offers an effective method for precise power regulation in Inductive Wireless Power Transfer (IWPT) systems [1-3]. This control strategy is implemented using a current-controlled variable inductor within the LCC-S resonant compensation network topology [4]. By adjusting the DC current in an auxiliary winding, the inductance of the variable inductor can be modulated, allowing fine-tuned control over the output power of the IWPT system. The primary advantage of magnetic control lies in its ability to regulate power precisely by adjusting the series inductance without changing the system frequency. Implementing magnetic control with a current-controlled variable inductor provides a compact, efficient solution that only requires an additional low-voltage, low-power DC-DC converter, such as a synchronous buck converter, to supply and regulate the magnetizing current into the auxiliary winding. This setup, depicted in Figure 1, enables a reliable closed-loop control system to modulate the auxiliary winding current, dynamically adjusting the inductance of the magnetic device to regulate the output power of the IWPT system [5]. In this paper, a comprehensive investigation into the power transfer capability advantages of the LCC-S compensated WPT system, focusing on its dependence on the variable inductor configuration, will be described and discussed.

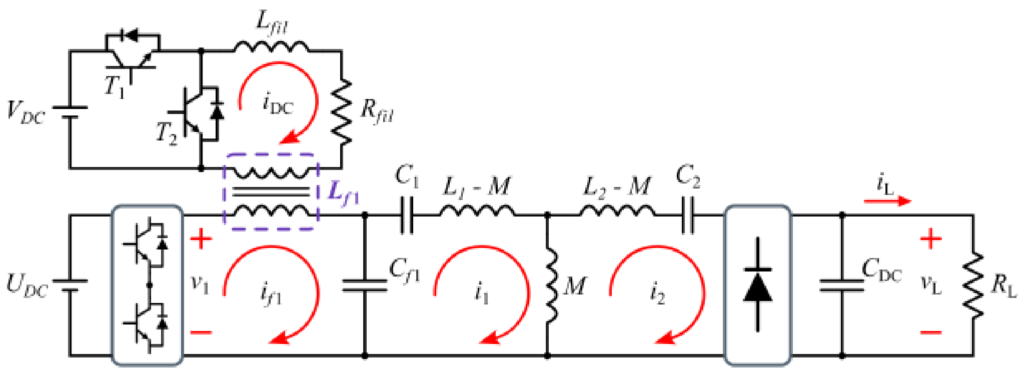

Figure 1: Scheme of the LCC-S compensated IWPT system with magnetic control, implemented through the controlled variable inductor L_{f1}, supplied on the auxiliary winding with a synchronous DC-DC buck converter.

[1] L. Solimene, F. Corti, S. Musumeci, F. J. López-Alcolea, A. Reatti, and C. S. Ragusa, 'Experimental validation of magnetic control strategy in LCC-S compensated wireless power transfer systems', IET Power Electronics, 2024, doi: 10.1049/pel2.12718.
[2] L. Solimene, F. Corti, S. Musumeci, C. S. Ragusa, and A. Reatti, 'Magnetic Control of LCC-S Compensated Wireless Power Transfer System', in 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2022, doi: 10.1109/SPEEDAM53979.2022.9842241.
[3] L. Solimene, F. Corti, S. Musumeci, A. Reatti, and C. S. Ragusa, 'A controlled variable inductor for an LCC-S compensated Wireless Power Transfer system', in IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, 2022, doi: 10.1109/IECON49645.2022.9968576.
[4] L. Solimene, F. Corti, S. Musumeci, C. S. Ragusa, A. Reatti, and E. Cardelli, 'Design and modelling of a controlled saturable inductor for an LCC-S compensated WPT system', Journal of Magnetism and Magnetic Materials, 2022, doi: 10.1016/j.jmmm.2022.170056.
[5] F. Corti et al., 'Closed-Loop Control of Inductive WPT System Through Variable Inductor', IEEE Open Journal of Power Electronics, 2024, doi: 10.1109/OJPEL.2024.3450202.

Invited

Modelling of Eddy Current Losses in Ferrite Cores

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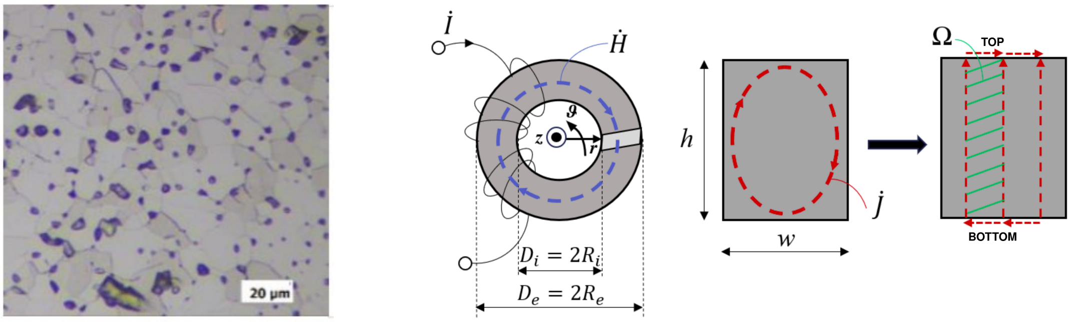
Ferrites have been widely studied in the past and are also currently of interest to the scientific community dealing with soft magnetic materials. They are based on iron oxide powders typically combined with nickel, zinc or manganese. The powder pressurization generates a crystallographic structure made by grains with good magnetic properties and medium electric properties (comparable with a semiconductor material), separated by very thin thicknesses of grain boundaries with poor magnetic and electric properties, as shown in Fig. 1(a).



(a) (b)

Figure 1: (a) Typical ferrite core structure [1]. (b) Sketch of the toroidal ferrite core and sketch of the real and simplified eddy current paths [2].

This kind of microstructure grants a combination of high magnetic permeability and low electric conductivity. In this way, ferrites cores succeed to limit the eddy currents losses when they have to work at high frequencies (up to several tens MHz). Since eddy current losses predominate the other kinds of losses when ferrites cores work at high frequencies, the possibility to have a reliable model to predict them is desirable to evaluate the performances of these cores.

The computation of eddy currents can be done using Maxwell equations. Thus, one possible tool to evaluate losses due to eddy currents is the FEM (Finite Element Method). However, due to the big difference between grain and boundary size (three or also four orders of magnitude), a huge computational effort is required. For this reason, our research group is involved in the proposal of simplified strategies to model this phenomenon. The general approach proposed to break down computational times consists in the hypothesis of specific and simplified paths for the eddy currents, as shown schematically in Fig. 1(b). The studies on the modelling techniques and their validation involve also a work around the estimation of the physical parameters which characterize the ferrite, and the best way to include them inside the proposed models.

[1] H. P. Rimal, G. Stornelli, A. Faba and E. Cardelli, "Macromagnetic Approach to the Modeling in Time Domain of Magnetic Losses of Ring Cores of Soft Ferrites in Power Electronics," in IEEE Transactions on Power Electronics, vol. 38, no. 3, pp. 3559-3568, March 2023, doi: 10.1109/TPEL.2022.3223184.

[2] Vittorio Bertolini, Marco Stella, Riccardo Scorretti, Antonio Faba, Ermanno Cardelli, "Eddy current losses model and physical parameters evaluation for ferrite magnetic cores in frequency domain", Journal of Magnetism and Magnetic Materials, Volume 594, 2024, 171905, ISSN 0304-8853, https://doi.org/10.1016/j.jmmm.2024.171905.

Invited

Design of Inductive link for battery charging for future space rover and drones

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Current rovers and drones, such as those recently sent to Mars, are powered by solar panels or Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) systems. The idea is to remove solar panels or MMRTGs from rovers and drones, and charge them through wireless charging stations, which can be powered by sunlight or MMRTGs. The key is that a single charging station could power several rovers and drones (see Fig. 1).

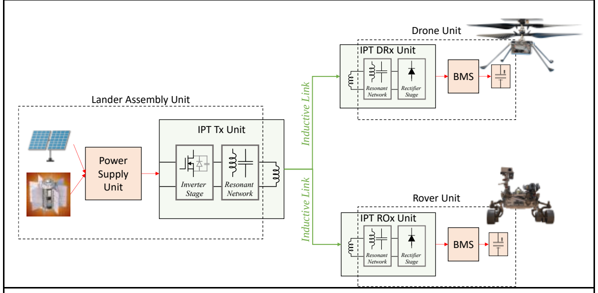

Fig. 1. Basic block diagram of charging system for drones and rovers.

Each receiver (drone unit and rover unit) must receive different voltage and power from the universal transmitter. In the case of the drone unit it is 24V and 2kW, and in the case of the rover unit it is 48V and 10kW.

Based on previous topology analysis [1], it is known that the optimal coils to maximize the performance of this circuit are, for the transmitter-drone system:

$$L_{drone} = \frac{R_L}{\omega\sqrt{1+k^2}} \quad (1)$$

$$L_{trans} = L_{drone}\left(\frac{1}{k}\frac{V_{in}}{V_{24v}}\right)^2 \quad (2)$$

And for the transmitter-rover system:

$$L_{rover} = \frac{R_L}{\omega k\sqrt{2}} \quad (3)$$

$$L_{trans} = L_{rover}\left(\frac{V_{in}}{V_{48v}}\right)^2 \quad (4)$$

In order to maximize the efficiency of wireless power transmission, frequency and magnetic coupling studies are performed for each system as a whole. *If the paper is accepted, further details on the circuit analysis will be provided.*

Using Ansys Maxwell® and analytical models [2] (Fig. 2), a transmitter capable of transmitting the desired power to the drone and the rover in an optimal way has been designed. Drone's coil will be designed to reduce the weight, and rover's to maximize the coupling factor. *If the article is accepted, details of the designed coils will be given. All information related to simulation and experimental validation will be included.*

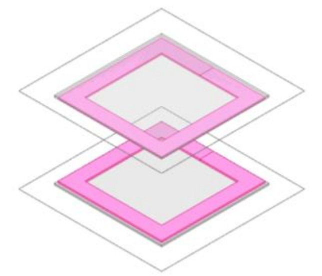

Fig. 2. Design of a transmitter and receiver in Ansys Maxwell

[1] A. Delgado, N. A. Requena, R. Ramos, J. A. Oliver, P. Alou and J. A. Cobos, "Design of Inductive Power Transfer System With a Behavior of Voltage Source in Open-Loop Considering Wide Mutual Inductance Variation," in IEEE Transactions on Power Electronics, vol. 35, no. 11, pp. 11453-11462, Nov. 2020, doi: 10.1109/TPEL.2020.2984097.

[2] A. Delgado, G. Salinas, J. A. Oliver, J. A. Cobos and J. Rodriguez-Moreno, "Equivalent Conductor Layer for Fast 3-D Finite Element Simulations of Inductive Power Transfer Coils," in IEEE Transactions on Power Electronics, vol. 35, no. 6, pp. 6221-6230, June 2020, doi: 10.1109/TPEL.2019.2949438.

Design and modelling of higher bending modes in a magnetoelectric device

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The Internet of Things is driving advancements in sensors, communication components, and power sources. Ideally, these components should be powered by sustainable energy readily available in the environment [1].

A magnetoelectric (ME) composite, comprised of piezoelectric and magnetostrictive layers, enables magnetic-to-electric energy transduction through functional materials properties. Through operation in mechanical resonance, ME devices appear to be one of the most promising technologies for wireless power transfer (WPT), when small device sizes (or low frequencies) are required.

Previous work focused on various ME devices modelling, of which the magneto-mechano-electric equivalent circuit method is very common [2]. In this study, we expand the model to account for ME operation in higher bending modes of the cantilever by incorporating the Euler-Bernoulli cantilever equation. The accuracy of our model will be compared with experimental results for Ni/PVDF composite cantilever devices.

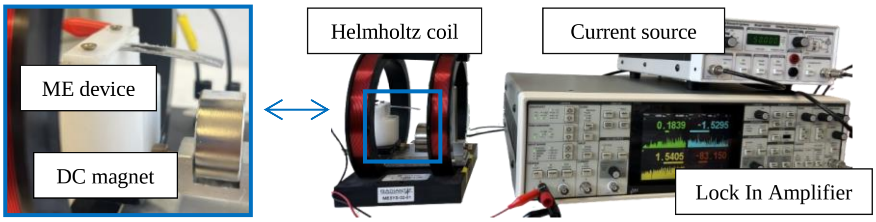

Figure 1: ME measurement set-up.

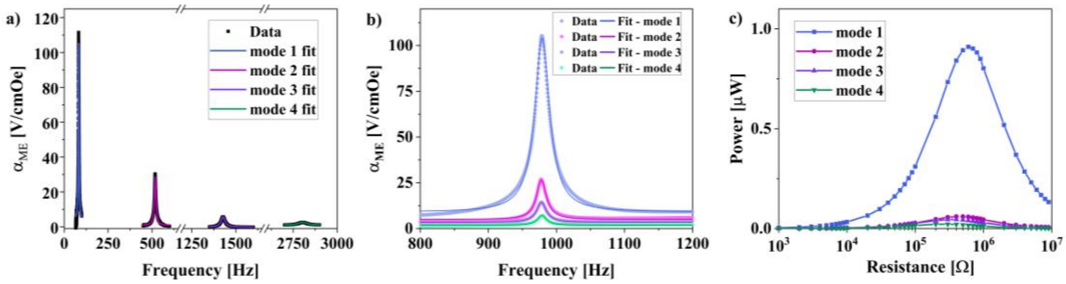

Figure 2: ME measurements with low AC magnetic field drive (H_{ac}=0.13 [mT]). a) α_{ME} (dE/dH -ME voltage coefficient) vs. frequency in different modes in the same ME device. b) α_{ME} vs. frequency in different devices, designed to have the same resonance frequency, in different modes. c) the power of the different devices.

Our results suggest a good agreement between the derived models and ME output (both open circuit and power), up to the 4^{th} operating mode. We will discuss the usage the higher modes for device and application design (accounting for *e.g.*, frequency requirements) as well as performance and materials analysis.

[1] M. G. Kang, R. Sriramdas, H. Lee, J. Chun, D. Maurya, G. T. Hwang, J. Ryu, S. Priya, Adv. Energy Mater. **8(16)** (2018), 1–11.

[2] S. Dong, J. Zhai, Chin. Sci. Bull. **53** (2008), 2113-2123

Robust Component Optimization for Multi-Transmitter Wireless Power Transfer Systems

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[b] University of Florence, Florence, Italy

Wireless Power Transfer (WPT) offers several advantages over traditional wired power transmission. Devices can be charged by simply placing them on or near a charging surface, without the need to plug in connectors, reducing tear and enhancing the durability of both the power source and the device.

Dual Transmitter Single Receiver (DTSR) WPT static systems have several practical applications across various fields. For example, it can be exploited for consumer electronics to ensure consistent power delivery regardless of the device's position on the charging pad, providing more robust and faster wireless charging solutions for laptops, potentially integrated into desks or workstations.

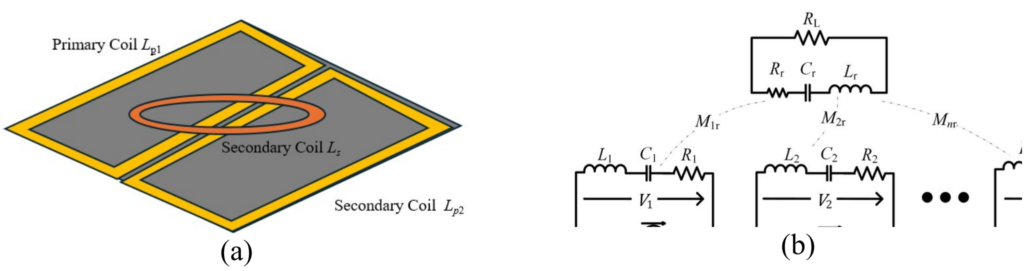

Figure 1: Dual transmitter single receiver. (a) Graphical representation. (b) Equivalent circuit.

Accurate tuning of resonant components is crucial for achieving high efficiency. A small variation of the resonant components can drastically affect the system's performance. This issue is even more pronounced in DTSR systems due to the large number of components, which increases the likelihood of operating in sub-optimal conditions. Furthermore, depending on the position of the receiver, the coupling between the primary and secondary may not be symmetrical. All these aspects must be taken into account during the design phase of the system. For this reason, the aim of this work is to exploit the use of a genetic algorithm capable of optimising the value of components to maximise efficiency and ensure high robustness with respect to component tolerances.

To this end, starting with the derivation of an accurate analytical model describing the magnetic coupling between the coils, a procedure is proposed for the automatic design of the entire system. Building on previous work aimed at component optimisation [1]-[2], the aim of this article is to extend this approach to DTSR systems, which are currently little studied and modelled in the literature.

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[1] V. Bertolini, F. Corti, M.Intravaia, A. Reatti, E. Cardelli, "Optimizing power transfer in selective wireless charging systems: A genetic algorithm-based approach", Journal of Magnetism and Magnetic Materials, Volume 587, 1 December 2023, 171340.

[2] F. Corti, M. Intravaia, A. Reatti, F. Grasso, E. Grasso, A. Trivino Cabrera, "Component design procedure for LCC-S wireless power transfer systems based on genetic algorithms and sensitivity analysis", IET Power Electronics, 2024, https://doi.org/10.1049/pel2.12648.

Transient grating investigation of magneto-elastic coupling dynamics in $Co_{78}Tb_xGd_{22-x}$ thin films

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[a] Department of Molecular Sciences and Nanosystems, Ca'Foscari University of Venice, Italy
[b] European X-ray Free Electron Laser, Schenefeld, Germany
[c] Elettra Sincrotrone Trieste, Basovizza TS, Italy
[d] IOM-CNR, Basovizza TS, Italy

The transient grating (TG) technique is a unique tool to study magnetization dynamics in thin films at a finite wavevector [1,2]. In this technique, two temporally and spatially overlapping parallel polarized pump pulses incident on a sample form a periodic light intensity pattern. The interaction between the TGs of intensity and a magnetized sample stimulates laser-induced demagnetization at the regions exposed to the highest light intensities, followed by a remagnetization process that can be explained by the Landau-Lifshitz-Gilbert (LLG) equation. With this approach, our optical TG experiment performed on $Co_{78}Tb_{12}Gd_{10}$ and $Co_{78}Gd_{22}$ thin film samples, magnetized perpendicular to the sample plane, has revealed novel insights into the magnetization dynamics driven by the magneto-elastic coupling. Both sample systems show similar features of acoustic oscillations of 2.2 GHz frequency (blue plots in Figure 1 (a) and (b)), as obtained by the detection of the parallel component of the probe diffracted from the induced dynamic gratings. However, the magneto-optical responses are clearly different. The doping of Tb into the alloy significantly changes the TG signal obtained by detecting the perpendicular component of the same diffracted probe (orange and green plots in Figure 1 (a) and (b)). While the $Co_{78}Gd_{22}$ sample exhibits a dominant, non-oscillatory response that rises and decays exponentially, the $Co_{78}Tb_{12}Gd_{10}$ sample shows oscillatory features having the same frequency of 2.2 GHz, as the observed acoustic waves. Such a coincidence of frequencies corresponding to the acoustic and magnetic oscillations suggests a clear indication of the coupling between the two entities. Tb's non-zero orbital moment enhances the coupling between the spin and lattice systems providing an intermediate scattering channel for angular momentum relaxation that is absent in the Gd-only sample. This primary conclusion is further supported by the observation that these oscillations change their phase upon reversal of the direction of the externally applied magnetic field, signifying the magnetic nature of the waves.

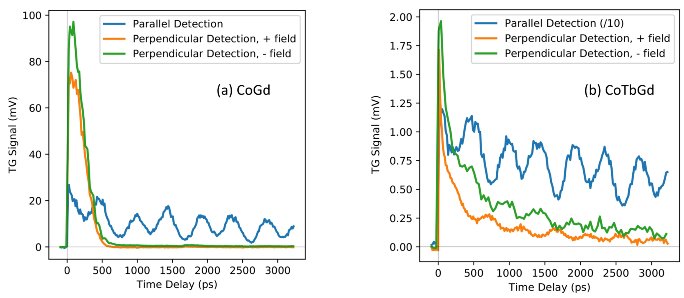

Figure 1: TG signal obtained from (a) CoGd and (b) CoTbGd samples. Blue plots for parallel detection; orange and green for perpendicular detection with opposite field directions (+ & - fields)

[1] D. Ksenzov, et. al., Nano Lett. 21, 2905 (2021).

[2] P. Carrara et al, Phys. Rev. Applied, 18, 044009 (2022).

Parasitic capacitance effects in wireless chargers for underwater vehicles

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The integration of wireless charging technology in electric vehicles has aroused the interest of researchers in recent years. Specifically, one of the growing areas is wireless charging in Unmanned Autonomous Vehicles (UAVs). This field is the focus of this study, since the need of autonomy of these vehicles, as well as their weight requirements, make wireless charging a suitable solution for certain applications, such as underwater observation.

The effects of seawater in wireless power transmission should be carefully studied during the design of the power coils. This study aims to analyse one of these variables of interest, which is the parasitic capacitance (C_e) between power inductors [1]. Therefore, the objective of this contribution is to find the optimal solution in order to avoid the effects of C_e during the coil design, thus simplifying the process.

To achieve the optimal solution, a comparative study has been performed according to two criteria: the relation between the C_e and the coil area, and the effects of the parasitic capacitance in the system efficiency. To do so, four different coil sizes have been proposed, considering numbers of turns (N) from 15 to 30. By using Ansys Maxwell software, it has been identified that C_e increases with the number of turns in seawater. Thus, it is interesting to study the effect of the parasitic capacitance in the system variables. Through Kirchhoff's Current Law, the voltage and current variations have been calculated considering and disregarding C_e, founding the optimal results in cases of N=20 and N=25, where the inclusion of C_e involves variations of 0.87 A – 1.51 V and 0.93 A – 7.81 V, respectively.

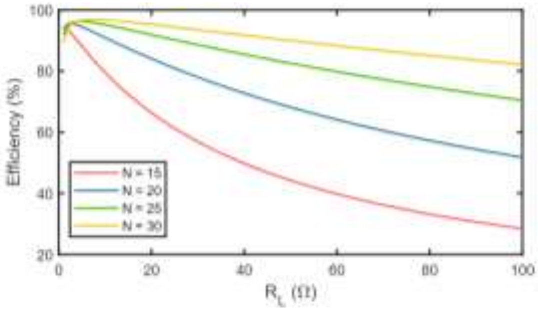

Figure 1. Efficiency comparative study, according to different numbers of turns.

To determine the final selected topology, an efficiency (η) study has been carried out. As can be seen from Figure 1, η values are similar in cases of lower values of R_L. Similarly, it can be deduced that η increases with the rise of the number of turns as the coupling coefficient k does. In this way, for our specific application, we consider that the solution of N=20 presents more optimal results, since it has high values of η, with few effects due to the parasitic capacitance. These results have been experimentally validated in our laboratory, proving the validity of this proposal.

[1] M Lin, F. Zhang, C. Yang, and et.al. Design of bidirectional power converters coupled with coils for wireless charging of AUV docking systems. Journal of Marine Science and Technology, 27:873–886, 2022

Opportunities and Challenges in Spintronics Technology

Invited

Superconducting artificial synapses integrated into a self-training neuromorphic architecture

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Superconducting electronics is a compelling technology for designing neuromorphic computing systems [1]. The technology uses Josephson junctions (JJ), which have a natural spiking behavior and can transmit voltage spikes over long distances with near-zero loss. One important building block of a neural network that still needs to be developed in superconducting electronics is the synapse, whose role is to adjust the strength of the connection between two neurons by changing the synaptic weight. In this presentation, we propose two types of artificial synapses developed at NIST and demonstrate their integrations in neural networks.

The first artificial synapse is a hybrid magnetic-superconducting device consisting of a Josephson Junction with a barrier of magnetic nanoclusters [2,3]. The critical current of these junctions can be tuned by varying the magnetic order of the clusters, which can be used to perform synaptic weighting. The second artificial synapse is obtained with a SQUID-based circuit using a flux storage loop for the synaptic weight [4]. Using SPICE simulations, we demonstrate that the synaptic circuit can be tuned using digital single flux quantum pulses.

In the second part of this presentation, we demonstrate the implementation of the synapses in a neural network. We integrate the SQUID-based artificial synapses into a small-scale self-training neural network architecture using SPICE simulations [4]. The network follows reinforcement learning rules that update local weights internally. This property allows the network to learn new functions by changing the target output for a given set of inputs without needing any external adjustments. Finally, using the same constraint as for the network mentioned above, we extend our simulations in Python to a larger problem to classify the handwritten digits from the MNIST dataset and show that the MNIST network can be trained in about 100 ms [4].

[1] Schneider *et al*, (2022) Supercond. Sci. Technol. **35** 053001

[2] Schneider *et al*., Sci. Adv. (2018) **4** e1701329

[3] Jué *et al.,* Appl. Phys. Lett. (2022) 121, 240501

[4] Schneider, Jué *et al*., arXiv:2404.18774

Invited

Heisenberg exchange in magnetic thin films

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The semiconductor industry is integrating ferromagnet-based microelectronic devices such as magnetic RAM (MRAM) into existing silicon-based technologies. MRAM has much shorter write times and higher write endurance than the embedded Flash currently used. An important materials parameter for the free layer in an MRAM device is the Heisenberg exchange. Even though several methods, which include neutron scattering or analysis of standing spin-waves through the films thickness, exists to determine the Heisenberg exchange in magnetic materials, all of them face challenges in the application to ultrathin films relevant for MRAM. We have developed an approach, which is based on the measurement of the spin-wave manifold with Brillouin Light Scattering spectroscopy, and designed an apparatus, which allows us to measure spin-waves propagating in any direction with respect to the external magnetic field, see Fig. 1.

In this talk, I will first review different measurement approaches to determine the Heisenberg exchange, before discussing its thickness dependence in sputter deposited CoFeB ultrathin films. I will then focus on thicker Permalloy films, where we compared the results obtained from ferromagnetic resonance measurements of perpendicular standing spin-waves with Brillouin Light scattering spectroscopy. We demonstrate, how the generally used approximation for the dipolar field for propagating spin-wave fails, when the requirement for $k \cdot t \ll 1$ is not fulfilled, where k is the spin-wave wavevector and t is the film thickness. Instead, we employ an analytical solution for bulk spin-waves with exchange and magnetostatic boundary conditions [2].

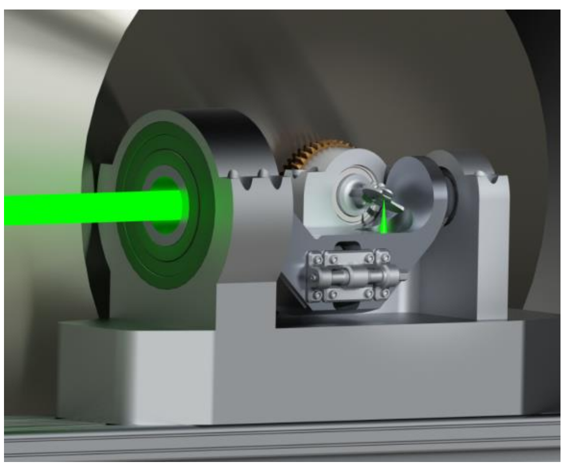

Figure 1: Measurement apparatus to measure the spin-wave dispersion with Brillouin Light Scattering spectroscopy. This apparatus allows precise, automated measurement of the dispersion over the two angles of incidence.

[1] G.A. Riley, J.M. Shaw, T.J. Silva and H.T. Nembach, J. Appl. Phys. 120, 112405 (2022)

[2] J.S. Harms and R.A. Duine, J. Magn and Magn, Mater., 557, 169426 (2022)

Invited

Mutual synchronization of thousands of spin Hall nano-oscillators

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Mutually synchronized spin Hall nano-oscillators (SHNOs) [1] can be used for neuromorphic computing [2,3]. However, the number of mutually synchronized SHNOs remains limited to 50 in chains [4] and 64 in 2D arrays [2]. To synchronize larger arrays, one must increase the oscillator coupling strength, for example, by packing them more closely, which requires smaller SHNOs. Here, we present a detailed experimental study on how to shrink the width of nano-constriction SHNOs. We show that current shunting through the Si substrate becomes problematic at extreme miniaturization, resulting in poor scaling below 50 nm. We, therefore, investigate the use of different seed layers and find that an ultra-thin (3 nm) AlOx layer between the Si substrate and the W layer in W/CoFeB/MgO-based SHNOs provides a dramatic improvement. Using further optimization of the spin-orbit torque, replacing W with a $W_{88}Ta_{12}$ alloy [5], we demonstrate 10 nm SHNOs operating at threshold currents as low as 30 uA [6]. We finally fabricate very large SHNO arrays based on this optimized stack and find that we can synchronize thousands of SHNOs [7].

[1] A. A. Awad et al., Nature Physics **13**, 292 (2017).

[2] M. Zahedinejad et al., Nature Nanotechnology **15**, 47 (2020).

[3] M. Zahedinejad et al., Nature Materials **21**, 81 (2022).

[4] A. Kumar et al., Nano Letters **23**, 6720 (2023).

[5] N. Behera et al., Phys. Rev. Appl. **18**, 024017 (2022)

[6] N. Behera et al., Advanced Materials **36**, 2305002 (2024)

[7] N. Behera et al., unpublished.

Invited

Nonreciprocity of hybridized surface acoustic/spin waves in a magnetic multilayer containing layers with non-collinear magnetizations

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Nonreciprocity of propagation of surface acoustic waves (SAWs) in a microwave frequency band can be achieved using magnetoelastic interaction of SAW with spin waves (SWs) propagating in magnetic heterostructures [1,2]. Recent works have shown that ultimate isolation of counter-propagating hybridized SAW/SW is achieved in structures consisting of a synthetic antiferromagnet (ferromagnetic (FM) bilayer with antiferromagnetic RKKY interlayer coupling) placed on top of a piezoelectric acoustic waveguide [3].

In this work, we study in detail a more practical and technologically simpler system based on an FM bilayer, where layers are coupled by only dipole-dipole interaction, and have non-collinear magnetizations μ_1 and μ_2 of the FM layers, similar to the system studied experimentally in [4,5].

We show that the in-plane magnetic anisotropy with non-collinear easy axes in the FM layers is the only essential factor for the realization of strongly nonreciprocal propagation of hybridized SAW/SW. We formulate requirements to relative orientation of the layer's magnetizations and wave propagation direction necessary for the realization of an efficient SAW isolator. We also demonstrate examples of SAW transmission characteristics which prove the possibility of achieving an isolation exceeding 40 dB for sub-mm-long FM bilayer with insertion losses of just a few dB larger than those of a pure SAW device.

In addition to fabrication simplicity, the proposed magnetoelastic heterostructure exhibits a reasonable robustness of its nonreciprocal characteristics with respect to deviations in the layer's magnetizations and/or the bias field directions – an important benefit for the mass-production of practical SAW/SW isolators.

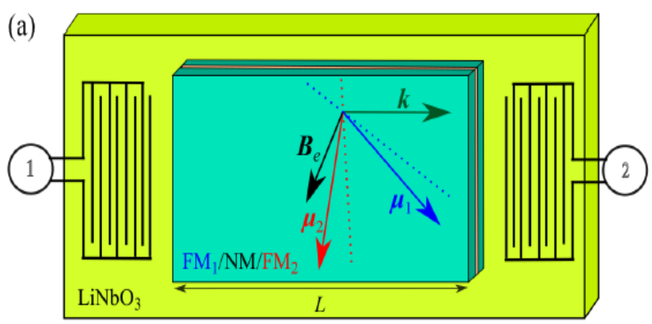

Figure 1. (a) A sketch of the magneto-acoustic structure, showing ferromagnetic - nonmagnetic-ferromagnetic (FM1/NM/FM2) multilayer situated on top of a piezoelectric LiNbO3 waveguide and two IDTs used for excitation and reception of SAWs. B_e is the in-plane bias magnetic field and ***k*** is the SAW/SW wave vector

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Tuning of ferroelectric Rashba semiconductors via alloying for energy-efficient computing devices

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The energy consumption of information technology is projected to reach 50% of global electricity production by 2040, driving the need for beyond-CMOS alternatives. Intel has proposed an exciting path toward ultra-efficient non-volatile transistors, leveraging ferroelectricity, ferromagnetism, and spin-based read-out mechanisms for computing [1]. However, their realization requires substantial material advancements [2].

Ferroelectric Rashba semiconductors (FERSCs) emerged as promising candidates endowed by non-volatility and ferroelectric control of spin-orbit coupling: the ferroelectric polarization in epitaxial GeTe films can be reversed by gating, switching the sign of the spin-to-charge current conversion (S2CCC) and paving the way to the development of the so-called ferroelectric spin-orbit transistors [3,4].

However, the realization of these devices would require to reduce the voltages required for switching, and to improve substantially the efficiency of S2CCC. Our investigation shows that alloying GeTe with SnTe in $Ge_xSn_{(1-x)}Te$ allows the material to move in the desired direction. Remarkably, the giant Rashba effect persists above room temperature [5] and Sn inclusion reduces the switching field to sub-1V levels (see Fig. 1). These findings uncover a materials engineering approach towards the realization of advanced logic-in-memory devices.

C.R. acknowledges the PRIN 2022 project SORBET (grant no. 2022ZY8HJY) by MUR.

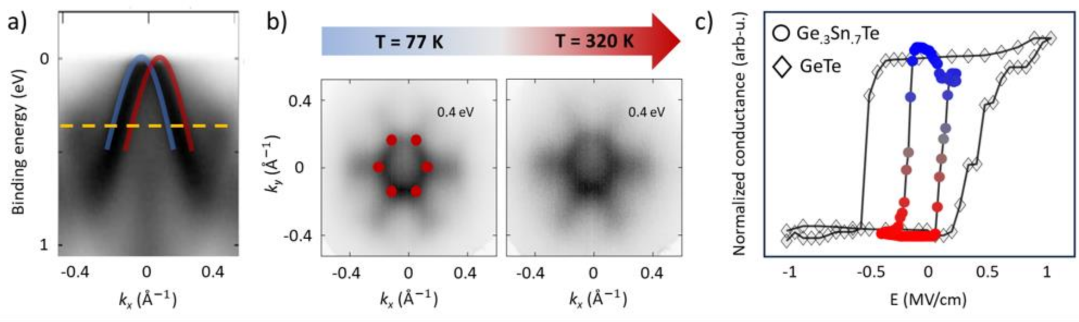

Figure 1: (a) Rashba-like bands identified in $Ge_{0.3}Sn_{0.7}Te$ thin films using angular-resolved photoemission spectroscopy. (b) The Rashba contour persists up to above 320 K, suggesting a significant Curie temperature. Red dots indicates the bulk bands crossing of the isoenergy plane. (c) Ferroelectric hysteresis loops obtained by electro-resistive measurements [3].

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[2] D.C. Vaz, Nat. Commun. **15** (2024), 1902.

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Nonlinear amplification of microwave signals in spin-torque oscillators

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Spintronics technology is driving the development of innovative memories based on the concept of spin-transfer torque. Advances in spintronics-based microwave devices, such as oscillators and detectors, have been the subject of intense investigation, leading to several research results in computing and microwave technology. However, only a few concepts for spintronic amplifiers have been proposed, typically requiring complex device configurations or material stacks. Recently, we have demonstrated a spintronic amplifier based on two-terminal magnetic tunnel junctions (MTJs) fabricated with CMOS-compatible material stacks already used for spin-transfer torque memories [1].
We achieve a record gain (greater than 2 for some devices) for an input power on the order of nW (<-40 dBm) with an appropriate choice of bias field direction and amplitude. Micromagnetic studies indicate that this number may be doubled. Some key points for understanding the origin of the amplification for a given field range will be discussed. In particular, we will discuss the key role of the coexistence between the bias-excited dynamic state of the MTJ and the injection locking phenomenon in driving the microwave emission amplification.

[1] Keqiang Zhu, et al, Nature Communications,14, 2183 (2023).

Energy-efficient control of magnetic states

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Control of magnetization switching is critical for the development of novel technologies based on magnetic materials. Transitions between magnetic states can follow various pathways which are not equivalent in terms of energy consumption and duration. In this study, we propose a general theoretical approach based on the optimal control theory to design external stimuli for efficient switching between target magnetic states. The approach involves calculation of optimal control paths (OCPs) for the desired change in the magnetic structure. Following an OCP involves rotation of magnetic moments in such a way that the strength of the external stimulus is minimized, but the system's internal dynamics is effectively used to aid the switching. All properties of the control pulses including temporal and spatial shape can be derived from OCPs in a systematic way.

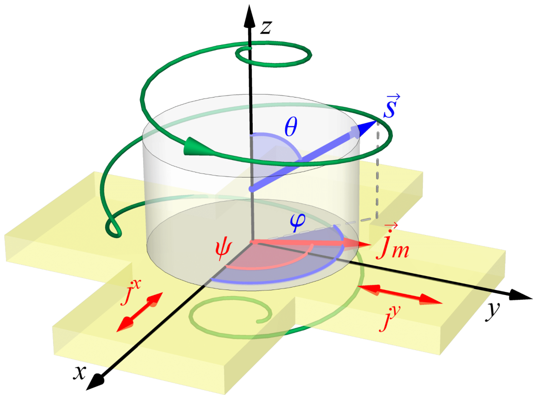

Figure 1: Energy-efficient switching of a nanomagnet (cylinder) by an optimal 2D electric current pulse $\vec{j}_m$ flowing at the heavy-metal substrate (cross). The calculated optimal control path is shown with the green line. The direction of the normalized magnetic moment $\vec{s}$ of the element (optimal current $\vec{j}_m$) is shown with the blue (red) arrow.

Various applications of OCP calculations are presented, including energy-efficient switching of a nanomagnet by means of external magnetic field [1] or electric current [2,3] (see fig. 1), spin-wave assisted magnetization reversal in nanowires [4], and optimal skyrmion motion in synthetic antiferromagnets.

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Sensing and Harvesting Devices Employing Multi-Functional Materials

Invited

Energy harvesting of waste heat using thermomagnetic materials

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To date, there are very few technologies available for the conversion of low-temperature waste heat into electricity. Thermomagnetic generators are one approach proposed more than a century ago. Such devices are based on a cyclic change of magnetization with temperature. This switches a magnetic flux and, according to Faraday's law, induces a voltage. We demonstrated that guiding the magnetic flux with a pretzel-type topology of the magnetic circuit improves the performance of thermomagnetic generators by orders of magnitude [1]. From an ideal material's perspective, several similarities with magnetocaloric materials [2] can be found, like a sharp first-order like magnetostructural transition, low hysteresis and high thermal diffusivity. This makes some magnetocaloric materials good candidates also for thermomagnetic energy harvesting, like e.g. $(MnFe)_2P$-based and La(Fe,Si)13-based compounds.

Recently, the EU MSCA initial training network Heat4Energy [2] was started with the aim of making three thermomagnetic energy converters for low grade waste heat (<100°C) to electricity with different power output ranges. While the smallest demonstrator operates with thin film materials, the two larger machines use bulk material, for which different processing and shaping routes are explored. In collaboration with the industrial stakeholders of the project, up-scalability and practical application issues of materials processing will be addressed during the project. After an introduction into the technological background and the ITN project, we will present first results on 3D printing and non-destructive imaging of the thermomagnetic parts.

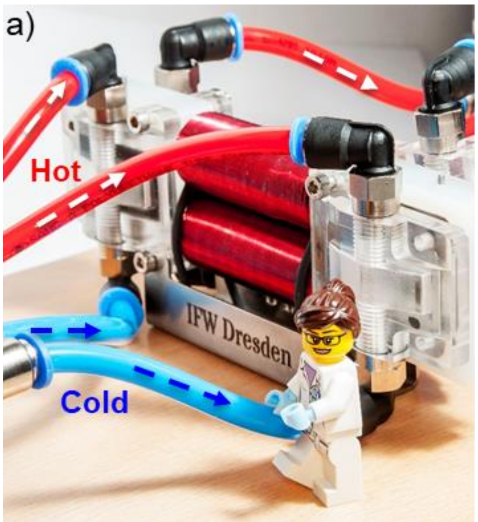

Figure 1: Themomagnetic generator for the conversion of waste heat into electricity using a Pretzel-type magnetic flux topography. From [1]

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[3] Dzekan et al., APL Mater. 9, 011105 (2021)

[4] https://heat4energy.eu/

Invited

Piezo-resistive behaviour of magnetically controlled multifunctional polymeric composite foams

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Multifunctional polymeric composite foams (named MAPs in the following, standing for Multifunctional Advanced Porous materials) having an anisotropic distribution of reinforcing and/or functionalizing particles are lightweight sustainable metamaterials that can efficiently be manufactured through the application of a suitable magnetic field (MF) during the production process [1]. MAPs are characterized by coupling of structural and functional anisotropy, obtained through the alignment of particles along desired directions, with a regular, highly porous structure. They can be produced with biodegradable and biobased polymers by injection moulding or batch foaming, thus rendering them a sustainable choice [2], consistently with the "Do Not Significant Harm" principle. In particular, magnetic micro-sized spherical particles were successfully adopted to impart magnetostrictive and anisotropic mechanical properties to MAPs [3], along with anisotropic thermal diffusivity and improved sound absorption capability. Here, we further develop MAPs by combining magnetic particles with different aspect ratios (spherical, 0D, with linear, 1D, or planar, 2D) to promote the formation of electrically conductive paths at particle filler contents well below the electrical percolation threshold, see e.g. fig.1. These fillers are used to further reduce particles' volume content at constant or improved performance. The magnetic species will be exploited to move or rotate non-magnetic particles in cell walls or struts. The newly developed MAPs will, therefore, show improved electrical properties, that will be exploited to impart a piezo-resistive behavior or EMI shielding capability. Additionally, such MAPs can still act as smart material (self-sensing) due to the strain-dependent conductivity. The effects of the aligned aggregates features on the piezo-resistive behaviour under DC and variable-frequency electric fields will be evaluated. Furthermore, an electrical impedance analysis will be conducted by measuring the system impedance at different compressive deformations using a custom setup already available at University of Sannio.

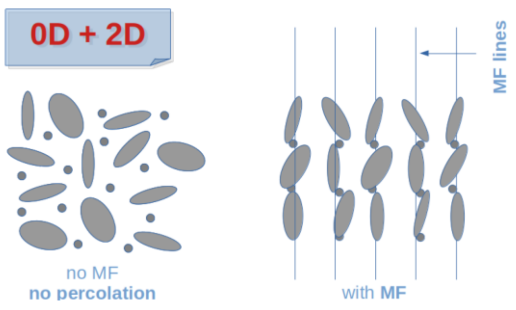

Figure 1. Particles arrangement in a MAP (porous structure has been excluded for clarity) after manufacturing without (left) or with (right) MF.

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[3] M. D'Auria et al, Composites Part B: Engineering, 212, (2021), 108659.

Coupled magnetic tunnel junctions arrays for sensor applications

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We have designed [1,2] a spintronic accelerometer exploiting a system of magnetic tunnel junctions (MTJs) integrated on excitable substrates, such as microelectromechanical systems (MEMS), that can transduce the external stimulus (a_{ext}) into a mechanical excitation. This translates into an excitation of the magnetic system via the stray field that couples the MTJs. When the distance between the MTJs changes, this displacement reflects into a variation of the stray field distribution. This results in a change in the output voltage generated by the MTJs working as spin torque diodes (STDs), via spin diode effect [3]. By exploiting the different timescales characterising the coupled magneto-mechanical system, it becomes possible to extract the acceleration directly from this change in the output voltage.

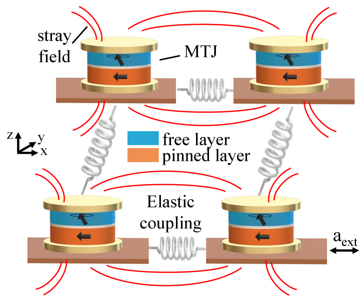

Figure 1: Sketch of the MTJs' system investigated in this work.

We extend the original design to an array of magnetic tunnel junctions, exemplified in Fig.1. Arrays of MTJs allow to extend the detection from 1D to 2D and can yield an improvement of the sensitivity and energy efficiency of the accelerometer. Furthermore, this design could also be exploited in other applications, such as microwave amplifiers and reservoir computing. Here we explore different design configurations and perform systematic studies on the dynamics of the array of MTJs, both mechanical and magnetic, to find those conditions that yield a stable synchronisation between the MTJs, a linear output signal from the fixed-MTJs and allows to maximise the output sensitivity.

Acknowledgements. This work was supported under the project number 101070287 – SWAN-on-chip – HORIZON-CL4-2021-DIGITAL-EMERGING-01; the MUR-PNRR project SAMOTHRACE (ECS00000022), funded by European Union (NextGeneration EU); the projects PRIN 2020LWPKH7 – The Italian factory of micromagnetic modeling and spintronics and PRIN_20225YF2S4 – Magneto-Mechanical Accelerometers, Gyroscopes and Computing based on nanoscale magnetic tunnel junctions (MMAGYC), funded by the Italian Ministry of University and Research.

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[3] Finocchio, G. *et al.* Appl. Phys. Lett. **118** (2021), 160502.

High resolution flexible planar-Hall magnetic field sensors and its applications

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Flexible and stretchable magnetic sensors have attracted a lot of attention recently as they have unique properties, being ultra-thin, light weight, highly flexible and stretchable. They can provide new opportunities in human health monitoring, wearable electronics, and other fields such as process monitoring. In recent years, therefore, considerable research efforts have been made to develop flexible and stretchable magnetic sensors to meet the requirements of future technologies, and significant progress has been made [1-3]. Moreover, the magnetic properties of these sensors are comparable to those of industry standard rigid magnetic field sensors, with the added ability to adapt to complex surface geometries and to scan in direct contact with the sample surface [4,5].

In the present study, highly flexible exchange biased planar-Hall sensors on different polymer substrates are fabricated and the most important optimization steps required to increase their resolution in nT level are identified for extremely-low-frequencies (<10 Hz). In order to achieve this, the role of other key parameters such as layer stacks, sensor geometries, substrates and fabrication steps have also been investigated. Moreover, the effects of repeated bending cycles on sensor sensitivity, linearity and noise performances are investigated to determine the long-term stability and reliability of the manufactured devices. Finally, the sensor performance is evaluated with rigorous bending and fatigue tests, that simulate real-world conditions encountered in wearable applications. This research contributes to the advancement of flexible sensor technology by providing insight into the material and sensor performance under mechanical stress, paving the way for reliable and high-performance flexible sensor systems.

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[3] Melzer, Michael, et al. *Adv. Mate.* 27.7 (2015): 1274.

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[5] Kim, Mijin, et al. *IEEE Magn. Lett.* 11 (2020): 1-5.

A laboratory-scale prototype of thermomagnetic generator for harvesting of waste heat

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Thermomagnetic power-generation, based on magnetocaloric materials, emerges as a promising technology for harvesting and converting low-grade waste from sources operating at temperatures below 100°C [1,2]. While intensive research efforts have been dedicated to materials and prototypes design in recent decades, a substantial gap persists between fundamental material research and the effective integration of materials into efficient devices.

In this contribution, we present a laboratory-scale prototype of thermomagnetic generator (TMG) designed for rapid evaluation of thermomagnetic materials for energy-harvesting applications [3]. The core of the TMG is a thermomagnetic motor, based on the Curie wheel principle, that converts thermal energy into mechanical energy. It works between two controllable temperature reservoirs, allowing the evaluation of materials performance on an adjustable temperature range. The motor shaft is connected to a custom-built, two-phase, miniaturized, permanent magnet electric generator specifically optimized for low-speed operation, which generates electric power and enables the simultaneous measurement of torque, rotation speed and mechanical power output. The TMG can operate with only 200 mg of active material. The thermomagnetic rotor is made using a reliable and straightforward preparation method starting from coarse powder of the magnetic material [4]. Thanks to the modular design of the TMG, different operating parameters (e.g. magnets arrangement and positioning, rotor size and shape, heat exchange mechanisms) can be modified and tested to evaluate their impact on the overall power output.

As an example, we report a complete thermomagnetic assessment of several Ni-Mn-based Heusler alloys within the 20-60 °C temperature range. The correlation between the maximum mechanical output of thermomagnetic generator and the work of thermomagnetic cycles calculated from magnetization data is studied to provide a unique framework for evaluating magnetic materials intended for heat harvesting applications. Furthermore, we investigate the role of heat exchange in determining the maximum output of the thermomagnetic motor by varying the geometrical and thermodynamic proprieties of the rotor. Thermal imaging technologies were employed to investigate thermal gradients in TM rotors during operation.

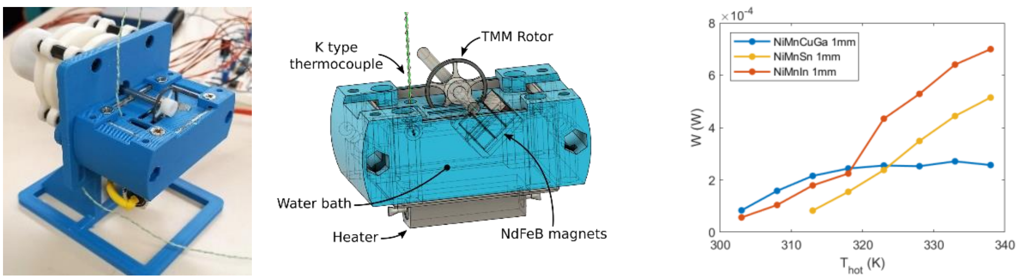

Figure 1: On the left: photograph and sketch of the TMG prototype. On the right: maximum mechanical power of the generator as a function of temperature of the hot reservoir obtained exploiting NiMnIn, NiMnSn and NiMnCuGa Heusler alloys as active material.

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[2] D. Dzekan et al., APL Mater. 9, 011105 (2021)
[3] F. Cugini et al., Submitted
[4] C. Coppi et al., Adv. Eng. Mater. 25, 2200811 (2023)

Magneto-Thermoelectrics in Cryogenic, Room, and High-Temperature Regimes: Material and Device Innovations

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The field of magneto-thermoelectrics encompasses various strategies to enhance thermoelectric effects, including the use of externally applied magnetic fields to improve energy conversion efficiency. This study evaluates the performance of magneto-thermoelectric devices across cryogenic, room, and high-temperature regimes by optimizing material selection, magnetic field generation, and device engineering.

In the cryogenic regime, superconducting magnets are ideal for generating strong magnetic fields with minimal energy loss. Materials such as Bi and Bi-Sb alloys exhibit significant enhancement under fields up to 5 T due to their anisotropic Fermi surfaces. In topological insulators like Bi_2Te_3, magnetic fields up to 3 T amplify the Nernst effect by disrupting spin-momentum-locked surface states. High-temperature superconductors like $YBa_2Cu_3O_7$ show enhanced Nernst signals near their superconducting transition temperature, particularly in the vortex-liquid phase where vortex movement is most pronounced.

At room temperature, fields between 1 and 3 T can significantly enhance thermoelectric effects in materials like Heusler alloys, half-Heusler compounds, and manganites. The anomalous Nernst effect in ferromagnetic and antiferromagnetic topological materials generates significant transverse voltages even at fields below 1 T, making them promising for low-field applications. In the high-temperature regime and magnetic fields up to 3 T, ferromagnetic oxides, skutterudites, and antiferromagnetic compounds (e.g., $Mn_{1-x}Cr_xSb$) exhibit enhanced performance up to 800 K, whereas SiGe alloys remain the benchmark beyond this range.

For both room and high-temperature regimes, permanent magnetic magnets are preferred for generating fields up to 2 T due to their scalability and lack of extensive cooling requirements. While superconducting magnets can offer higher fields, they necessitate local cooling to cryogenic temperatures and quench protection, posing additional engineering challenges.

This study highlights the critical role of material and magnet design in optimizing magneto-thermoelectric devices. Future work will involve integrating these materials into prototypes, such as cryogenic coolers [1] and solid-state thermal switches [2], and explore scalable applications like waste heat recovery by energy harvesting [3] and magnetic field sensors. By addressing integration challenges and heat management, this research aims to advance the role of magneto-thermoelectrics in sustainable energy solutions.

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Self-bias magnetoelastic resonance sensors with improved mass sensitivity performance: The effect of nanocrystallization induction by annealing.

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The growing demand for cost-effective, wireless sensing technologies necessitates the development of efficient and optimized sensors capable of accurately detecting external agents. Magnetoelastic resonators present a promising solution, combining versatility, low cost, and wireless detection [1]. These platforms have attracted significant attention for their ability to detect various physical and biological parameters, with ongoing efforts to enhance sensitivity through optimizations in composition, surface functionalization, and geometry [2, 3]. Our recent work explored thermal treatments as a novel approach to improving performance, demonstrating that crystallization processes significantly enhance the sensitivity of magnetoelastic mass sensors.
Experimental results confirm that increasing the annealing temperature boosts both the resonant frequency and quality factor of the platforms. The sensor annealed at 550ºC exhibited a 45% increase in resonant frequency and a remarkable 1700% improvement in quality factor compared to the as-quenched state. Nanocrystallization induced self-biased resonance through intrinsic magnetization, arising from the crystallization of Fe_2B and FeCo phases. Furthermore, the 550ºC-annealed sensor showed enhanced stability, with a 40% increase in sensitivity and a 38% improvement in accuracy. These findings underscore the pivotal role of thermal treatments in optimizing magnetoelastic mass sensors for the detection of external agents.

[1] P. G. Saiz, R. Fernández De Luis, A. Lasheras, M. I. Arriortua, A. C.a Lopes, ACS Sensors, 2022, 7 (5), 1248-1268
[2] P. G. Saiz, R. Fernández de Luis, L. Bartolome, J. Gutiérrez, M. I. Arriortua, A. C. Lopes, J. Mater. Chem C, 2020, 8, 13743
[3] P.G.Saiz, D. Gandia, A.Lasheras, A.Sagasti, I.Quintana, M.L. Fez-Gubieda, J. Gutiérrez, M.I.Arriortua, A.C.Lopes, Sens. Actuator B-Chem., 2019, 296, 126612

Tracking the 3D motion of a sub-mm magnet for tactile sensing applications: development of a hybrid platform combining a graphene-based Hall sensor with AMR sensor arrays

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Magnetoresistive (MR) sensors are known for their high sensitivity and signal-to-noise ratio, and, among them, anisotropic MR (AMR) sensors are particularly attractive owing to their relatively inexpensive and simple fabrication process and to the possibility of achieving small feature sizes. On the other hand, graphene has emerged as an appealing candidate for the development of highly sensitive, CMOS-compatible and cost-effective Hall sensors [1]. In this work, we present the design and fabrication of a novel 3D magnetic sensor integrating a graphene-based Hall sensor with AMR sensor arrays in a single compact platform. This architecture is specially devised to track the motion of small sub-mm permanent magnets in all spatial directions, which is of interest, for instance, for the realization of miniaturized 3D magnetic tactile sensors (see scheme in Fig. 1a).

The AMR sensor arrays are custom-designed via a combination of finite-difference-based micromagnetic computations (MuMax3), finite-element simulations (Ansys Maxwell) and analytical magnetic field calculations (Magpylib [2] Python package). The Hall sensor microfabrication starts from a commercial CVD monolayer graphene film and follows a two-step electron-beam lithography (EBL) process for graphene Hall bar patterning (via reactive ion etching) and metal contact deposition (Fig. 1b). A two-step EBL procedure is also applied for the AMR sensors, which are fabricated on top of the Hall bars after the latter have been encapsulated under a 1-µm-thick parylene layer for electrical insulation. The AMR sensors feature a Ta/NiFe/Ta thin-film stack and Au barber poles for output biasing (Fig. 1c).

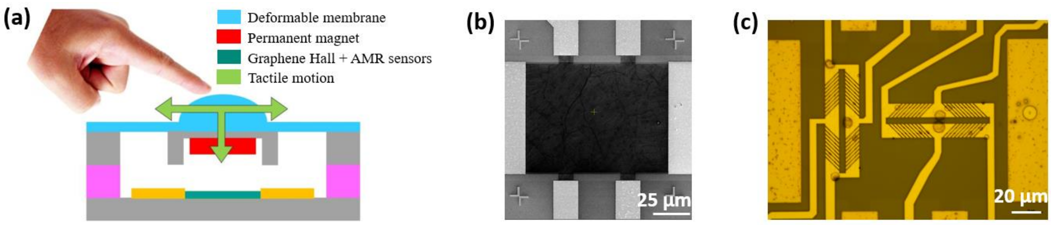

Figure 1: (a) 3D magnetic tactile sensor where a sub-mm permanent magnet embedded in a flexible membrane moves relative to a hybrid Hall/AMR magnetic sensor upon the application of an external force. (b) SEM micrograph of a graphene Hall bar. (c) Optical microscope image of an AMR sensor array sitting on top of a graphene-based Hall sensor.

By enabling the direct detection of all three spatial components of the magnetic field, the output of this magnetic sensor platform can be used for permanent magnet motion reconstruction in 3D via the resolution of a magnetic inverse problem and is expected to offer an increased position tracking accuracy compared with purely AMR-based solutions [3]. Possible applications of this original magnetic sensor concept are not only limited to novel miniaturized 3D tactile sensors but also encompass other sensor microsystems capable of probing a variety of physical observables (e.g., fluid flow, acceleration, etc.).

[1] D. Collomb et al, J. Phys.: Condens. Matter **33** (2021), 243002.

[2] M. Ortner et al, SoftwareX **11** (2020), 100466.

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2025 IEEE Conference on Advances in Magnetics (IEEE AIM 2025)

Bressanone, Italy - 9-12 February 2025

POSTER SESSIONS

MONDAY, FEBRUARY 10th, 2025

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A2	**Gabriel Vieira**, Centro de Desenvolvimento da Tecnologia Nuclear (Brasil) *Exploring the Incorporation of Recycled Nanocrystalline Powders into Feedstock for 3D Printing of Bonded Nd-Fe-B Magnets*	ID 194
A3	**Vittorio Bertolini**, University of Perugia (Italy) *Design of a Neural Network Method for Assessing Magnetic Losses in Nanocrystalline Transformers*	ID 134
A4	**Adriano Di Pietro**, INRiM Torino (Italy) *Machine learning enhanced Kerr Microscopy magnetization pattern recognition*	ID 149
A5	**Antonino Laudani**, University of Catania (Italy) *Physics-Informed Neural Networks for Magnetism*	ID 238
A6	**Oumayma Chdil**, University of Ljubljana (Slovenia) *Advancing Magnetic Refrigeration with Artificial Intelligence*	ID 164
A7	**Hubert Brueckl**, University for Continuing Education Krems (Austria) *Machine learning based prediction of mechanical properties of WC-Co cemented carbides from magnetic data only*	ID 5
A8	**Bramantya Bramantya**, University of Warsaw (Poland) *Machine Learning-Aided Ab Initio Crystal Structure Prediction of Magnetic Metal-Organic Frameworks*	ID 177
A9	**Bogdan Idzikowski**, Polish Academy of Sciences Poznań (Poland) *Novel directions in the search and design of modern materials for sustainable development*	ID 227
A10	**Johann Fischbacher**, University for Continuing Education Krems (Austria) *Micromagnetic and reduced-order model simulations of microstructural defects in recycled Nd2Fe14B magnets*	ID 203
A11	**Francesca Casoli**, CNR - IMEM Parma (Italy) *Micromagnetic modeling of Ni2MnGa thin films*	ID 215
A12	**Beatrice Muzzi**, CNR - ICCOM Firenze (Italy) *Aerobic ethanol oxidation by magnetic inductive heating of palladium on nickel foam*	ID 289
A13	**Denisa Oleksakova**, Technical Univeristy of Košice (Slovakia) *Evaluating the Effect of Surface Treatment on Powder Particles in Soft Magnetic Composites*	ID 129
A14	**Joydeep Majhi**, Indian Institute of Technology Bombay (India) *Investigating magnetocaloric properties and Heisenberg exchange interactions in NdMnO3 perovskite: A computational study*	ID 285
A15	**Blaž Belec**, University of Nova Gorica (Slovenia) *Pursuing optimal magnetic properties of recycled SrFe9O12 through magnetic ordering quenching*	ID 25
A16	**Peter Kollár**, P. J. Šafárik University in Košice (Slovakia) *Effect of duration of particles dry coating process on magnetic properties of Fe@Al2O3 soft magnetic composites*	ID 128
A17	**Simone Fabbrici**, CNR - IMEM Parma (Italy) *Simulating the impact of materials' properties on the active magnetocaloric regenerator*	ID 204
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A23	**Federica Celegato**, INRiM Torino (Italy) *Magneto-polymer supraparticles for rapid and reliable identification tags using Magnetic Particle Spectroscopy*	ID 9
A24	**Luca Boarino**, INRiM Torino (Italy) *Urea catalysis by electrodeposited Ni nanostructures*	ID 200
A25	**Feng Liu**, Chengdu University of Information Engineering (China) *A novel laser imaging method for real-time inspection of high-speed rails*	ID 155
A26	**Giorgia Battistini**, University of Pisa (Italy) *Multi-DoF 3D printed spherical electromagnetic actuator*	ID 252
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	Frequency control for LCC-S wireless power transmission	
A32	**Sujit Panigrahy**, Univ. Grenoble Alpes, CEA, CNRS, Grenoble (France)	ID 156
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	Spin-torque diode effect driven by magnetization phase-transitions: a theoretical analysis	

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B3	**Anna Giordano**, University of Messina (Italy) *Voltage-controlled magnetic anisotropy driven non-linear parametric resonance*		ID 237
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B8	**Mohammad Haidar**, American University of Beirut (Lebanon) *Interference patterns of propagating spin wave in spin Hall oscillator arrays*		ID 88
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B11	**Volker Wiechert**, University of Konstanz (Germany) *Photoinduced spectral manipulation of coherent magnonics in ultrathin iron garnets*		ID179
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B13	**Riccardo Fornari**, University of Perugia (Italy) *Static and dynamic properties of exchange-coupled artificial spin-ice CoFe/Ru/NiFe multilayers*		ID316
B14	**Raffaele Silvani**, University of Perugia (Italy) *Adaptive Magnetic Devices Utilizing Integrated Micro-Magnets*		ID400
B15	**Zhenbin Zhu**, Beihang University (China) *Optimizing terahertz emission in magnetic materials using light ion irradiation*		ID102
B16	**Samih Isber**, American University Of Beirut (Lebanon) *Optimizing spin pumping in Yttrium Iron Garnet/Platinum bilayers under varying oxygen pressure*		ID97
B17	**Mariia Trukhanova** *The dynamical magnetoelectric effect of spin origin and the evolution of polarization*		ID30
B18	**Debarghya Dutta**, IIT Bombay (India) *Electronic and magnetic properties of Sr2TiFeO6 implementing ab initio density functional theory*		ID286
B19	**Oleksandr Pylypovskyi**, Helmholtz-Zentrum Dresden-Rossendorf (Germany) *Modification of magnetic properties via the surface magnetic symmetry in antiferromagnets*		ID76
B20	**Carlo Alberto Brondin**, CNR - ISM (Italy) *Dy and Er magnetic impurities diluted in insulating hosts, promising candidates to realize stable single-atom magnets*		ID123
B21	**Athira P**, National Institute of Technology Andhra Pradesh (India) *Re-entrant spin glass behaviour, nonlinear magnetodielectric coupling and multicaloric effect in Fe 2 (MoO 4) 3 multiferroic*		ID136
B22	**Feliks Stobiecki**, Polish Academy of Sciences (Poland) *The role of domain walls in magnetization reversal of 2D periodic ferrimagnetic heterostructures*		ID3
B23	**Tomohiro Uchimura**, Tohoku university (Japan) *Manipulation of quantum metric in a topological chiral antiferromagnet at room temperature*		ID146
B24	**Vladislav Bilyk**, Radboud University (The Netherlands) *Terahertz-driven magnetoelectric torque in the collinear antiferromagnet Cr2O3*		ID218
B25	**Rémy Dangoisse**, Université Grenoble Alpes, CNRS (France) *Visualisation of a triangular Ising antiferromagnet with two-dimensional lattices of non-magnetic fullerenes*		ID28
B26	**Rougemaille Nicolas**, CNRS - Institut Néel (France) *The arctic square ice*		ID31
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B29	**Marco Madami**, University of Perugia (Italy) *Brillouin light scattering measurements of Dzyaloshinskii Moriya interaction: reproducibility and uncertainty*		ID235
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B32	**Irdi Murataj**, INRiM Torino (Italy) *Magnetisation reversal in FeGa 3D nanostructures*	ID36

Magnetic properties of Fe-Si based amorphous alloy prepared by Selective Laser Melting for soft magnetic applications

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Amorphous soft-magnetic materials play an important role as core constituents in improving the energy transformation efficiency of electrical machines and passive electrical components [1]. Although the melt-spinning process remains one of the main techniques for obtaining amorphous soft-magnetic ribbons, new and efficient production methods based on additive manufacturing have been developed in recent years. These techniques allow to overcome technical limitations characteristic of casting processes and also to print complex 3D geometries. The aim of this work is to investigate the magnetic properties of Fe-Si based alloy prepared by selective laser melting and compare them with the amorphous ribbons obtained by a conventional melt-spinning process.

Ribbons were obtained by a conventional melt-spinning process, in which the pre-alloy was first inductively melted in a quartz tube equipped with a nozzle under vacuum and then injected onto a rotating copper wheel by insufflating high-purity Ar. The produced ribbons have thickness around 20-30 µm. On the other hand, the 3D printed cubic samples were obtained by additive manufacturing via Selective Laser Melting using powder of the same alloy as precursor. The effect of changing printing parameters, such as laser power (20-160 W) and scan speed (350-900 mm/s), has been investigated. The processing conditions in the Selective Laser Melting have in fact a crucial role on the microstructure of the printed parts and therefore on their magnetic properties [2,3].

Room temperature quasi-static hysteresis loops of all printed samples and as-cast ribbons were measured by VSM magnetometry. In comparison to the ribbon, the 3D printed cubic samples exhibit lower permeability, higher coercivity, and similar saturation magnetization values, but reached at higher fields. The tuning of these printing parameters has been discussed to maximize the amorphous fraction, control the formation of crystalline phases, and consequently optimize the soft magnetic properties of the final products. This study highlights the critical link between microstructure engineering through manufacturing techniques and the resulting magnetic performance, offering insights into optimizing both for enhanced energy efficiency in electrical applications.

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[1] J. M. Silveyra, E. Ferrara, D. L. Huber, T. C. Monson, Science, 362 (2018), 6413.
[2] L. Thorsson et al. Materials and Design, 215 (2022), 110483.
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Exploring the Incorporation of Recycled Nanocrystalline Powders into Feedstock for 3D Printing of Bonded Nd-Fe-B Magnets

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The recycling of Nd-Fe-B magnets is becoming increasingly significant due to the growing volume of end-of-life magnets and concerns regarding the security of rare earth element supplies. Thus far most efforts have aimed to obtain sintered magnets by reintroducing the end-of-life magnet into the traditional powder metallurgy processing route. Nevertheless, reprocessing means unavoidable pickup of oxygen, leading to a depletion of the Nd-rich phase in the recycled magnet, hindering the densification and the development of proper magnetic properties [1].

Recycling strategies for Nd-Fe-B magnets may be optimized by focusing on the production of bonded magnets rather than sintered ones. In bonded magnets, densification is primarily influenced by the binder , and high coercivity can be achieved by employing nanocrystalline powders produced through grain refinement techniques, such as the hydrogenation-disproportionation-desorption-recombination (HDDR) process [1, 2].

Additive Manufacturing (AM) is an innovative and game-changing approach for utilizing nanocrystalline powders in the fabrication of bonded magnets. It enables the production of net-shape, high-complexity parts and also opens the possibility of aligning magnetic moments during the printing process, which can introduce magnetic anisotropy in the printed devices [2,3].

Therefore, the aim of this work is exploring two methods of incorporating Nd-Fe-B nanocrystalline powders obtained from scrap magnets into PLA (polylactic acid) filaments used in 3D printing via Fused Deposition Modelling (FDM). The volumetric concentration of the magnetic phase in the filaments was assessed by density measurements via Archimedes, vibrating sample magnetometry (VSM), thermogravimetry and SEM cross-section images. The objective was to incorporate the expected volume fraction of magnetic material into the polymeric matrix, as well as to gradually increase the magnetic powder fraction and assess the feedstock printability.

Magnetic load as high as 30% in volume was achieved in the PLA matrix. The obtained bonded magnets via FDM printing have shown increasing remanence as the magnetic phase volume fraction increased in feedstock, as well as a slight coercivity loss of around 10% in relation to the recycled powder, which lies around 750 kA/m. Aging experiments showed that such loss may be related to oxidation of the particles during AM processing.

The successful development of a ready-to-use FDM feedstock for printing complex-shaped bonded magnets has been demonstrated. This advancement not only expands the potential applications of bonded magnets but also alleviates some of the pressures on the rare-earth magnet production chain.

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[2] C. Zhang, Rev. Adv. Funct. Mater. **31** (2021), 2102777.

[3] A. Ahmed, Rev. Polym. J. **228** (2021) 123926.

Design of a Neural Network Method for Assessing Magnetic Losses in Nanocrystalline Transformers

Michele Quercio[a], Vittorio Bertolini[b], Lorenzo Sabino[a], Antonio Faba[b], Francesco Riganti Fulginei[a], Fabio Crescimbini[a], Ermanno Cardelli[b]

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[b] Università degli Studi di Perugia

This study focuses on developing a neural network-based method to accurately assess magnetic losses in nanocrystalline transformers, which are increasingly utilized in modern power distribution systems due to their high efficiency and superior magnetic properties. Nanocrystalline materials, characterized by their ultra-fine grain structures, offer significant advantages, including high magnetic permeability, low coercivity, and reduced core losses. These attributes make them ideal for applications ranging from renewable energy systems to industrial power supplies. However, a precise evaluation of loss parameters, such as hysteresis and eddy current losses, is critical for optimizing the performance and efficiency of these transformers. To address this need, the proposed method employs neural networks, a powerful subset of artificial intelligence capable of modeling complex systems and predicting outcomes based on input data. The neural network system designed in this study is explicitly trained on square waveform inputs, which are instrumental in accurately simulating the operating conditions of transformers. This training regimen allows the neural network to learn and predict the nuanced behaviors of magnetic losses under various conditions. Implementing this neural network approach is expected to provide highly accurate predictions of magnetic losses, thereby facilitating transformer design optimization. The resulting insights can lead to significant improvements in energy efficiency and the operational reliability of power systems. Furthermore, using neural networks represents a forward-thinking approach, integrating advanced machine learning techniques into electrical engineering and materials science. Overall, this research aims to enhance the performance of nanocrystalline transformers and paves the way for broader applications of artificial intelligence in the analysis and optimization of complex material systems.

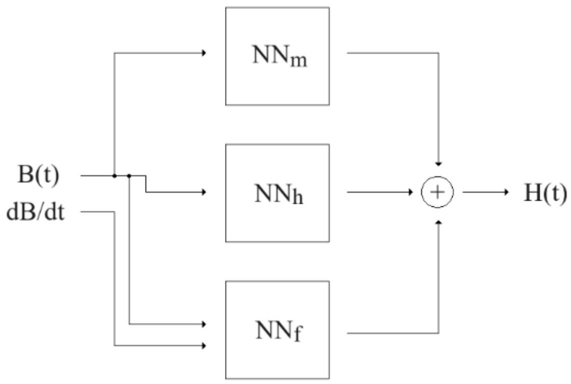

Figure 1. Architecture of the Neural Network

1. Quondam-Antonio, S., Riganti-Fulginei, F., Laudani, A., Lozito, G. M., & Scorretti, R. (2023). Deep neural networks for the efficient simulation of macro-scale hysteresis processes with generic excitation waveforms. *Engineering Applications of Artificial Intelligence*, *121*, 105940.

Machine learning enhanced Kerr Microscopy magnetization pattern recognition

Gabriele Merlino[b], Adriano Di Pietro[a], Alessandro Magni[a], Marco Coïsson[a], Gianfranco Durin[a], Federica Celegato[a], Gajanan Pradhan[a], Gabriele Barrera[a], Michaela Küpferling[a], Paola Tiberto[a]

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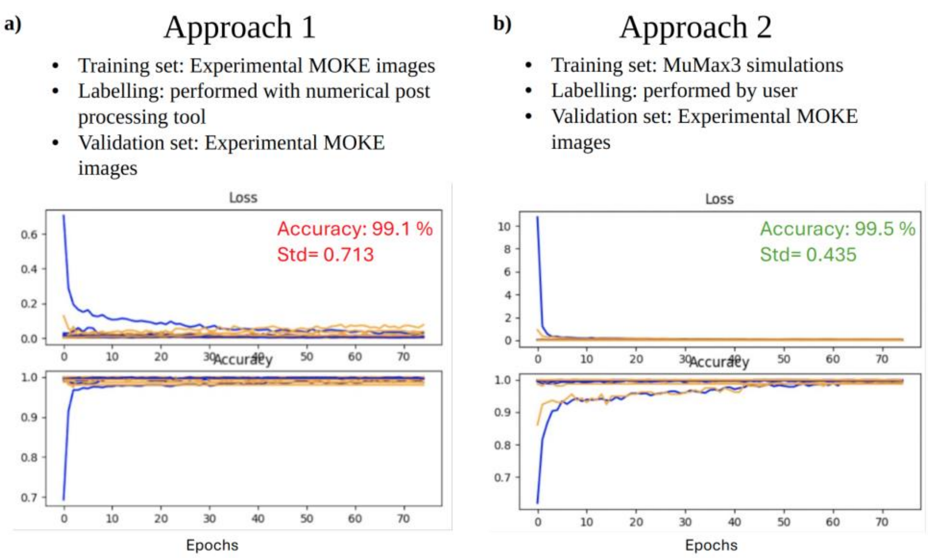
Magneto-optical Kerr microscopy [1] is a widespread technique in today's magnetism research landscape because of its high versatility. While imaging magnetic samples and making qualitative observations can be done with relative ease, obtaining high quality quantitative measurements is situational and often requires a high degree of image post processing. In this work we show how machine learning approaches can be a useful tool in reducing the necessary post processing requirements, while still allowing the user to extract the relevant quantitative physical information from MOKE images. We train a classifier to recognize magnetization patterns in magnetic FeGa microdisks using two different approaches. In the first case, the training set is composed of experimental images whose internal magnetic structure is labelled according to 5 prevalently occurring ground state magnetic textures [2]. The labelling in this case is performed with a numerical post processing tool. In the second case, the training set is composed by a synthetic database obtained through a series of micromagnetic [3] simulations (947) in which the phase space of the different magnetic textures has been explored via different field histories. The labelling of the synthetic database is performed case by case by the user. We demonstrate how the classifier trained with the synthetic database can recognize the MOKE magnetization patterns of the validation set (which are always obtained through experiments) with a higher accuracy and reduced standard deviation (see Fig.1-b) compared to the classifier trained on the experimental images from the beginning (see Fig.1-a). We highlight how the strength of the synthetic database approach lies in the more reliable identification of single and multi-vortex states.



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Physics-Informed Neural Networks for Magnetism

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Physics-Informed Neural Networks (PINNs) are a class of machine learning models that incorporate physical laws directly into their architecture, enabling them to solve complex problems in fields like magnetism. PINNs are part of Physics-Informed Machine Learning (PIML), but are often applied by taking into account specific solutions related to activation functions. Unlike traditional neural networks, which rely purely on data to learn patterns, PINNs, by enforcing physical constraints (e.g., conservation of energy, magnetic flux continuity) within the neural network, ensure that the predictions adhere to known magnetic principles, even when data is sparse. This integration allows them to model magnetic systems more accurately while requiring less data, as the physics itself guides the learning process. Indeed, PINNs mitigate this to compensate for limited data, by using physical laws: for this reason they can be an excellent tool for studying magnetism with fewer data points.

The applications actually are related to the prediction of key material properties, such as coercivity and Curie temperature, by combining both experimental data and physical theory, but also to the optimization of magnetic devices, where PINNs help optimize performance by simulating magnetic fields and interactions in complex geometries.

Clearly PINNs have many advantages, but they also present challenges. Developing accurate models requires expertise in both neural networks and the underlying physics. Additionally, integrating physical knowledge into ML frameworks can be computationally demanding. Probably, as computational power grows and interdisciplinary collaboration increases, PINNs can be expected to become an additional tool for magnetism.

It is important to underline the potential of this approach, but also the importance of such an informed approach compared with traditional data driven ones.

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Advancing Magnetic Refrigeration with Artificial Intelligence

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Abstract :

Various prototypes for magnetic refrigeration have been developed in recent years. However, their optimization continues to present significant challenges. This study introduces a highly effective method, utilizing artificial intelligence, to enhance the cooling performance of multi-layer active magnetic regenerators. To this end a validated numerical model was employed to predict the temperature differential between the hot and cold ends of a four-layer active magnetic regenerator. By simultaneously optimizing ten crucial parameters-such as geometric design and operational conditions, the thermodynamic efficiency of the prototype can be increased by nearly 25%. This new method holds great potential for researchers and engineers, as it allows the optimization of multiple parameters without the need for expensive experimental testing.

Machine learning based prediction of mechanical properties of WC-Co cemented carbides from magnetic data only

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Based on experimental data and extensive experience, magnetic coercivity and saturation moment are traditionally used to estimate the microstructure and quality of cemented carbides, especially in the manufacturing industry. Cemented carbides, also known as hardmetals, are tailor-made according to their tasks by powder metallurgy and find a wide range of applications: metal cutting, mining, machining and metal forming, among others [1]. The most prominent and widespread hardmetal is tungsten carbide (WC) with cobalt (Co) binder and some additives like mixed carbides. Although the quality control draws on a great deal of experience, the magnetic measurements in binary or ternary systems with complex manufacturing processes are often not clearly interpretable.

This work demonstrates that predictions of the structural and mechanical properties of manufactured WC-Co elements can be derived from magnetic data alone using an artificial neural network (ANN). The following observables serve as labels (hyperparameters) in the ANN trainings and are predicted in the output when analyzing unknown samples: Cobalt content by weighing (Co%), the added portion of mixed carbides (XC%), the added portion of doping materials (XD%), transverse rupture strength (TRS), fracture toughness resp. the stress intensity factor (K_{IC}), the equivalent circular diameter resp. mean WC grain size (ECD), and the Vickers hardness (HV30). A collection of WC-Co pellet samples with a wide variety of powder compositions and processing parameters was produced to cover a wide range of characteristic features for the ANN training. The total field distribution, extracted from first-order-reversal-curves (FORC), serves as input data for the ANN. This work shows that microstructural parameters such as mean grain size and mechanical properties such as hardness and fracture toughness (cf. example in figure 1) can be derived from the purely magnetic measurements with high accuracy, while parameters such as additives concentration and transverse rupture strength have large errors and cannot be predicted.

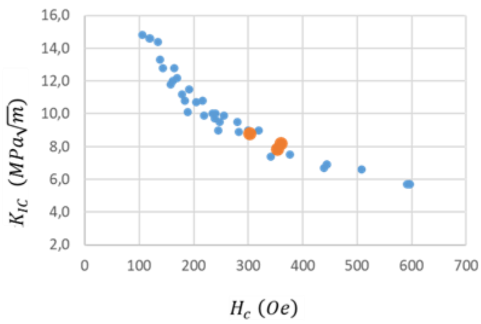

Figure 1: Stress intensity factor K_{IC} vs. coercive field Hc of training samples (blue dots) and three predictions of unknown samples (orange dots)

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Machine Learning-Aided Ab Initio Crystal Structure Prediction of Magnetic Metal-Organic Frameworks

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Magnetic materials play a crucial role in modern technology, with applications ranging from electric engines to data storage systems. Although well-established inorganic magnets, such as those based on rare-earth metals, are widely used, they have limitations in tunability [1]. Enhancing the tunability of magnetic properties can be achieved by adjusting the alignment of magnetic ions within their structures [2].

Metal-organic frameworks (MOFs), which consist of transition metal ions (nodes) linked by organic molecules, present promising opportunities for developing novel magnetic materials. The metal atoms provide magnetic moments, while the organic linkers control the spacing and orientation of the magnetic centers, influencing the material's overall magnetic performance. However, choosing the right combination of metals and linkers to achieve desired magnetic properties is difficult due to the vast number of possible configurations, resulting in polymorphs with varying magnetic behaviours. While experimental testing is possible, it is often time-consuming and labor-intensive.

Our approach for theoretical investigation of magnetic MOFs relies on crystal structure prediction (CSP) using ab initio random structure searching (AIRSS) [3] in combination with Wyckoff Alignment of Molecules (WAM) [4]. AIRSS generates crystal structures by placing metal nodes and organic linkers into trial unit cells, while WAM analyzes the point group symmetry and determines which crystallographic space groups are compatible with the symmetry of individual MOF components. This approach increases efficiency by considering both molecular and crystallographic symmetry. Energy ranking is a critical step in evaluating the experimental feasibility of these generated structures, typically achieved through periodic DFT-U. However, due to the large size of MOFs, such calculations can be computationally demanding. To overcome this, we are utilizing the graph neural network-based MLIP, CHGNet [5]. Initial tests with this pretrained potential on our MOF systems have yielded promising results, showing low RMSE and MAE values for energy (0.38 and 0.34) and magnetic moment (0.08 and 0.04), indicating a good fit of the pretrained machine learning potentials compared to DFT results. We plan to further refine this model specifically for our MOF systems and incorporate it into our CSP workflow. With well-trained ML potentials, we aim to predict both the structures and properties of magnetic MOFs prior to experimental synthesis.

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Novel directions in the search and design of modern materials for sustainable development

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Sustainability in an industry dependent on synthesis of metallic materials requires reliable access to affordable raw materials and improvement of energy efficiency of final products. For instance, development and reduction of synthesis cost of permanent magnets, which are widely used in many areas, are of the great importance nowadays. The best known ones characterized by the highest energy product are based on rare earth elements, such as Sm or Nd, with well-known representatives in $Nd_2Fe_{14}B$, Sm_2Co_{17} or $Sm_2Fe_{17}N_3$. The range of new compositions (*e.g.* $Hf_2Co_{11}B$, MnBi, $Mn_{50}Bi_{49}Pd$) and possible applications is broad and still growing. With the development of new phases and the improvement of intrinsic and extrinsic properties [1, 2], permanent magnets are still implemented in a rather trivial way, as a replacement of electromagnets, in loudspeakers and actuators, but also find more sophisticated applications in magnetic resonance imaging, in information storage devices, magnetic levitation, as bearings, or as miniaturized magnetic field sensors.

Current research driven by a strong demand for magnetic cooling as an environmentally friendly and efficient technology, focuses on such systems as amorphous and nanostructured bulk materials, as well as thin films, multilayers, and quantum dots. The solutions based on these systems are also realizations of the idea of energy harvesting associated with the search for new methods for efficient energy production and cooling or heating processes. There has been great interest in new high performance magnetocaloric materials characterized by high magnetic entropy and adiabatic temperature changes. Usually, the refrigeration capacity of soft magnetic amorphous materials is much higher than that of their crystalline counterparts. Although the values of entropy changes at the transition temperature for amorphous materials are lower than those of crystalline systems, a higher refrigeration capacity and excellent mechanical properties still make them attractive candidates for further studies as candidates for magnetic refrigeration systems [3].

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Micromagnetic and reduced-order model simulations of microstructural defects in recycled $Nd_2Fe_{14}B$ magnets

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Demagnetizing effects due to nonmagnetic pores and triple junctions, the presence of oxides at grain surfaces, or imperfect grain boundaries (gb) causing exchange coupling between misaligned grains are some of the effects that reduce the performance of recycled $Nd_2Fe_{14}B$ magnets. We used micromagnetic energy minimization [1] and a reduced-order model [2] to estimate the impact of gb phases and imperfections on the coercivity of magnets with an average grain size of 7 µm. The model size for micromagnetic simulations using the finite element (FE) method is limited to grain sizes of a few hundred nanometers due to the computational capabilities. The accurate computation of microstructural features like gb or surface defects requires a nanometer-scale resolution of the FE mesh. To treat micrometer-sized models, we applied a two-step approach. We computed the reduction of the switching field with respect to the Stoner-Wohlfarth (SW) model using FE micromagnetic simulations on simplified models. Those results together with analytic and literature values defined a map of local switching fields close to the grain surfaces. The reduced-order model is capable of computing an effective demagnetization field of a magnet consisting of hundreds of micrometer-sized grains within an applied external field. It computes the demagnetization curve by comparing the total effective field against the local switching fields.

Fig. 1a) shows that only strong misalignment (>45°) between exchange-coupled grains reduces the switching field significantly with respect to the SW model. Fig. 1b) shows that a higher degree of texture (DOT) improves coercivity by 32%-42% but the effect reduces to

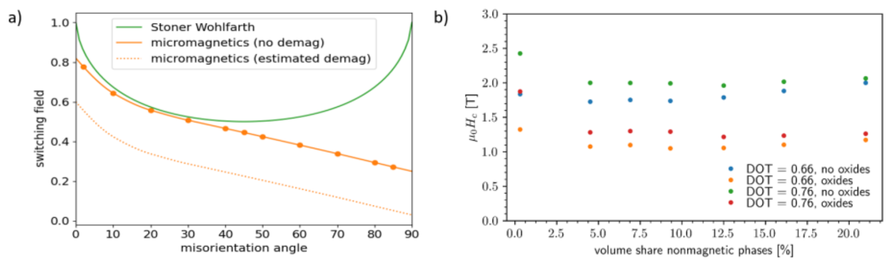

Figure 1: a) Switching field (normed by the anisotropy field) of two exchange-coupled and misaligned grains. b) Coercivity of a 60x60x60 µm³ magnet with 650 grains and different DOT, with or without oxides at grain surfaces. Volume share of the 8 nm thick nonmagnetic gb: 0.3%, rest is due to pores/triple junctions.

less than +12% when the volume share of nonmagnetic phases is >16%. The absence of oxides improves coercivity by 29%-71%, more pronounced when triple junctions are present. The amount of pores/triple junction (>4.5%) has limited influence.

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Micromagnetic modeling of Ni_2MnGa thin films

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Magnetic shape memory compounds are among the most promising classes of materials for multiple-stimuli actuation and energy harvesting, thanks to the multifunctionality arising from their distinctive magnetostructural transformation. Ni_2MnGa is a model system within this class of compounds; it shows a martensitic phase transformation from a cubic phase (austenite) to a lower symmetry phase (martensite) by decreasing temperature. We grow Ni-Mn-Ga films with thickness up to 400 nm by sputtering on MgO(100) or Cr/MgO(100). The $L2_1$ austenitic phase grows epitaxial at high temperature and transforms to the 7M monoclinic martensitic phase when samples are cooled down to room temperature. The martensitic phase shows a complex twin microstructure, with characteristics that we can engineer by growth parameters, external stimuli (temperature, magnetic field, stress) and patterning on the micron and nanometer scale [1 and references therein]. Each twin microstructure imposes a specific geometrical arrangement of the easy-magnetization axes, giving rise to distinctive magnetization patterns and magnetization processes. Consequently, Ni-Mn-Ga films display a unique versatility of the magnetic properties, which can be modified by choosing a specific twin microstructure (X- or Y-type), combining the two microstructures, or modifying their spatial arrangement on the scale of tens of microns. Each twin microstructure also shows characteristic magnetothermal properties, i.e., thermal hysteresis and sharpness, which can be improved by choosing a specific microstructure (Fig. 1).

The support of a micromagnetic model, built on the film microstructure and experimental characteristics, has been essential for interpreting the magnetic behaviour of films with Y-type microstructure [2]. We will here show the most recent results obtained by applying the micromagnetic model to films with X-type microstructure, considering the effect of film thickness, variable twin size and different kinds of interfaces (conjugation and non-conjugation interfaces, ref. 3).

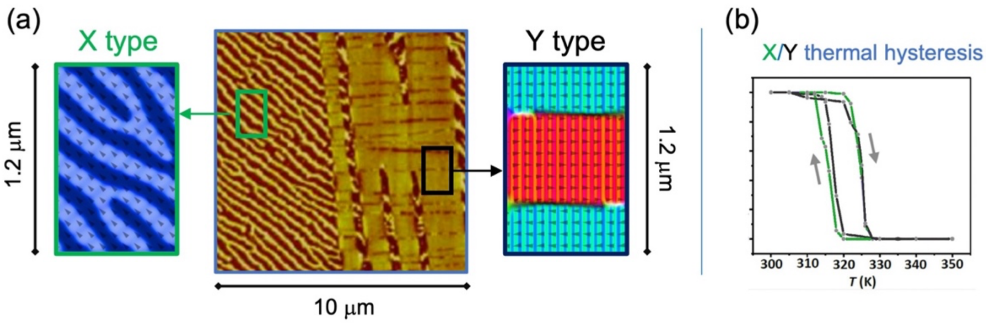

Figure 1: a) MFM image of a Ni-Mn-Ga film and corresponding micromagnetic configurations of X/Y microstructures; b) thermal hysteresis of X/Y microstructures across the martensitic transformation

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Aerobic ethanol oxidation by magnetic inductive heating of palladium on nickel foam

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The heterogeneous aerobic oxidation of bio-derived ethanol to acetic acid is an important chemical transformation and a valuable alternative to the industrially applied production. Supported palladium nanoparticles are suitable for the aerobic ethanol oxidation in water [1]. We present an alternative mode to carry out the aerobic ethanol oxidation with palladium by exploiting the magnetic induced heating of nickel. In order to increase the nickel surface, which is mandatory for the interaction with the magnetic field but also crucial for the dispersion of palladium nanoparticles on it, we used nickel foam as a cheap magnetically active support material (Figure 1). Palladium was supported by applying two different synthesis strategies: (*i*) Spray coating of the previously surface-oxidized Ni foam with a colloidal Pd acetone solution generated by metal vapour synthesis technique [2]; (*ii*) Electrodeposition of palladium directly on nickel, without the presence of a nickel oxide layer. Preliminary catalytic reaction with both types of heterogeneous palladium-based catalysts carried out under magnetically induced heating of the nickel foam showed the formation of acetic acid with high selectivity (> 85%). In addition, both types of catalysts revealed to be stable against nanoparticle leaching into the water solution. The catalytic activity of both types of heterogeneous palladium-based catalysts for the aerobic ethanol oxidation was screened by varying the palladium content and the power of the magnetic field used. Several recycling experiments for each catalyst were conducted, along with an inductive coupled plasma analysis of each water solution after catalysis to prove the stability of the heterogeneous catalyst. For comparison reason, both types of catalysts were used to catalyze the same reaction by using a traditional electrical heating.

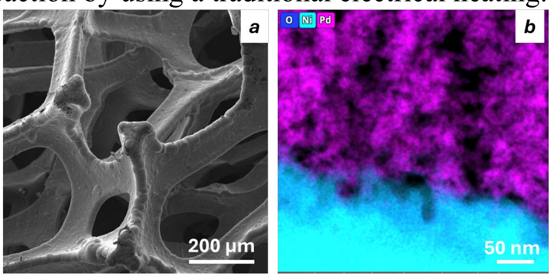

Figure 1: a) SEM image of Ni/NiO foam and b) EDX map of Ni/NiO/Pd lamella

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Evaluating the Effect of Surface Treatment on Powder Particles in Soft Magnetic Composites

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Soft magnetic materials exhibit interesting characteristics like low coercivity and total energy losses and high permeability. Progressive and modern material research indicates a constant expansion of the achievable range of magnetic properties in soft magnetic materials. Compacted soft magnetic materials, prepared by the compaction of powder, find application in diverse electromagnetic scenarios.

Soft magnetic composites are the fast-growing subgroup of soft magnetic materials requiring relatively low investments for their production. In most cases, these materials are made from ferromagnetic powders milled in different types of mills under different conditions. One of other ways to improve the properties of both powder and compacted materials can be an innovative method of modifying powder particles significantly affecting magnetization processes in compacted material prepared from surface modified powders particles. After this process the milled and surface modified powders could be coated with an organic, inorganic, or organic-inorganic coating to reduce eddy current losses.

The aim of the work was to investigate how the preparation process affects the magnetic properties of soft magnetic composites. We assume that the positive effect of smoothing process is that surface irregularities hindering the displacement of the domain walls will be partially removed. The negative in-fluence can be occurred by introducing structural defects into the surfaces of thin layers by mechanical processing and it can negatively influence the domain wall displacement.

Two samples of soft magnetic compacted composites were prepared for further investigation. Fe powders were mechanically milled in planetary ball mill Retch PM100 at room temperature for 3 hours with ball to powder ratio 9:1 and the rate per minute was 300. The first sample was prepared by the compaction of powder prepared in the press by uniaxial pressure of 700 MPa at the temperature of 410 °C for 5 minutes. The second sample was prepared by the compaction at the same conditions, but the surfaces of powdered particles were smoothed before the compaction. Before compaction of powders, we used SiO_2 coating employing the Stöber method, as it allows uniform particle coverage.

The detailed understanding of the magnetization processes that take place in these small powder particles interacting with other surrounding particles by a magnetic field can offer further feed-back leading to the next improvement the soft magnetic properties of resulting compacts.

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Investigating magnetocaloric properties and Heisenberg exchange interactions in $NdMnO_3$ perovskite: A computational study

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In this study, we investigate the magnetic characteristics and magnetocaloric effect of $NdMnO_3$ perovskite [1] in order to comprehend its potential applications in magnetic refrigeration and spintronics. We analyse the electrical density of states and band structure of this perovskite utilising density functional theory (DFT) calculations [2] with generalised gradient approximation, revealing its behaviour as a ferromagnetic half-metal and anti-ferromagnetic semiconductor material. Following that, using Monte Carlo simulations based on the Heisenberg model with nearest and next-nearest neighbour interactions, we investigate various magnetic parameters including magnetization, susceptibility, specific heat, internal energy and the Curie temperature (T_C). This helps to establish the thermal magnetic entropy profiles with temperature and external magnetic field for the material, and hence quantify the adiabatic temperature change. We also investigate the subtle interplay between crystal field effects and exchange interactions [3] involving Mn-Mn, Nd-Nd, and Nd-Mn magnetic atoms. Additionally, we examine the relative cooling power (RCP) across different magnetic field strengths, shedding light on the magnetocaloric potential of $NdMnO_3$ under various conditions.

The collective insights obtained from our computational study shows $NdMnO_3$ perovskite as a viable option for use in spintronics and magnetic refrigeration. We underline the significance of magnetic anisotropy in determining the magnetocaloric behaviour of this material, opening the door for the development and enhancement of effective cooling systems based on perovskite oxides.

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Pursuing optimal magnetic properties of recycled $SrFe_9O_{12}$ through magnetic ordering quenching

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The growing emphasis on the green transition has boosted the demand for permanent magnets (PMs) which are essential for green energy technologies and mobility transition. The best-performing PMs rely on rare earth elements (REEs), which, despite their superior performance over ferrite-based magnets, face many challenges, such as price volatility, supply risk and significant harmful environmental impact [1]. A good alternative for replacing the REE PMs, at least partially, is strontium hexaferrite (SFO). SFO is already one of the most commercially used ferrite PM [2, 3].

Despite significant activity in this field, research is still ongoing to surpass the highest BH_{max} of commercially available sintered SFO magnets. Not only the sintering temperature and time but also the cooling regime can affect the magnetic properties. The cooling rate from high temperatures can change the cation distribution in ferrites, modifying the room-temperature phase distribution, microstructure, and, finally, magnetic properties [4].

In pursuit of obtaining the best magnetic properties of SFO by means of the highest coercivity (H_C), commercial SFO powders pressed into the pellets were consolidated at temperatures ranging from 900 -1050 °C and then cooled naturally, or quenched in H_2O or in liquid nitrogen. The composition, microstructure and magnetic properties were thoroughly analysed. In light of the sustainability agenda, we also prepared magnets from recycled SFO powders (outsourced from the Kolektor d.o.o. company) using the same protocols. This allowed us to determine if the recycled powders retain magnetic properties and, thus, if they are appropriate for further reuse.

Acknowledgements:
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Effect of duration of particles dry coating process on magnetic properties of Fe@Al_2O_3 soft magnetic composites

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Soft magnetic composites (SMCs) attract the attention, because they possess the combination of properties that the traditionally used ferromagnetic materials do not [1]. Due to high electrical resistivity, they offer low power losses at higher frequencies, and relatively high permeability. They find use in many applications such as generators, inductors, transformers, sensors or electromotors SMCs are composed of at least two components: the first component consists of ferromagnetic materials, most often based on iron, and the second inorganic dielectrics providing isolation of the particles to prevent the flow of eddy currents between the particles [2].

The aim of the work was to investigate the effect of the duration of Al_2O_3 dry coating by mechanofusion method on Fe particles with a size of 125-200 µm on magnetic properties as core losses and complex permeability of SMCs.

Two series of samples differing from each other by dry coating time (15 minutes and 30 minutes) and samples in each series differs from each other by the amount of the weight percentage of Al_2O_3 powder in powder mixture (2%, 5%, 10% and 15%) were prepared and investigated.

The EDX mapping shows, that 30-minute coating process does not result to better coating that 15-minute coating.

The longer dry coating process leads to deterioration of the magnetic properties of SMCs for any amount of used Al_2O_3 powder. On the other hand, the shorter dry coating time can lead to improvement of magnetic properties of samples. The optimum weight percentage of Al_2O_3 content for dry coating process with duration of 15 minutes is around 5 % - 10 %, because of the lowest loss and the highest permeability.

This work was realized within the frame of the project “FUCO” financed by Slovak Research and Development Agency under the contract APVV-20-0072 and by Scientific Grant Agency of Ministry of Education of Slovak Republic and Slovak Academy of Sciences – projects VEGA 1/0016/24, 1/0403/23 and 1/0132/24.

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Simulating the impact of materials' properties on the active magnetocaloric regenerator

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Magnetocaloric materials are the enabling components of magnetic refrigeration, an emerging cooling technology that promises lower environmental impact and better sustainability than conventional vapour compressor based refrigeration. Although being actively studied for a couple of decades now, still no commercial products are currently available: additional effort is required in order to improve both the materials properties and the implementation of their magnetocaloric effect (MCE) in cooling devices

We performed finite element simulations of a magnetic refrigeration system operating with the active magnetic regenerator principle. The model consists of a parallel plates' regenerator, hot and cold heat exchangers, and a working fluid to transport heat. It uses experimental measurements of ΔT (H,T) and c (H,T) as an input to account for the MCE, and provides as output the temperature span and cooling power, as well as the pressure difference and field fluid velocity of the heat exchange fluid.

We evaluated into the model several materials showing different magnetocaloric properties: gadolinium with conventional MCE as a benchmark; NiMnIn based Heusler compounds with either conventional MCE at the austenitic curie point or with inverse MCE at the martensitic transformation. Furthermore, we considered also a specific composition of NiMnIn showing cooccurrence of both direct and inverse MCE: the impact on the heat pump performances of the operational parameters such as magnetic field distribution and temperature profile on the regenerator have been assessed.

The results indicate that gadolinium, which is endowed with the best intrinsic magnetocaloric figures of the materials here compared, also performs better than the Hesuler compounds in terms of temperature span and cooling capacity. On the other hand, some of the Heulser compounds which demonstrated inferior results in terms of temperature span, yet showed a better coefficient of performance. This suggests that further modifications to the operative conditions should be performed on the model, with the purpose of finding the optimal working conditions for every magnetocaloric material studied.

reynolds number in electrodynamics

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ABSTRACT

In this work:

- the electric charge definition is formulated;
- the refined formula of the electric charge non-invariance is given;
- the concept of "the charged particle spin" is clarified;
- the electric charge momentum conservation law is obtained;
- the angular momentum conservation law for electric charge is obtained;
- the formula for the kinetic energy of the translational motion of an electric charge is constructed;
- Steiner's theorem for electrodynamics is formulated;
- the rotational motion dynamics equation is constructed for electric charge;
- the formula for the kinetic energy of the rotational motion of an electric charge is constructed;
- a Planck's formula analog for the magnetic field was obtained;
- another kind of uncertainty relation was obtained;
- formula for the interval between two events is constructed in the electric charge space;
- a Reynolds number analog for electromagnetism is obtained;
- the experiments results on finding the Reynolds number in electrodynamics are given.

Key words: *the electric charge non-invariance, the angular momentum of electric charge, the kinetic energy of the rotational motion of an electric charge, a Planck's formula for the magnetic field, a Reynolds number in electrodynamics.*

topography-driven pathways to enhance extraordinary magnetoresistive device performance

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Magnetoresistive magnetic sensors play a crucial role in sensing magnetic fields, with applications spanning from information storage to biomagnetism. Extraordinary magnetoresistive (EMR) sensors are a promising class of magnetoresistive sensors, exhibiting a magnetoresistance of 7.5×10^{5} % at 4 T [1] at room temperature. The EMR is a geometrical effect resulting from a field-dependent alteration in the current paths within devices composed of two materials with differing conductivities. Most EMR devices use a concentric circular geometry, with a metal circle placed within a semiconductor circle. However, this design is difficult to achieve experimentally despite being easily modeled with finite element simulations that show good agreement with experimental data [1].

In this numerical study, we extend traditionally 2-D modeled concentric circular EMR devices into the third dimension. With a 3-dimensional COMSOL model, we investigate the impact of topography on device performance by varying parameters such as the height and sidewall width of the metal contact, as these topographical changes are often realistic in sensor production. We show that the thickness of the metal shunt directly impacts device performance and can be optimized to further enhance its performance. Furthermore, we demonstrate that devices with embedded metal shunts can be outperformed by top-contacted devices, which are simpler to fabricate by directly depositing metal onto the semiconductor. Finally, utilizing the insights from this study, we reduced the relative error between the numerical simulations and the experimental data from a traditionally achieved 35.8 % to 4.5 %.

Acknowledgements: We acknowledge the support of Novo Nordisk Foundation Challenge Programme 2021: Smart nanomaterials for application in life-science, BIOMAG Grant NNF21OC0066526.

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Thermal hysteresis in Ho thin films - experimental results and modeling

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We present the results of theoretical modeling and experimental studies of thermal hysteresis in holmium (Ho) thin films with a thickness of 200 nm at applied magnetic fields of 100 Oe, 1 kOe, and 10 kOe. The isofield magnetization curves, measured at 100 Oe and 1 kOe do not exhibit hysteresis during the heating and cooling processes. In contrast, M(T) measured at 10 kOe shows significant differences between the heating and cooling processes. The thermal hysteresis width covers almost the entire range between the Curie temperature and Néel temperature and is controlled by the external magnetic field. The peculiarities of the magnetic phase diagram of thin films in comparison with the bulk samples of Ho are also discussed.

The MagneDyn beamline at the FERMI free electron laser

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The scope of this communication is to outline the main marks and performances of the MagneDyn beamline [1] at the Free Electron Laser FERMI which was designed and built to perform ultrafast magnetodynamic studies in solids. Open to users since 2019, MagneDyn operates with variable circular and linear polarized femtosecond pulses delivered by the externally laser-seeded FERMI free-electron laser (FEL). The very high degree of polarization, the high pulse-to-pulse stability, and the photon energy tunability in the 50-300 eV range allow to perform advanced time-resolved magnetic dichroic experiments at the K-edge of light elements, e.g. carbon and at the M- and N-edge of the 3d-transition-metals and rare earth elements, respectively. To this end two experimental end-stations are available. The first is equipped with an in-situ dedicated electromagnet, a cryostat, and an extreme ultraviolet (EUV) Wollaston-like polarimeter[2,3]. The second, designed for carry-in users instruments, hosts also a spectrometer for pump-probe resonant X-ray emission and inelastic spectroscopy experiments with a sub-eV energy resolution. A pump laser setup, synchronized with the FEL-laser seeding system, delivers sub-picosecond pulses with photon energies ranging from the mid-IR to near-UV for optical pump-FEL probe experiments with a minimal pump-probe jitter of few femtoseconds. The overall combination of these features renders MagneDyn a unique state-of-the-art tool for studying ultrafast magnetic phenomena in solids.

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Effects of air annealing on magnetic and structural properties of $Co_{0.25}Fe_{0.75}Fe_2O_4$ nanoparticles: a potential approach for fine-tuning the magnetic properties

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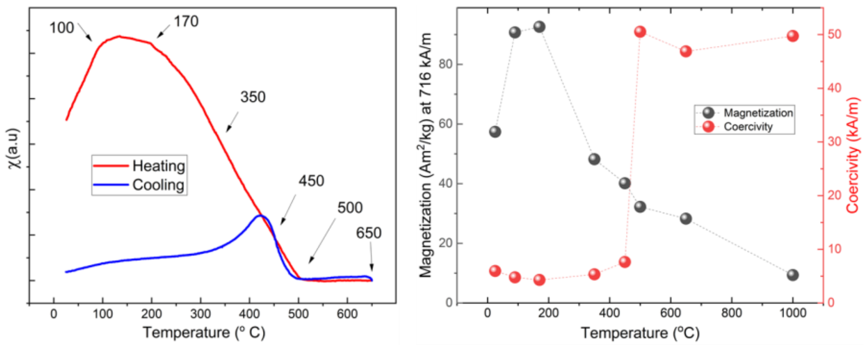
It is well-known that the cation distribution in cobalt ferrite can be significantly affected by various parameters such as cobalt content, synthesis method, and heat treatment [1]. Heat treatment can be applied either during the synthesis or as a post-synthesis procedure. The temperature dependence of the susceptibility is one of common methods for determining the Curie temperature. In such measurements, in both soft and hard magnetic materials, the initial susceptibility is often seen to exhibit a sharp maximum (known as Hopkinson effect) slightly before the Cuire temperature. However, this peak may be broadened due to non-homogeneity or cation redistribution in the sample.

In this work, we synthesized $Co_{0.25}Fe_{0.75}Fe_2O_4$ nanoparticles using coprecipitation. Based on the $\chi(T)$ measurement of the as-synthesized sample, a three-hour air annealing was conducted on the sample at different temperatures. Then the samples were allowed to cool down to room temperature. The $\chi(T)$ measurement of the annealed samples indicated magnetic/structural stability. In addition, the room temperature magnetization curves suggested a great potential for controlled tuning of the magnetic properties, i.e. room temperature magnetization, coercivity, and squareness of the sample, using this approach. This control over magnetization and coercivity could be particularly useful in applications such as magnetic hyperthermia, where a high saturation magnetization and a moderate effective anisotropy are advantageous. Moreover, X-ray diffraction analysis showed a considerable enhancement in phase transition of the samples at high temperatures compared to pure magnetite nanoparticles.



$\chi(T)$ measurements of the as-synthesized sample, the chosen annealing temperatures, and room temperature magnetization and coercivity of the samples

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Magneto-polymer supraparticles for rapid and reliable identification tags using Magnetic Particle Spectroscopy

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Things are perpetually linked to each other and to people via Internet, leading to a global exchange of information (i.e. Internet of Things), favouring the development of advanced multidisciplinary capabilities and shaping our daily, working and social lives.

Conventional physical objects, which generally neither generate digital data nor communicate, are being brought into the digital world through tags that generate an easily readable and unique identification code such as barcodes, radio frequency identification (RFID) codes and quick response (QR) codes. In this context, nanotechnology is favouring the realization of innovative tags capable of tracking, identifying, and encrypting information.

In this work, magneto-polymeric supraparticles have been proposed as unique magnetic fingerprints readable by magnetic particle spectroscopy (MPS) technique.

Supraparticles, prepared by an oil-in-water emulsion solvent evaporation method, consist of magnetic nanoparticles (MNPs) of selected composition (e.g. Fe_3O_4, $NiFe_2O_4$, $MnFe_2O_4$) embedded in a polymer matrix (e.g. PLA, PS, PBAT, PHBH) forming a magnetic polymer nanocomposite.

Microscopic characterisation shows that the superparticles are spherical in shape for all samples although some peculiar morphological features depend on the polymer used in the synthesis. The size distribution is centred around 50 μm.

The room-temperature DC hysteresis loops show a hysteretic behaviour with values of the coercive field and saturation magnetization strictly related to the compositional properties of the MNPs and to their concentration in the polymer matrix (see Figure 1A).

MPS measurements were performed to acquire the harmonic spectra of the magnetic signal arising from the magneto-polymeric supraparticles using a high-frequency hysteresis loop tracer (operating in a sinusoidal alternating magnetic field with H = 0-160 Oe and a f = 1-10 kHz) combined with a spectrum analyzer.

It is shown that the harmonic spectrum results in a complex fingerprint capable of encoding a large number of individual codes due to its superior sensitivity to small variations in the magnetic properties of the MNPs hierarchically assembled into supraparticles, see Figure 1B.

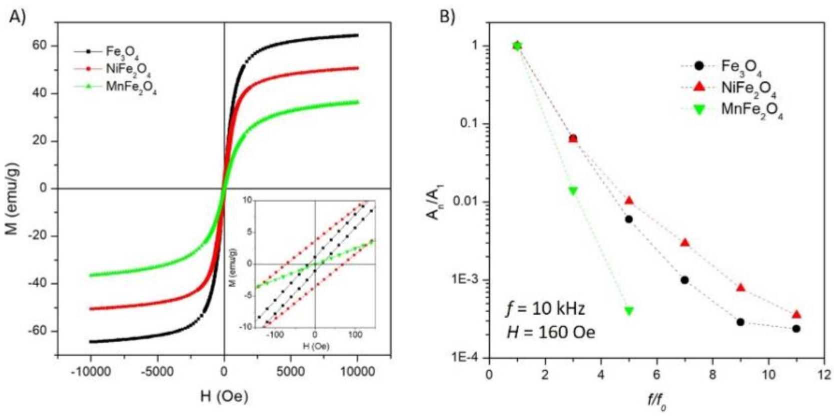

Figure 1 : A) DC hysteresis loops of Fe_3O_4, $NiFe_2O_4$, $MnFe_2O_4$ MNPs; B) corresponding harmonic spectrum at f = 10 kHz

Urea catalysis by electrodeposited Ni nanostructures

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The use of silicon nanostructured templates combined with magnetic filling materials for the achievement of anisotropic morphologies has been recently investigated, resulting in a variety of applications as magneto-optical devices [1], perpendicular media for high density data storage [2], sensors in nanobiology [3].

Among the rising environmental applications, it would be advantageous to treat urea contained in urine at the source to reduce the energy cost and the environmental impact of biological nitrogen removal in wastewater treatment plants. In this perspective, nanostructured silicon templates have been electrodeposited with nickel as catalyst and tested for urea electrocatalytic oxidation.

In this work, N+ silicon substrates 14-16 mOhm cm have been anodised in an ethanol and hydrofluoric acid solution to obtain anisotropic dendritic nanopores with diameters ranging from 20 to 40 nanometers in diameter and a few micrometers in depth (see Fig. 1a). The pores have been filled by electrodeposition of nickel (SEM image in Fig. 1b). Room-temperature hysteresis curves have been measured by ultra-sensitive magnetometry (alternating gradient force magnetometer, AGFM) with magnetic field H applied in the parallel (black line) and perpendicular direction (red line) with respect to the substrate as shown in Fig. 1c. Ni is also a very versatile catalyst [4], whose catalytic activity is linearly dependent on the number of active Ni site. The Ni catalytic activity of electrodeposited Ni has been measured by Cyclic Voltammetry and the response is reported in Fig. 1d revealing high efficacy for urea electrocatalytic oxidation (red curve).

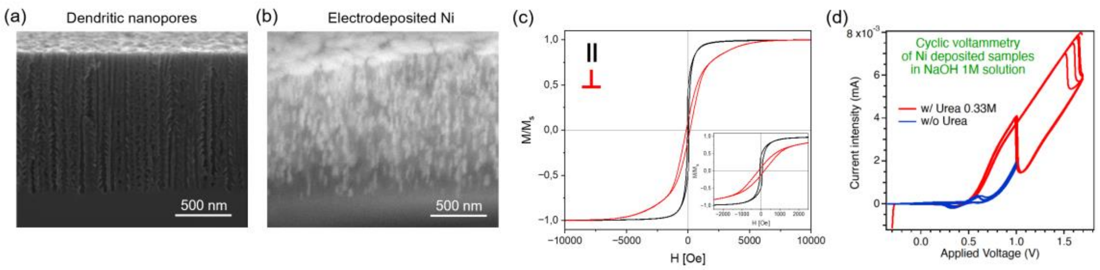

Figure 1: (a) SEM cross-section of silicon dendritic nanopores array. (b) SEM cross-section of electrodeposited nickel inside silicon dendritic nanopores and (c) relative hysteresis loops in parallel and perpendicular configurations. (d) Cyclic Voltammetry of NaOH 1M solution with and without urea 0.33M of nanostructured Si template electrodeposited with Ni.

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a novel laser imaging method for real-time inspection of high-speed rails

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With the massive construction and increasing speed of high-speed railways around the world, the integrity of steel rails, which is an important infrastructure of the railway network, is particularly important. In recent years, non-contact non-destructive testing methods have been widely used in in-service rail inspection, such as ultrasonic, eddy current and machine vision technology (see Fig.1 laser line vision). At present, the maximum speed of the rail inspection vehicle reaches 120km/h [1], but it still cannot meet the requirements of non-stop online inspection of high-speed trains (speed of 250-350km/h).

In order to be suitable for the real-time online detection of high-speed train operating speed (>300km/h), we propose an imaging method consisting of line laser and line scan camera. It reconstructs the three-dimensional characteristics of the surface by acquiring and analysing the intensity of the reflection of the analyte on the laser strip (see fig.2 for the schematic diagram). Compared with the traditional laser profile measurement [2], we use line scan camera instead of area scan camera. Because of no redundant data, the measurement speed is greatly improved. At the meantime, there is no need to extract the centre line, which not only avoids the error of the algorithm, but also improves the real-time data processing efficiency again. Furthermore, this method can be generalized to other planar measurements with small undulations or defects. It will provide a quick and precise measurement of micro-dimensions and surface defects for what is now known as 2.5D objects.

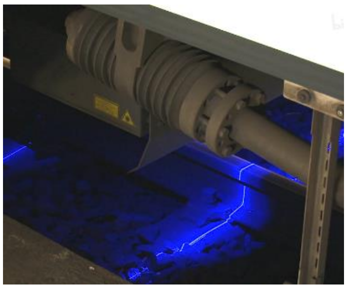

Figure 1: laser line detection

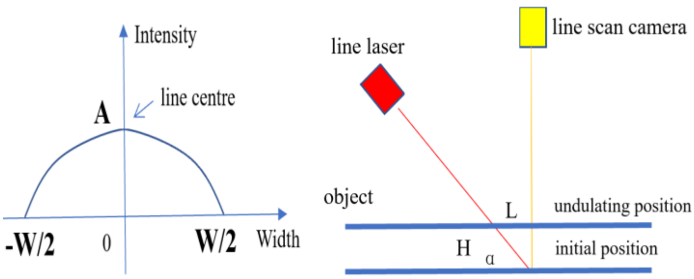

Figure 2: Left: intensity distribution of a laser line
Right: schematic of line-scan laser measurement system

However, the method also has some limitations and aspects that require further research. For example, the height of the undulation that can be detected is relatively small (about ±1mm). Whether the change in intensity of laser line is stand for surface undulation or stain (it may cause reflectance change) needs to be extra determined. Detection performance in rain, snow, fog and other weathers requires further research.

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Multi-DoF 3D printed spherical electromagnetic actuator

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Additive Manufacturing (AM) is a layer-by-layer material addition technology used to fabricate desired parts with different shapes and dimensions. Recently, there has been a growing interest in the field of AM as it has emerged as an alternative manufacturing process, offering virtually unlimited potential for a wide range of industrial and special-purpose applications, such as electrical actuators. Combining 3D printing technology with electromagnetic design is an opportunity to reimagine the architecture, performance, and manufacturability of these devices.

In this framework, the AM technique can be exploited to manufacture a spherical induction actuator with 3 Degrees of Freedom (DoF). Considering different configurations and designs, such a device could be effectively used in robotics to actuate knees and elbows, propellers of drones or wind turbines, and industrial joysticks for forklifts or heavy-duty cranes. However, considering only conventional productive operations, its structure inherently complicates the manufacturing process.

The analyzed geometry is ASFER, a spherical induction actuator (Figure 1). It consists of a properly laminated stator with a set of windings able to produce rotation with respect to three axes. The rotor is made of a concentric double-layer hollow sphere, composed of inner solid ferromagnetic material and a conductive (copper) sheet outside [1].

Its analysis is based on the Finite Element (FE) simulation of the device's 3D model. The actuator performances are investigated through the parameterization of the geometry.

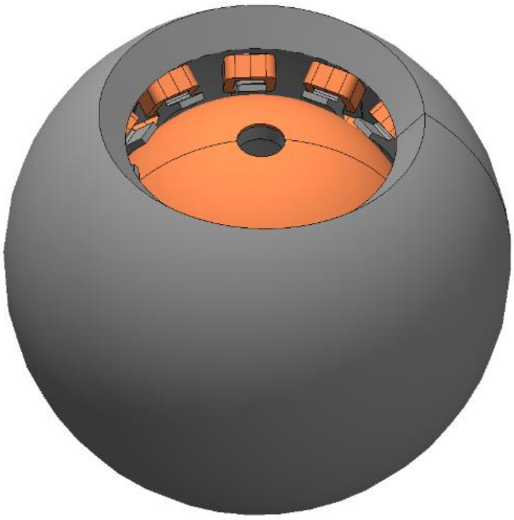

Figure 1: a) prototype of ASFER actuator.

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Halbach Array Design for Axial Flux Wind Generators

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This study introduces an innovative design for a 150 kVA direct-drive wind turbine, operating at 90 rpm on a horizontal axis. The turbine employs an Axial Flux Permanent Magnet (AFPM) configuration, utilizing the Yokeless and Segmented Armature (YASA) topology. This topology is distinguished by its compact form factor and high-efficiency power transmission, a feature particularly advantageous in direct-drive systems as it eliminates the need for a gearbox in variable-speed operations [1]. However, a significant challenge in such designs arises from the use of high-performance materials, particularly rare-earth permanent magnets (PMs) like samarium and neodymium. The superior magnetic properties offered by these materials are counterbalanced by their high costs and associated environmental and social challenges. The extraction and refining of rare earth elements involve hazardous processes, imposing significant risks to ecosystems and human health, with a negligible recycling rate of approximately 1%. Consequently, there is an objective to investigate design strategies that could reduce the dependence on rare-earth PMs, with the possibility of integrating alternative, less efficient materials.

One potential solution to mitigate the use of rare earth materials is the implementation of segmented Halbach arrays. These arrays are a magnet configuration in which the magnetic field is enhanced on one side of the array while being minimized, ideally to zero, on the opposite side [2]. To optimize such designs and minimize the use of high-performance materials, a detailed sensitivity analysis is essential. However, the computational burden of such analyses, particularly when using traditional 3D finite element method (FEM) simulations, is prohibitively high. Thus, a quasi-3D modelling approach, based on two-dimensional simulations of segmented Halbach arrays, is necessary [3]. This method allows for the optimization of electromagnetic performance while significantly reducing computational demands without compromising accuracy in terms of torque generation.

The final validation of the most promising design solutions demonstrates high accuracy with substantially reduced computational time compared to traditional 3D FEM methods. Additionally, the study highlights the potential for significant cost savings and reduced reliance on high-performance materials in YASA AFPM designs. This approach aligns with principles of sustainability and the circular economy, marking an important step forward in the development of environmentally responsible wind turbine technology.

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Comparative Analysis of Field-Oriented Control and Sliding Mode Control for Linear Induction Machine

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This research aims to optimize the performance of a 3.5 kW Linear Induction Machine (LIM) by refining the traditional Field-Oriented Control (FOC) approach. The conventional FOC works on the control of torque and Flux on real-time feedback of motor current but the response time of FOC is slower in terms of dynamic requirements, when the speed or load varies abruptly [1], In order to make the motor more stable and independent of load and speed variation by internal or external disturbances, a flux observer with SMC is introduced in LIM. The improvement involves incorporating a Flux Observer and Sliding Mode Control (SMC) into the system[2]. The Flux Observer guarantees more precise flux estimation [3], which helps to achieve better regulation of torque and flux control, while SMC is introduced in the speed control loop to enable fast reaching towards the desired speed. Together, these improvements not only speed up the motor's response but also optimize its ability to handle abrupt changes in load and speed, making it more robust compared to the conventional FOC method. A MATLAB simulation confirms these improvements, demonstrating faster speed tracking and better performance under varying conditions.

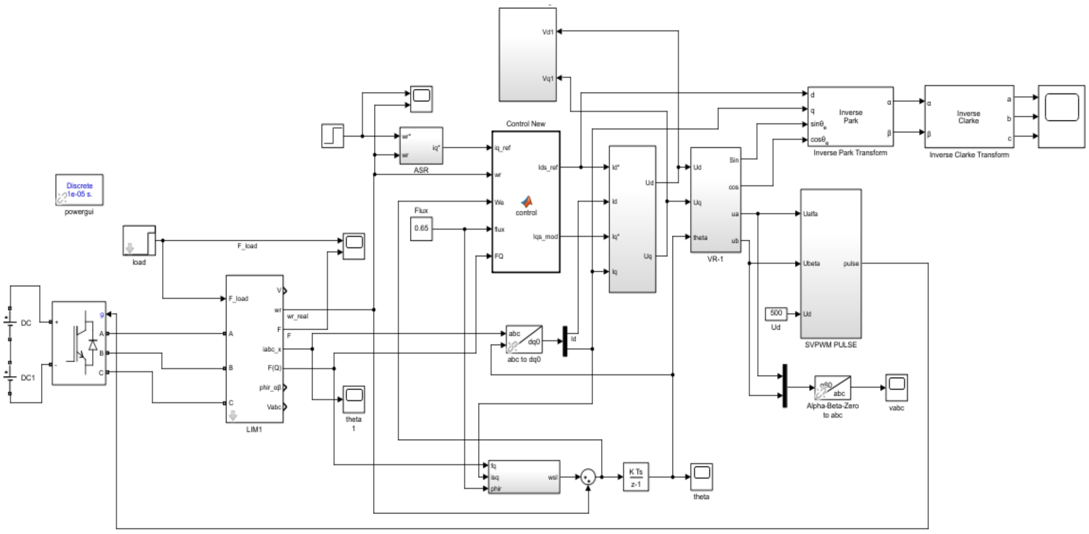

Figure 1: MATLAB Simulink model of LIM with integrated Field Oriented Control and Slide Mode Control

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Investigation of Active Magnetic Bearing with pole embedded Hall sensors

Adam Krzysztof Piłat

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The Active Magnetic Bearing in the typical form of 8 poles with paired coil was designed and manufactured with Hall sensors embedded into every pole to measure the magnetic flux density directly in the gap between rotor and stator (Fig. 1). In parallel a 2D and 3D models were realized in COMSOL Multiphysics software (Fig. 1bc) in stationary and time domain modes to analyse forces, currents and magnetic flux density under desired control and rotor position. The experimental investigation on rotor stabilising control was performed to identify magnetic circuit properties.

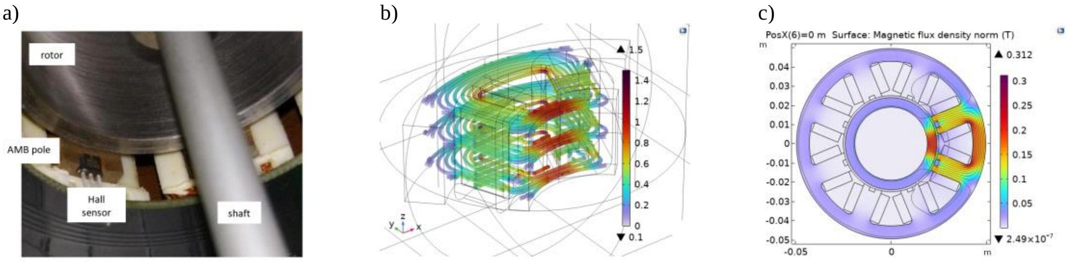

Fig. 1. a) Eight pole radial AMB with embedded Hall sensors, b) 3D numerical model c) 2D numerical model in sensor plane

One can notice that typically used electromagnetic force characteristic in the mathematical form depends on the coil current and rotor distance. The actual relationship between coil current, magnetic flux density and rotor displacement was sought. Some experimental results were compared with the numerical modelling results. A discussion concerning the use of numerical modelling for control purposes completes the conducted researches.

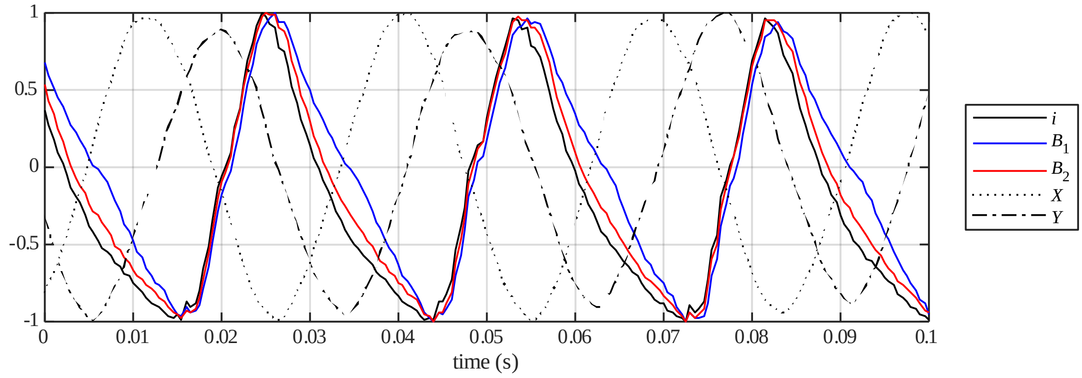

Fig. 2. Selected measurements observed during rotations of the levitating rotor.

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WPT in Electric Micro-Mobility: Implementation of a Wireless Charging System for Electric Bike-Sharing Service

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European Commission has proposed a list of principles to promote cycling across Europe, as it is a sustainable, accessible and inclusive, affordable and healthy means of transport [1]. Over the years, many companies have introduced bike-sharing and e-bike-sharing services in major cities, driven by local and European initiatives [2]. While for bike-sharing services the operator's activities are mainly logistical, the management of e-bike-sharing requires that the operator ensure that the bicycles are charged when they are picked by the users.

This paper proposes the incorporation of wireless charging through Wireless Power Transfer (WPT) for e-bike sharing services to allow users to use charged bicycles every time. In this paper, a WPT model realised on Simulink software is proposed, highlighting the characteristics of the system to safely transmit power for the service [3]. Figure 1 shows the equivalent model used for the implementation of the WPT system.

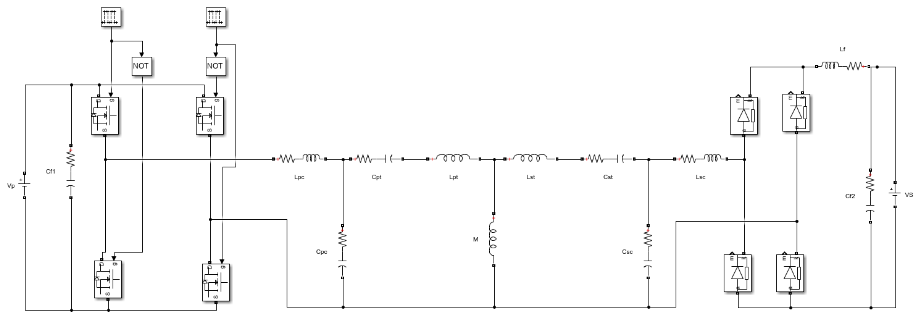

Figure 1: WPT system for stationary charging of electric bicycles implemented on Simulink.

The work will simulate the charging profile of the system showing its adaptability in e-bike-sharing service .

[1] European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Proposing a European Declaration on Cycling", Brussels, 4-10-2023, COMM(2023) 556 final ANNEX: https://transport.ec.europa.eu/document/download/60033b3b-0652-495c-add3-ffea2388ff81_en?filename=European_Declaration_on_Cycling_text.pdf

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Frequency control for LCC-S wireless power transmission

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Wireless power transfer applications at high frequency requires suitable power electronic topologies to implement a resonant structure able to deliver power from primary to secondary sides of the wireless system with elevated efficiency. Among different resonant topologies, LCC-S excels at delivering high power with elevated efficiency for high coupling factors, and the output power can be modulated by acting on the input frequency [1]. In this work a double control loop strategy is implemented to modulate the output voltage by operating on the switching frequency of the input PWM. The duality of the converter is required due to the presence of a non-monotonic control curve that changes the slope at resonant frequency. Thus, two different compensation networks, one for operating below resonant frequency, and one for operating above resonant frequency, must be implemented. The compensation networks in both cases were implemented using discrete PI controllers, for further implementation on microcontroller devices. To correctly tune the PI controller, a time-domain model (without FHA) of the system was implemented in PLECS environment which allowed the estimation of the control (frequency) to output transfer function. The two PI controllers were validated in time domain simulation to assess their capability to deliver pulsed output power to a load, with the purpose of implementing a battery/supercapacitor charging system.

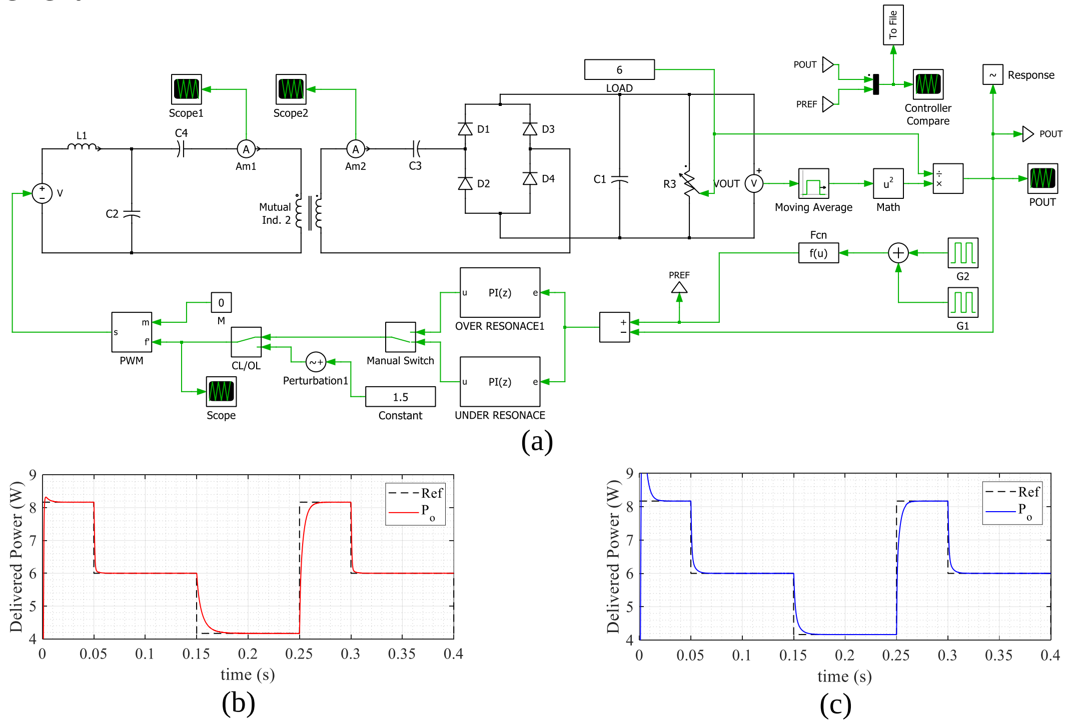

Figure 1: Wireless Power Transfer topology with LCC-S resonant tank (a); output power response control under resonance (b); output power response control over resonance (c).

[1] Corti, F., Intravaia, M., Reatti, A., Grasso, F., Grasso, E., & Cabrera, A. T. (2024). Component design procedure for LCC-S wireless power transfer systems based on genetic algorithms and sensitivity analysis. IET Power Electronics.

Microwave signal rectification with perpendicular magnetic tunnel junctions

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Perpendicular magnetic tunnel junctions (pMTJs), widely used in memory applications, can also be employed as narrowband or broadband radiofrequency signal detectors [1, 2]. Their RF-to-DC rectification properties can be leveraged for the development of low-power wake-up receivers or energy harvesting applications [3] respectively that are key for reducing energy consumption in autonomous wireless sensor nodes. An important property of pMTJ devices is that their internal fields can be tuned by adjusting the device's diameter as well as the different magnetic layer thicknesses. For instance increasing the free layer (FL) thicknesses t_{FL} from 1.4 to 1.8 nm induces a transition of the magnetic orientation from out-of-plane (OP) to in-plane (IP). In a previous study [2] we analysed in detail the narrowband, passive (no DC current) RF-DC rectification properties for devices with an IP-FL for which best detection signals have been obtained under an IP-field. It was shown that strong signals in the mV range arise (i) when the effective perpendicular magnetic anisotropy is small, and (ii) by reducing the device's diameter, which enhances spin-transfer torque efficiency, (Fig. 1(a)). Here we present a complete analysis for a large parameter space of these pMTJs in terms of geometry (IP-FL and OP-FL, diameters ranging from 20 nm to 150 nm) and control parameters: IP and OP fields, passive and active detection (respectively without and an additional DC current). Our results indicate that the optimal conditions for narrowband, passive detection, besides the IP-FL under IP fields [2], are an OP-FL under OP fields, where the pinned layer is excited. Further results are the possibility to tune the detection frequency band by several GHz in the active detection through the DC current (Fig. 1(b)), likely due to Joule heating. Furthermore, broadband detection in the range of 0-1GHz was observed for IP-fields for devices whose FL is close the IP-to-OP transition (Fig. 1c).

Financial support is acknowledged from Horizon Europe Swan-on-chip (N° 101070287).

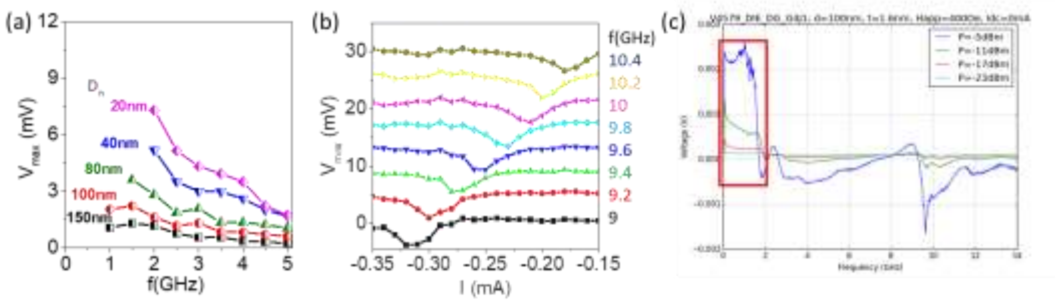

Figure 1: (a) Maximum rectified DC voltage vs. frequency for pMTJs of different diameters and a FL thickness t_{FL} = 1.8 nm. (b) Example of frequency tuning with DC bias current. (c) Broadband detection for a pMTJ device of t_{FL}=1.6nm.

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[2] A. Sidi El Valli, Appl. Phys. Lett., **120**, (2022) 012406.

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Spin-torque diode effect driven by magnetization phase-transitions: a theoretical analysis

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Spin torque diodes (STDs) are currently among the most widely studied spintronic devices thanks to their capabilities, among which we list the frequency response that can be resonant or broadband depending on the system properties and the excitation [1]. Metamaterials, such as FeRh, that exhibit a temperature-induced first order antiferromagnetic (AFM)-to-ferromagnetic (FM) phase transitions have recently attracted attention as alternative materials for spintronic applications. In FeRh this phase transition occurs close to room temperature, and it can be induced by Joule heating via electrical current injection. Moreover, this system also exhibits two resistance states depending on the magnetic phase [2].
In this work we propose a novel use of the phase transitions in a STD. We develop a two-sublattice analytical approach and a macrospin model to investigate systematically the STD response induced by these phase transitions in metamaterials, such as FeRh. We first analyse the phase diagram describing the equilibrium magnetization state as a function of the perpendicular magnetic anisotropy constant (K_u) and the inter-sublattice exchange constant (A_0), as shown in Figure 1. We identify three regions: i) AFM, where the two sublattices are in the AFM state; ii) FM, where the two sublattices are in the FM state; iii) FM/AFM, where the equilibrium state depends on the initial state. We characterise the phase transition and find that it occurs when the anisotropy energy balances the energy of the inter-sublattice exchange, given by the condition: $K_u = 4A_0\, a_0^{-2}$, where a_0 is the lattice constant of the material.
We then focus on the dynamical response of FeRh when subjected to an ac current with variable frequency to excite the STD phenomenon. To describe the effect of the temperature, we extract the temperature scaling of the magnetic properties from atomistic spin simulations and include within the macrospin approach. Our results show a broadband response in a large range of frequencies. These results are promising and can be useful for the design of alternative energy harvest systems.

Work supported by (i) PRIN 20222N9A73 “SKYrmion-based magnetic tunnel junction to design a temperature SENSor –SkySens” (Italian Ministry of Research), and (ii) PE0000021, “Network 4 Energy Sustainable Transition – NEST”, funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 – Call for tender No. 1561 of 11.10.2022 of Ministero dell’Università e della Ricerca (MUR) (CUP C93C22005230007) (iii) PETASPIN association (www.petaspin.com).

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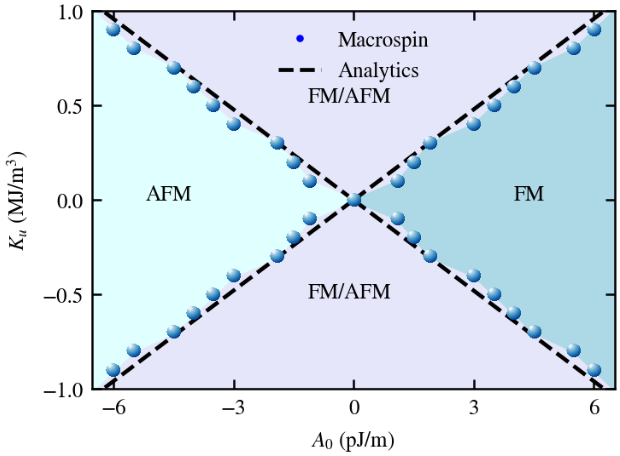

Figure. 1: Phase diagram of the equilibrium magnetization state as a function of the magnetic anisotropy (K_u) and inter-sublattice exchange constant (A_0). Points are macrospin simulations, dashed lines are analytical results from $K_u = 4A_0\, a_0^{-2}$.

Quantum tomography of magnons using Brillouin light scattering

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Quantum measurements of magnons are crucial for the development of quantum applications based on magnonics. Existing techniques introduce additional dissipation channels and are not apt for magnets in free space [1,2]. Brillouin light scattering (BLS) is a well established technique for probing the magnetization known for its high sensitivity and temporal resolution.

We theoretically analyze the efficacy of Brillouin light scattering (BLS) for quantum tomography of magnons (published in [3]). We consider a finite-length optomagnonic waveguide made of Yttrium Iron Garnet (YIG), see Fig. 1, where the output photons have imprints of the magnon state. While the signal-to-noise ratio (SNR) is low due to a small magneto-optical coupling, we show that significant improvement can be achieved by injecting squeezed vacuum of photons.

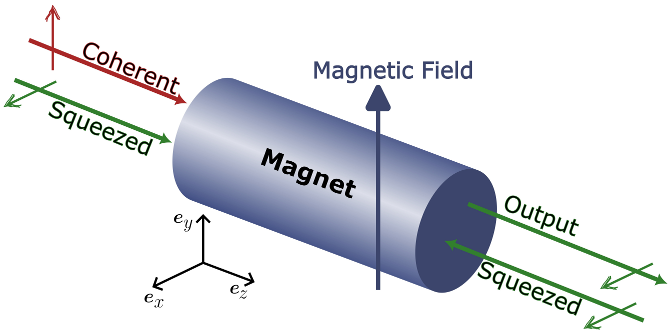

Fig 1: A setup consisting of an optomagnonic waveguide along with a large coherent laser input and squeezed optical vacuum

Then, we discuss a protocol of reconstructing the magnon's density matrix based on the observed statistics of the transmitted photons, using maximum likelihood principle. We find that the classical component of a magnon state, defined as the regions of positive Wigner function, can be reconstructed with a high accuracy. Reconstructing the nonclassical component requires improved SNR or larger datasets, and we explore potential methods to achieve these goals.

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Operational window of inverse temperature for stochastic magnetic tunnel junctions based probabilistic computing

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Probabilistic computing/computer (p-computing/computer) with stochastic magnetic tunnel junctions (s-MTJs) shows promise to address some computationally hard problems for conventional deterministic computers [1,2]. In p-computing, the Ising model is often used to solve problems, where the "inverse temperature" has to be set to an appropriate value; however, its guideline has not been established. Here, we study the operational window of the inverse temperature by examining the contrast between correct and incorrect solutions of p-computing for various types of random telegraph noise (RTN) of s-MTJs [3-8].

We investigate the computing results based on the Ising model in terms of the difference in the appearance frequency of the lowest energy (E) states (correct solutions) compared to the higher E states (incorrect ones) in the statistics. We simulate the NAND-gate operation [9] using experimentally obtained RTN of s-MTJs [8] with various statistical properties (amplitude, distribution, etc.). We also test extreme cases: continuous random numbers [Fig. 1(a, b)]. The interaction between bits is implemented by sending a signal given by $-I_0\partial E/\partial x_i$ to the ith bit, where I_0 corresponds to the inverse temperature and x_i is the binary state of the ith bit. For the case of too high I_0, the system tends to be stuck in local minima in solution space, whereas the contrast becomes small for the case of too low I_0, giving the upper and lower bounds of I_0 ($I_0{}^*{}_{max}$ and $I_0{}^*{}_{min}$, respectively). Figure 1(c) shows the main result: (i) the operational window of I_0 decreases with decreasing the amplitude of RTN, and (ii) the window depends on the nature of the random telegraph noise. We discuss what determines the contrast, providing a guideline to design the s-MTJs and operate the p-computer.

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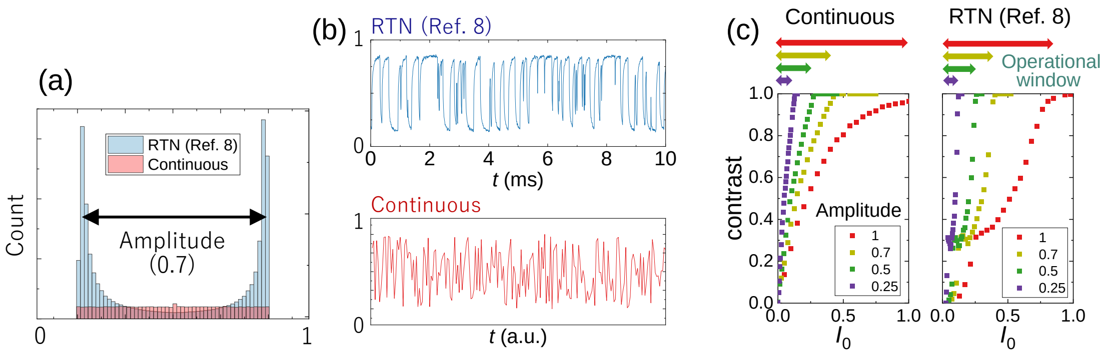

Figure 1(a) Histogram and (b) time-trace of RTN and continuous random number. (c) Operational window of I_0 for various amplitudes of the two random numbers.

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Voltage-controlled magnetic anisotropy driven non-linear parametric resonance

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Spintronic diodes (STDs) exhibit potential advantages over the semiconductor counterpart. They are compact (nanoscale size), CMOS-compatible, energy-efficient [1][2]. In addition, the STDs can be measured as a response of different driving forces such as spin-transfer-torque, magnetic field and voltage controlled magnetic anisotropy (VCMA) [3]. We have performed a systematic study of the resonance response of the MTJ as a function of spin-transfer torque and VCMA amplitudes. In particular, the dynamics is driven by the presence of VCMA and simultaneity by spin-transfer-torque driven by an ac in-plane spin-polarized current density (Jac =0.1MA/cm), and both current density and VCMA have the same frequency.

Our results predicted a fractional parametric resonance response driven by the simultaneous excitation of VCMA and ac spin-transfer torque for spintronic diodes working in the passive regime which has been also confirmed experimentally in magnetic tunnel junctions enabling the simultaneous excitation of spin-transfer torque and VCMA.

At low VCMA, the resonance is characterized by typical ferromagnetic resonance curves which can be coupled with a parametric excitation once a dc current is also supplied. At larger value of the VCMA we found that parametric excitation at twice the value of resonance frequency can be achieved at zero dc current and a non-linear parametric response is observed, and it is characterized by several harmonic at fractional peaks, all of which are an integer fraction (1/2,1/3, etc.) of the main resonance frequency. Finally, at large VCMA we found the excitation of high order parametric resonance characterized by the excitation of harmonics at 2, 3 and 4 times the ferromagnetic resonance.

This work opens a new direction for the use of spintronic diodes in the field of communication, as a single device would have the ability to detect more information carriers.

ACKNOWLEDGEMENTS

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magnon spectrum of skyrmions in frustrated magnets

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Skyrmions in frustrated magnets are promising candidates for novel information processing technologies due to their atomic size and extra helicity and vorticity degrees of freedom [1]. Control over skyrmions can be achieved using microwaves, and a theoretical description of the response of skyrmions to microwave fields is therefore a necessary step toward the development of these technologies.

Through linear spin wave theory, we calculate the excited modes of the skyrmion crystal state, the metastable isolated skyrmion, and systems of interacting skyrmions. We find that the skyrmion crystal retains the set of (counter) clockwise, breathing, and polygon deformation modes reported for skyrmions stabilized in chiral magnets. Unlike chiral magnets, no mode couples to the out of plane component of a microwave field.

Isolated skyrmions in these systems are rigid and do not host modes below the traveling magnon gap. Traveling magnon modes also display unusual long-range ordering, as shown in figure 1. Systems of multiple isolated skyrmions develop low energy modes below the gap due to the helicity and vorticity dependent ranged interaction potential reported in [2].

Control over skyrmion helicity can be achieved through the addition of in-plane anisotropy or external electric fields. We report spectral results for skyrmions in the presence of these interactions and find non-reciprocal dispersion of modes and varying helicity potentials between degenerate states, providing evidence of a second symmetry breaking in the system.

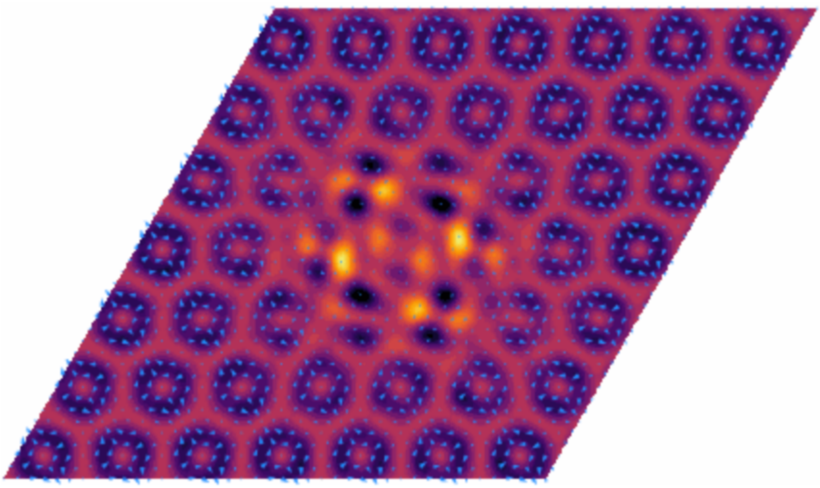

Figure 1: Snapshot of magnon wavefunction of a traveling magnon displaying unusual ordering.

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Domain structures in ultrathin Pt/Re/Co/Pt layers

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The magnetic properties of ultrathin ferromagnetic (FM) films with buffer/(**FM**)/overlayer structure, e.g., magnetic anisotropy, interfacial Dzyaloshinskii-Moriya interaction (**DMI**), coercivity field (H_c) are significantly influenced by the insertion of a heavy metal layers at the interface between FM and buffer or overlayer. Formation of skyrmions were also observed in Pt/Co/Os/Pt with Os modified overlayer [1] with skyrmions fluctuating while approaching spin reorientation transition (**SRT**) from perpendicular to in-plane state. Moreover, bubble domain/skyrmion creation was recently reported in W buffer modified Pt/W/Co/Pt [2]. In this work we report results of Re layer insertion to the bottom interface, resulting in the Pt/Re/Co/Pt stack knowing from ab intio calculations, that the Co/Re interface can produce a high iDMI strength [3].

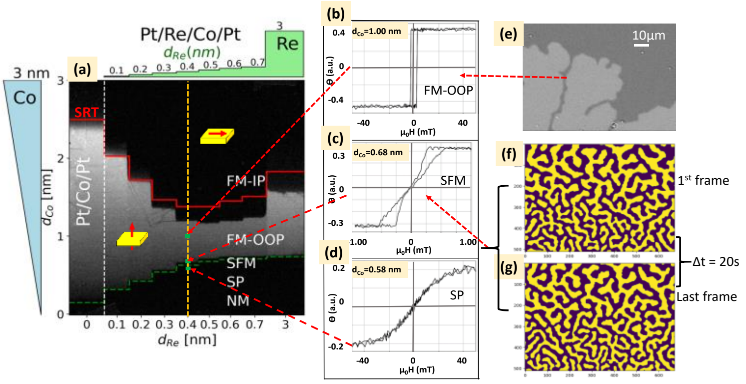

Figure 1. PMOKE studies of Pt/Re/Co/Pt structure: (a) remnant magnetization image; (b, c, d) magnetization loops registered for d_{Re}=0.4 nm along vertical yellow dashed line; (e) domain image registered for d_{Co}=1 nm; (f, g) time-depended domain structure evolution for d_{Co}=0.68nm (delay 20s).

The following epitaxial structure was deposited on the sapphire (0001) substrate by molecular beam epitaxy (MBE): (i) buffer: Pt (40nm) and Re in the form of steps with thickness range $d_{Re} = 0 \div 3$nm, (ii) FM as Co wedge $d_{Co} = 0 \div 3$nm and (iii) Pt overlayer (4nm), see the scheme in Fig. 1a representing the remanence image of the sample obtained using polar magneto-optical Kerr effect (**PMOKE**). While increasing d_{Co} one can distinguish (i) black area (small d_{Co}) with the following magnetic states: nonmagnetic (**NM**) then superparamagnetic (**SPM**) (Fig. 1(d)) and above the green bottom dashed line soft ferromagnetic (SFM) with negligible coercivity Fig. 1(c) and fluctuating domains (Fig. 1(f, g) – domain structure changes between the images registered with 20 s delay), (ii) white area corresponding to ferromagnetic state with the out of plane magnetization (**FM-OOP**) characterized by the square hysteresis loop (Fig. 1(b)) and wide domains which expand with increasing field (Fig. 1(e)) and (iii) black area (big d_{Co}) ferromagnetic state with in-plane magnetization (**FM-IP**). Magnetic anisotropy analysis with fixed d_{Re} allows us to determine $d_{SRT}(d_{Re})$ - Co layer thickness corresponding SRT (red-solid line in Fig. 1a). A strong decrease in domain size into sub-micrometer range was observed while approaching SRT. Domain structures studies were focused in the region of low d_{Co} while approaching SPM. Bubble/skyrmion lattice creation is possible by external magnetic field. Spontaneous domain annihilation/creation, and their geometrical fluctuations (so called “Living domains structure”) were investigated with the support of special image processing methods.

This work is supported by Polish National Science Center in the frame of projects: OPUS-19 (2020/37/B/ST5/02299) and M-ERA.NET 3, MUST (2022/04/Y/ST5/00164).

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Skyrmions in Biased Ferromagnetic and Antiferromagnetic Coupled Multilayers

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Synthetic antiferromagnets (SAFs) are an attractive and advantageous material platform, promising to improve the performance of spintronic devices[1]. When placing a non-magnetic spacer between two ferromagnetic (FM) materials, the FM layers can experience interlayer exchange coupling (IEC)[2]. Particular spacers, such as Ir and Ru, cause either FM or antiferromagnetic (AFM) coupling depending on their thickness, via the Ruderman–Kittel–Kasuya–Yoshida (RKKY) interaction[3]. AFM-IEC promotes the formation of a SAF. SAFs are appealing for device applications such as spin orbit torque magnetoresistive random access memory (SOT-MRAM) and skyrmion applications due to the suppression of the skyrmion Hall effect (SkHE)[4]. Recent studies have experimentally stabilized skyrmions in SAFs being driven with smaller current densities than their FM counterparts and with a negligible SkHE[5,6].

In this work, we advance the knowledge of SAF systems and test the limits of the SAF when coupling together different amounts of magnetic material or when increasing number of repetitions[7].
We use this knowledge to design a SAF bias layer, consisting of two Co layers, to be more robust and stable against external fields. This SAF bias layer was used to bias skyrmions in a ferromagnetic multilayer, the sample as shown in Figure 1a. Figure 2a shows an MFM image of dense skyrmions of around 75 nm at 0 mT. This method was also used to bias the multilayer SAF as shown in Figure 1a. Figure 2b shows an MFM image of less dense skyrmions of around 40 nm at 0 mT. The skyrmions in the multilayer SAF have low contrast compared to the FM multilayer, indicative of their SAF nature. This research paves the way for more efficient and practical applications of SAF skyrmions in future spintronic devices.

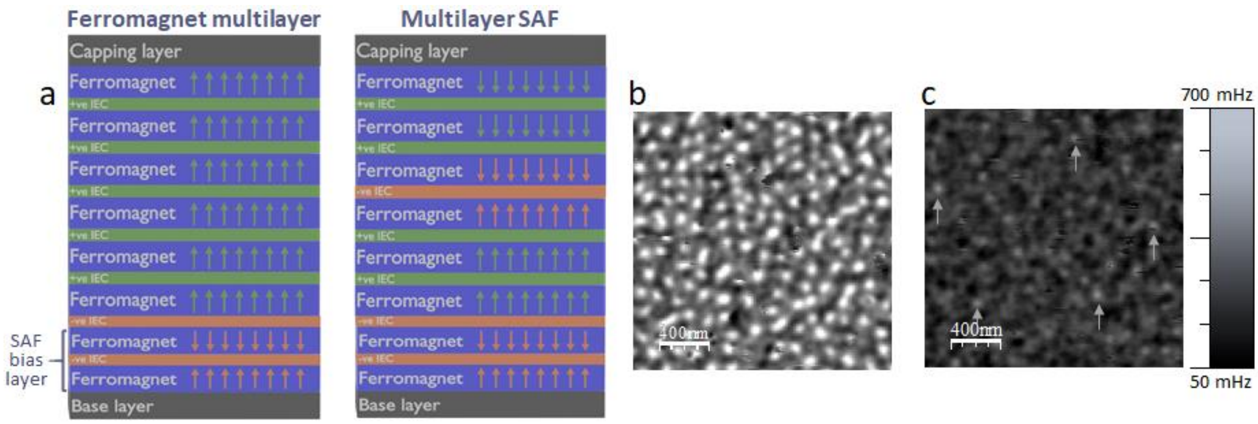

Figure 1: a) FM multilayer with six repetitions, biased via a two repetition SAF. Two three-repetition multilayers coupled together antiferromagnetically, biased via a two repetition SAF. Figure 2: a) MFM image of the FM multilayer showing a skyrmion lattice at 0 mT. b) Multilayer SAF MFM image showing skyrmions (some examples indicated with an arrow) at 0 mT. Both images are on the same contrast scale.

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Magnon phonon dynamics on CoFe/Pt multilayers

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Fs laser improved the generation and measurement technique of acoustic waves with sub-µm spatial resolution and frequency up to THz.[1,2] It was extended to generate and control magnons, i.e. strong coupling of phonon and spin waves enhance the precession amplitude, consequently the magnetic switching speeds.[3] We investigated thin CoFe/Pt multi-layers with in (out) of plane magnetic anisotropy, whose properties was published previously.[4] Time resolved magneto optic Kerr effect (TRMOKE) and reflectance (TRR) were used to show magnon and phonon wave oscillation in a thin magnetic CoFe/Pt multilayers. Those coherent and incoherent waves are generated and monitored by a 100 fs laser. Magnon and phonons damped oscillations, amplitude and phase will be analysed as well the magnetic spin precession behavior.

Fig.1 shows a TRMOKE/TRR for the in plane anisotropy sample. The TRR shows the phonon wave with a high attenuation besides a beating behavior (period ~15ps) from the phonon wave and the cavity resonance mode. The TRMOKE shown us a demagnetization (0,4ps) and remagnetization (1.6ps) and the TRR a phonon wave clearly resolved, with the phonon and cavity (f_p,f_m) oscillation frequency determined by the Fast Fourier transform (FFT) shown in the inset figure.

The f_p(180GHz) is generated on the metal after absorption of the laser pulse in the skin depth length, followed by the cavity mode oscillation f_m (247GHz), which were excited by the phonon wave amplitude tail. The data fitting of the coherent and mode phonons shows attenuation time of 9.5(10.2) ps respectively. The inverse magnetostriction effect were observed weakly on the TRMOKE(fig.1) besides the precession behavior, none interaction of the phonon wave & magnons could be observed here, since both frequency were too separeted besides the cavity have a quality factor of Q ~ 3,5. All those analyses were done also for samples with magnetic anisotropy out of plane where magnon oscillations were oberved.

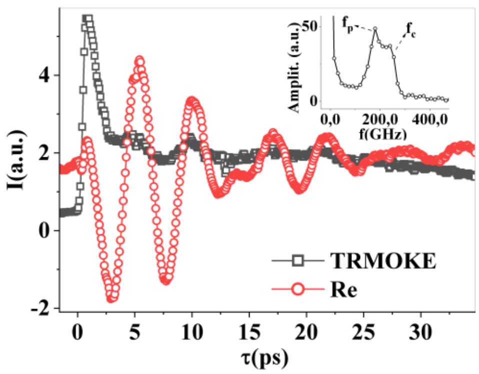

Fig2. TRMOKE (TRR) measured with high resolution showing demagnetization, remagnetization, and magnon phonon waves oscillations.

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Interference patterns of propagating spin wave in spin Hall oscillator arrays

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Spin torque oscillators offer a promising pathway for scaling down magnonic devices, proving to be highly efficient as the smallest microwave emitters with rich dynamics of both localized [1] and propagating excitations [2]. Notably, propagating spin waves driven in perpendicular magnetic anisotropy (PMA) materials can be tuned via dc current and magnetic fields, with wavelengths reduced to 100 nm [3] and can induce mutual synchronization over micron-scale distances, crucial for emerging spin wave computing platforms.

In this study, we discuss the observation of spin wave interference generated by magnetic oscillators [4]. We employ micromagnetic simulations for two coherent spin Hall nanowire oscillators positioned nearby, horizontally or vertically. The two nanowires produce circular waves with short wavelengths on the order of 100 nm, which interfere with each other as shown in Fig. 1. In the horizontal configuration, the spin waves exhibit constructive and destructive fringes, indicating amplification or cancellation of the amplitudes, respectively. The synchronization of spin waves in the current geometry of the two nanowires is facilitated by the combination of dipolar field and propagating spin waves. Additionally, the vertical alignment results in standing spin waves characterized by multiple antinodes and nodes. These observations are interpreted using a wave model that incorporates the superposition principle for each case.

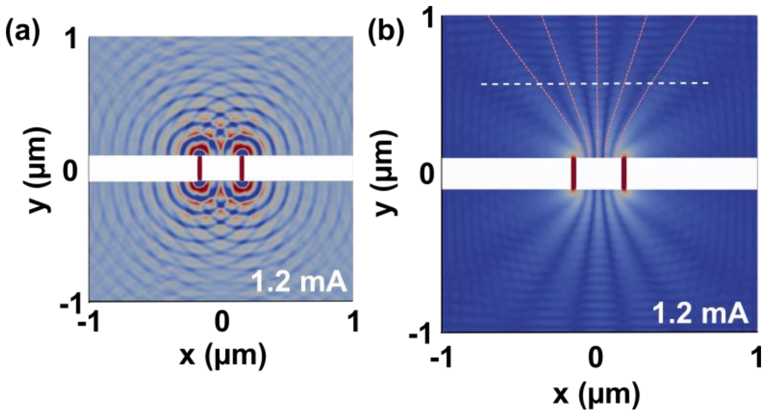

Figure 1: (a) Snapshots of the magnetization dynamics of the two oscillators showing the interference pattern measured at 1.2 mA. (b) Fast Fourier Transform (FFT) of the spatial mode profile of the z-component of the magnetization (mz) for the horizontal alignment of the nanowires at I = 1.2 mA.

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The dynamics of anti-dot arrays in dipolar-coupled bilayers with crossed anisotropies

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The implementation of reconfigurable units is one of the cornerstones of advanced magnonics [1.2]. We have recently shown that a bilayer made of two magnetic materials with out-of-plane (o-o-p) easy axis ($NdCo_x$) and in-plane easy axis (Perrmalloy, Py) results in a global reconfigurable magnonic material [3]. As the o-o-p anisotropy of $NdCo_x$ is relatively weak the domains present in the stack form a regular arrangement of stripes called stripe-domain structure. The left side of Fig 1depicts the o-o-p magnetization in the middle of the $NdCo_x$ layer. The stripe-domain structure has here the whole magnetization arranged in domains pointing successively up and down and separated by Bloch-type walls. A relevant feature of the formed bilayer is that the two magnetic layers are separated by a non-magnetic spacer, which results in a magnetic interlayer coupling of dipolar origin. So, the natural stripe-domain structure of $NdCo_x$ is imprinted in the Py (which is a suitable magnonic material). On the other hand, it's known that the magnets presenting weak magnetic o-o-p anisotropy have a rich dispersion diagram [4], The spin waves (SW) can run both along and transverse to the stripe-domains (see the central part of fig 1). In this work we have undertaken a further step and we have simulated the effects of an ordered array of anti-dots at the submicron scale (see the left side of fig 1) on dynamics. Results will be presented for two common kinds of anti-dot shapes: the triangular and the circular one [5].

This research has been supported by the Spanish AEI under grant PID-2022-136784-NB and under the FICYT regional grant AYUD/2021/51185 with the support of FEDER funds.

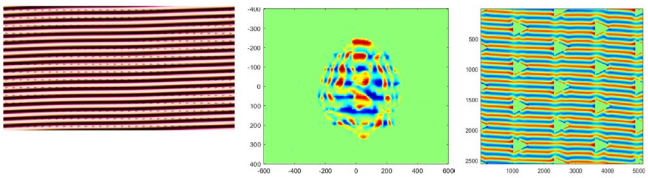

Figure 1: 10nm-Py/6nm-spacer/65nm-$NdCo_x$ trilayer with surface area $2.7 \cdot 5.4$ μm^2. Left) $NdCo_x$ layer: stripe-domain structure at the middle of the layer. Center) Py layer: SWs emitted from a point source. Right) Py layer: o-o-p magnetization of Py for an array of triangular holes.

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The modelling and design of efficient spin-wave transducers

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We developed a numerical computational framework for designing magnonic transducers, which combines circuit-level models with micromagnetic simulations to manage complex geometries in the magnonic domain. We have validated our model experimentally, demonstrating good agreement in the measured and predicted transmission characteristics of the fabricated channel.

For the electrical characterization of two-port magnonic devices we developed a lumped-element circuit model (Fig. 1c). The electrical and magnonic contributions of the device are represented as separate circuit components. The effects of spin waves – both the load on one antenna and the induced voltage on the opposite antenna – are represented by a frequency-dependent, complex 2x2 impedance matrix [1], which captures the spin-wave coupling between the ports of the device. To determine the components of the impedance matrix, the voltage induced in the antennas by spin waves is calculated using micromagnetic simulations (e.g. mumax^3[2]). We numerically compute the magnetic vector potential and the resulting electric field from the magnetization dynamics of the spin-wave medium and integrate the electric field along the conductors to get the induced EMF. For the input antenna, the ratio of the excitation current and the voltage induced back by the spin waves will give the radiation impedance of the transducer, one of the most important indicators of the excitation efficiency.

Using our model, we demonstrated a two-port magnonic device design in YIG, with 5 dB insertion loss across a 100 MHz band (fig. 1a-b). Our results show that low insertion loss is achievable without relying on external matching networks for micron-scale devices. We identified scaling rules for the radiation resistance of magnonic devices, and the limitations of miniaturization. Our work paves the way toward practical magnonic devices by providing an electrical model of magnonic devices that can be used by RF circuit designers. We hope to raise awareness in the community for the importance of low insertion loss in the device designs and help them to achieve it by providing design rules and modelling framework.

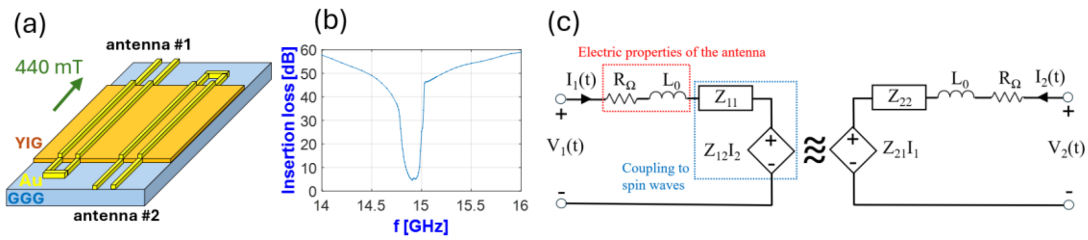

Figure 1: (a) Schematic of a YIG-based transducer pair. (b) Insertion loss of the designed transducer pair. (c) Lumped-element circuit model for a 2-port magnonic device.

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Photoinduced spectral manipulation of coherent magnonics in ultrathin iron garnets

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Iron garnets represent a highly promising class of materials for magnonics and magnetotransport, due to the low damping and the possibility to modify their magnetic properties via a wide range of dopants [1]. The eigenfrequency of the spin dynamics can be tuned either chemically or by applying an external magnetic field. Ultrashort laser pulses have emerged as a powerful tool for exciting [2], controlling coherent magnetization dynamics [3] and even switch the magnetization with neglible heat load [4]. In particular, recent experiments have demonstrated that these laser pulses can effectively reduce the magneto-crystalline anisotropy in Bi:YIG thin films, thus modifying the eigenfrequency of the magnetic resonance.

In my talk/poster I will report on our research efforts concerning single-crystals of Bi:YIG in quasi 2D ultrathin (thickness ~ 20 nm) form. First, we have recently developed an experimental scheme able to simultaneously detect the laser-induced optical and magneto-optical response with femtosecond temporal resolution, in a balanced-detection scheme. Second, we have employed our system to drive spin dynamics under a wide variety of experimental conditions, in particular tuning the excitation fluence and the externally applied magnetic field. The main observation is the modification of the eigenfrequency of the magnetic resonance via two different pathways (see Fig.1); namely an impulsive (femtosecond) modification of the magneto-crystalline anisotropy and a nanosecond lattice-mediated laser-induced heating of the magnetic system. We can quantitatively identify these two contributions in the spin dynamics in view of both the time-resolved nature of our experiment and the simultaneous detection of the optical dynamics. While these findings were achieved at room temperature, our approach can be extended to different quasi-2D ultrathin magnets, displaying phase transitions in the phase diagram as a function of temperature.

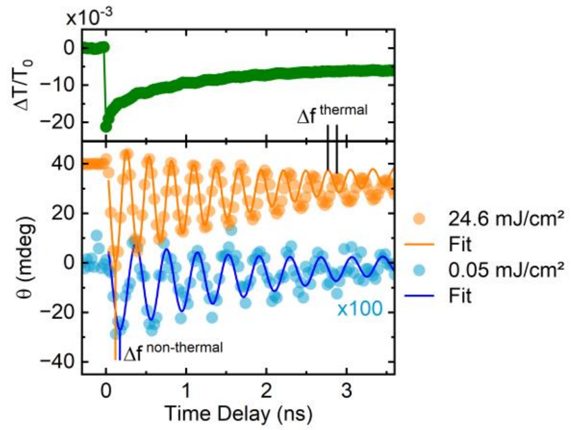

Figure 1: Time-resolved transient transmission and polarization rotation of the probe beam. For short delay times, a non-thermal frequency increase due to the modification of the anisotropy is visible. For longer delay times, the lattice-mediated heating can be seen, which also results in a frequency change.

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Anisotropic magnon transports in van der Waals altermagnetic and ferromagnetic insulators

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Magnon, as the quanta of spin wave, is a powerful tool for spin information transport in the nanoscale, which facilitates the development of wave-based computing technologies with low-energy-consumption. The emergent van der Waals (vdW) magnets that hold the long-range spin order at atomic thickness provide intriguing opportunities for magnonics in miniaturization. Importantly, the spin Seebeck effect (SSE) and spin Nernst effect (SNE) arising from the magnonic transport are effective approaches to generate longitudinal and transverse spin currents in magnetic insulators. However, SSE normally requires a large magnetic field that produces magnon imbalance in antiferromagnets, and SNE exploits the spin Berry curvature that is normally proportional to the strength of spin-orbit coupling in both antiferromagnets and ferromagnets.

Here, based on state-of-the-art first-principles calculations and model analysis [1, 2], we report the SSE and SNE in vdW altermagnetic and ferromagnetic insulators, which are entirely independent of magnetic fields and spin-orbit coupling [3]. In altermagnetic monolayers Cr_2Te_2O and Cr_2Se_2O, the breaking of combined symmetries of space inversion P, time reversal T, and translation τ, while preserving the combined symmetry of mirror $M\phi$ and τ, leads to anisotropic spin-momentum locking of magnons. This phenomenon is mediated by Goodenough-Kanamori-Anderson rules-favored anisotropic exchange coupling. Interestingly, this spin-momentum locking gives rise to the SSE and SNE, with very efficient generation of longitudinal and transverse spin currents when the thermal gradient is aligned with and deviates from the main crystal axes, respectively.

Moreover, anisotropic magnon dispersions can also be realized in synthesized ferromagnetic monolayers $CrPS_4$ and CrSBr, arising from $C4$ symmetry breaking-induced anisotropic exchange couplings [4]. Consequently, the anisotropic SSE and magnon Hall effect accompanied by the SNE are achieved when the thermal gradient is aligned with and deviates from the main crystal axes, respectively. These nontrivial magnonic transports can be further manipulated by the temperature and gate current. Our findings thus pave an avenue toward efficient heat-to-spin conversion based on vdW magnetic insulators, free from limitations such as Joule heating, external magnetic fields, and spin-orbit coupling.

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Static and dynamic properties of exchange-coupled artificial spin-ice CoFe/Ru/NiFe multilayers

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Artificial spin ice (ASI) systems are engineered arrays of interacting nanomagnets designed to mimic the frustrated spin arrangements in natural spin ice materials.[1] In 3D ASI systems, these structures extend into the third dimension, adding complexity to the interactions and magnetic excitations. In this study, we characterized both ASI structures and extended films of exchange-coupled CoFe (15 nm)/Ru (0.5 nm)/NiFe (15 nm) using magneto-optical Kerr effect (MOKE) measurements and vibrating sample magnetometry (VSM). These techniques enabled us to identify and quantify the linear and biquadratic interfacial coupling terms that define the system's magnetic behavior, providing detailed insights into the magnetization reversal mechanisms and interlayer interactions. Additionally, we investigated the system's dynamic properties through Brillouin Light Scattering (BLS) spectroscopy to investigate the spin-wave properties of both the ASI structure and the extended film as a function of the applied magnetic field. Experimental results were further interpreted with micromagnetic simulations using MuMax3, allowing for precise modeling of interfacial magnetic interactions and direct comparisons between simulated and experimental data.

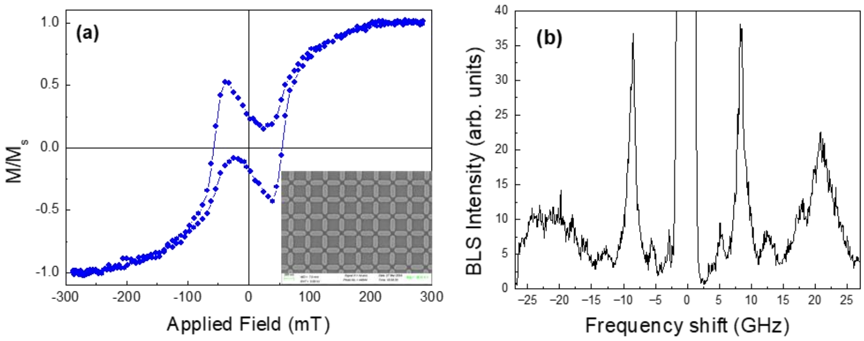

Figure 1: a) Magnetization curves measured by MOKE for the CoFe/Ru/NiFe ASI system. Inset show a SEM image of the ASI structure. b) BLS spectra measured at H=180 mT for the ASI CoFe/Ru/NiFe structure.

Acknowledgements
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Adaptive Magnetic Devices Utilizing Integrated Micro-Magnets

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Recently the research field of magnonics, aiming to use spin waves (SWs), the collective excitations of ordered magnetic materials, to carry, store and process information, has been rapidly growing due to its potential to develop technologies that enable high-frequency data transmission, in the GHz ranges, while minimizing energy consumption. However, the integration of magnonic devices with traditional electronics faces challenges in providing low-power solutions for application of bias fields to manipulate SWs propagation.

In this work we present a first example of tunable magnonic systems where a local bias field is produced by permanent micromagnets integrated with magnonic conduits. As it can be seen in Fig.1a we fabricated devices, where two permanent SmCo micromagnets are placed symmetrically with respect to a CoFeB magnonic conduit at varying distance *d*. The propagation of SWs, excited in the Damon-Eshbach geometry by using a coplanar waveguide, is investigated by micro-focused BLS measurements, applying an external bias field of 60 mT parallel to the short axis of the conduit. The direction of the external field is reversed to be either antiparallel or parallel with respect to the field produced by the micromagnets. Switching from the antiparallel to the parallel configuration we observed a strong reduction of the SWs propagation distance (Fig.1b,c). Moreover, we find that the effect of attenuation depends on the micromagnet-conduit distance up to become negligible when d=8 μm. Micromagnetic simulations show that this behavior can be explained taking into account that the bias field, produced by the micromagnets, induces a local variation of the internal field in the conduit and a shift in the SW dispersion relation.

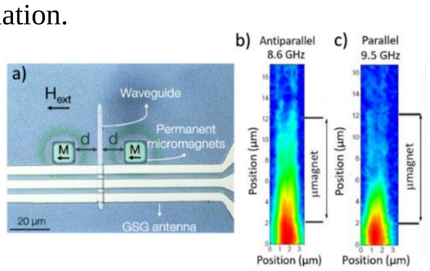

Figure 1 a) Device layout; b,c) BLS measurement of spin wave propagation under antiparallel (b) and parallel (c) alignment between the external field and the bias field generated by the permanent micromagnets.

Acknowledgements
Support from the European Community's HORIZON-CL4-2021-DIGITAL-EMERGING-01 Program, under Grant No. 101070536 MandMEMS is acknowledged. This work was funded by the European Union—NextGenerationEU under the Italian Ministry of University and Research (MUR) National Innovation Ecosystem Grant No. ECS00000041—VITALITY. CUP: Nos. B43C22000470005 and J97G22000170005.

Optimizing terahertz emission in magnetic materials using light ion irradiation

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Spin terahertz emission spectra have long been used to study ultrafast magnetic dynamics. Ferromagnetic (FM)/non-magnetic (NM) multilayers have attracted significant attention for their terahertz emission due to the spin-charge conversion mechanism. Traditional optical terahertz sources, such as photoconductive antennas and nonlinear crystals, are costly and have limited intensity, whereas spintronic terahertz sources generate strong terahertz radiation through the interaction of femtosecond lasers with FM/NM thin films, with peak electric fields reaching up to 300 kV/cm [1]. Recently, orbitronic terahertz sources based on the inverse orbital Rashba-Edelstein effect or the inverse orbital Hall effect in Ni have been discovered [2,3], sparking widespread research interest. Ion irradiation can also manipulate magnetism by altering the internal atomic arrangement of materials. In this paper, we used light ion irradiation equipment to perform He^+ ion irradiation on Cu/Ni heterostructures, investigating their terahertz emission properties through a terahertz time-domain spectroscopy system. As shown in Figure 1, we deposited Cu/Ni structures on glass substrates and compared their terahertz emission signals before and after ion irradiation, finding that the terahertz signals were significantly enhanced, demonstrating the enhancement of terahertz sources in magnetic materials through ion irradiation. We also varied the irradiation conditions and added annealing treatments, finding that within a certain range, increasing the irradiation duration and temperature both enhanced the terahertz signals, with the effect of irradiation duration being more pronounced. We will further study the physical mechanisms behind the enhancement of terahertz signals, believing this will pave the way for the development of terahertz sources and orbital-related research.

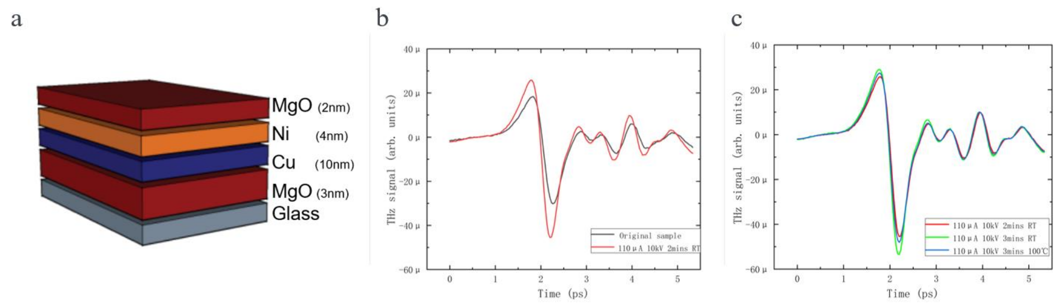

Figure 1: (a) Cu/Ni multilayers deposited on a glass substrate. (b) Enhancement of terahertz emission in the Cu/Ni sample upon irradiation. (c) Comparison of terahertz signals under different irradiation conditions.

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Optimizing spin pumping in Yttrium Iron Garnet/Platinum bilayers under varying oxygen pressure

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Yttrium Iron garnet (Y3Fe5O12, YIG) is especially appealing for microwave applications and spin pumping because of its low magnetic damping and insulating properties. Considerable effort has been put into preparing nanometer-scale YIG films using growth techniques such as sputtering, pulsed laser deposition, and liquid phase epitaxy. However, the quality of YIG films is susceptible to growth conditions and deposition processes [1-3].

Here, we study the influence of magnetic properties on the spin-pumping effect of the Yttrium Iron Garnet /Platinum (YIG/Pt) bilayer. YIG films were deposited by pulsed laser deposition under variable oxygen pressures. Using broadband ferromagnetic resonance techniques, the magnetic properties of the YIG films were measured. We analysed the spin-pumping effect in these films by measuring damping changes in samples with and without Pt layers, enabling the calculation of spin-mixing conductance. Experimental results show that films prepared at high oxygen pressure exhibit lower magnetization and reduced spin pumping, α_{sp}, leading to a decreased spin pumping conductance ($g^{\uparrow\downarrow}$). We report a variation in $g^{\uparrow\downarrow}$ ranging from 4.2×10^{18} to 15.6×10^{18} m^{-2}. These findings underscore the sensitivity of spin transport properties to deposition parameters in YIG-based spintronic devices.

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The dynamical magnetoelectric effect of spin origin and the evolution of polarization

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The multiferroics are the materials, where a single cell of a magnetically ordered crystal forms an electric dipole moment. In the II-type multiferroic materials, the electric dipole moment is induced in relation to the magnetic properties of the material [1]. There are three mechanisms of the formation of the electric dipole moment in the II-type multiferroics. The first mechanism is the exchange-striction mechanism arising from the Coulomb exchange interaction modeled using the Heisenberg Hamiltonian (which is also called the symmetric spin exchange interaction). The electric dipole moment of the couple of neighbour magnetic ions appears as a vector proportional to the scalar product of the contributing spins $\vec{s}_i$ and $\vec{s}_j$: $\vec{d}_{ij} = \vec{\Pi}_{ij} \cdot (\vec{s}_i \cdot \vec{s}_j)$. The second mechanism is related to the spin-current model [2], where the electric dipole moment was derived in the form $\vec{d}_{ij} = \alpha_{ij}\vec{r}_{ij} \times (\vec{s}_i \times \vec{s}_j)$. It arises from the antisymmetric spin exchange interaction or inverse Dzylaoshinskii-Moriya model.

The method of quantum hydrodynamics has been developed for the description of the magnetoelectric effect of spin origin [3, 4]. Its development for the multiferroics follows the work of the application of the quantum hydrodynamic method to major features of the ferromagnetic and antiferromagnetic materials. We have made a derivation of the electric polarization evolution equation for II-type multiferroics with both the electrostriction mechanism of the electric dipole formation and antisymmetric exchange mechanism, where we have considered the evolution under the Coulomb exchange interaction given by the Heisenberg Hamiltonian and interaction with magnetic field via the Zeeman energy [3]

$$\hat{H} = -\sum_{i=1}^{N} \hat{\vec{\mu}}_i \cdot \vec{B}_i - \frac{1}{2}\sum_{i,j\neq i}^{N} U(r_{ij})(\hat{\vec{s}}_i \cdot \hat{\vec{s}}_j), \qquad i\hbar\partial_t\psi(R,t) = \hat{H}\psi(R,t).$$

For the exchange striction mechanism, the polarization evolution for the ferromagnetic materials is derived in the form [3]

$$\partial_t P^\alpha = \frac{1}{3}\gamma g^\alpha_\Pi \varepsilon^{\beta\gamma\delta}(\partial^\mu B^\beta)S^\gamma \nabla^\mu S^\delta + G^\alpha(\vec{S} \cdot [\nabla^\mu \vec{S} \times \partial^\mu \Delta\vec{S}]).$$

The approximate form of the polarization is also considered for antiferromagnetic multiferroics if the electric dipole moment is proportional to the scalar product of the spins [4]. The polarization evolution equation is derived as the evolution of the quantum average of the operator of the electric dipole moment under the influence of the Zeeman energy and the Coulomb exchange interaction antiferromagnetic multiferroics. The equilibrium solutions for the obtained model of multiferroics are discussed, including the spiral structures. Electromagnons under the influence of an external electromagnetic wave field in the terahertz range are considered within the framework of the proposed theoretical model.

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Electronic and magnetic properties of Sr_2TiFeO_6 implementing ab initio density functional theory

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Double perovskite oxides with the formula $A_2BB'O_6$, featuring 3d transition metals at the B and B′ sites, offer a versatile platform for investigating diverse electronic and magnetic properties. Electron correlation (U) and Hund's coupling (J_H) play a crucial role in determining those properties. Sr_2TiFeO_6 is a notable compound in this category, featuring a mixed valence state of Fe/Ti occupying the B/B' sites. The transport and thermoelectric properties of Sr_2TiFeO_6 have been investigated in some experimental investigations [1-3].

In this study, we have performed a theoretical investigation of the ground state structure, and electronic, and magnetic properties of Sr_2TiFeO_6 using Density Functional Theory (DFT). The Hubbard U parameter was included to accurately represent the correlation effects within the Fe d orbitals. Our electronic density of states (DOS) calculations reveal that the FM state exhibits metallic behavior, with distinct contributions from the two Fe atoms indicating mixed valence states of Fe^{3+} and Fe^{4+}. This underscores the crucial role that Fe d-states play in determining the electronic and magnetic characteristics of Sr_2TiFeO_6. Furthermore, the calculation of exchange interactions suggests a predominant antiferromagnetic interaction between Fe atoms, complemented by a weaker ferromagnetic component. This complicated interplay of magnetic interactions demonstrates the complexity of magnetic behavior and the frustration of Sr_2TiFeO_6.

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Modification of magnetic properties via the surface magnetic symmetry in antiferromagnets

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Antiferromagnets (AFMs) represent a wide class of magnetically ordered materials. While they offer a lot of technologically promising properties and rich physics like efficient spin torques or ultrafast dynamics, a high degree of their magnetic compensation challenges the readout of their state [1]. Here, using the magnetoelectric two-sublattice AFM Cr_2O_3 with the easy axis of anisotropy as the case study, we show that the difference between the bulk and surface magnetic point symmetry groups (MPSG) can result in a sizeable Dzyaloshinskii-Moriya interaction (DMI) driven by the surface symmetry [2].

The bulk Cr_2O_3 crystals characterized by $\bar{3}'m'$ MPSG have two nominally compensated, high-symmetry crystallographic cuts: *m* plane $(1\,0\,\bar{1}\,0)$ and *a* plane $(\bar{1}\,2\,\bar{1}\,0)$. Their MPSGs correspond to m' and 2, respectively, are determined as subsets of the bulk MPSG by the requirement to leave the polar vector of the surface normal unchanged [3].

MPSG on the surface is lower than in the bulk. This is a factor of modification of the surface energy density *w* depending on magnetization and the Neel vector (the AFM order parameter). For the *m*-plane crystallographic cut, MPSG allows *w* to have the homogeneous DMI terms and even a weakly ferromagnetic response. The microscopic origin of this DMI is the combination of the single-, inter-ion anisotropies and antisymmetric exchange driven by the break of the spatial inversion at the interface. By building the phenomenological energy functional and by means of ab initio calculations, we show that *m*-plane Cr_2O_3 is the canted ferrimagnet with finite magnetization components out-of-plane and along the *c* axis. Furthermore, the magnetization direction is switched with the change of a bulk antiferromagnetic domain. At 0 K, the equilibrium out-of-plane magnetization is 0.1 Bohr magnetons per unit cell due to the spin canting by 0.5° from the interface. This corresponds to the surface-symmetry-driven DMI of the homogeneous type coefficient being about 1 mJ/m^2. We performed zero-offset Hall measurements on the m-plane single crystal Cr_2O_3 to detect the out-of-plane interfacial magnetization. Using the field-cooling procedure to set the preferential AFM domain, we found a sizeable transversal resistance ρ which changes the sign with the AFM domain at room temperature. The temperature dependence of ρ indicates the different temperature dependencies of the anisotropy and antisymmetric exchange contributing to the surface-symmetry-driven DMI. The same procedure for *a*-plane Cr_2O_3 indicates the presence of interfacial magnetization related to the weak ferromagnetism of this crystallographic cut in Cr_2O_3 [2].

Our findings contribute to the understanding of the available magnetic responses of nominally compensated AFM surfaces and interfacial phenomena like spin pumping.

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Dy and Er magnetic impurities diluted in insulating hosts, promising candidates to realize stable single-atom magnets

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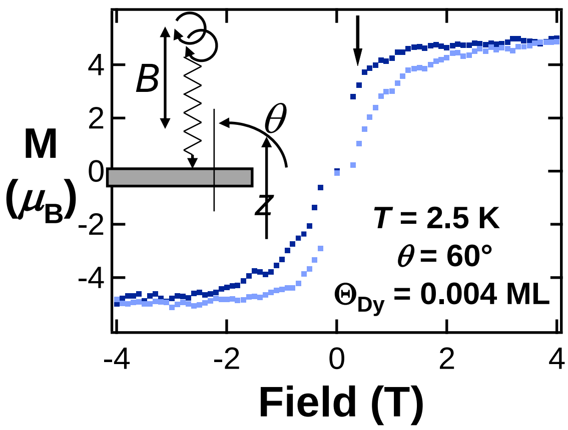
The study of the interaction between a magnetic impurity and a non-magnetic host is crucial, as their hybridization influences the electronic and magnetic properties of the system, including its anisotropy [1-4]. Significant advancements have been made towards using single-atom magnetic bits in devices, leveraging the strong localization of the 4f electrons in rare-earths (RE). Single Ho atoms adsorbed on thin MgO layers were shown to exhibit magnetic remanence up to 30 K [5], and the ability to read and write Ho magnetic "bits" was demonstrated [6]. Similarly, we have recently observed that Dy single atoms on $SrTiO_3$ [8] and BaO [9] exhibit slow paramagnetic relaxation. Magnetic stability is achieved by protecting the magnetic states of individual atoms from quantum tunnelling of magnetization and by avoiding scattering with substrate electrons. However, the thermal instability of surface-adsorbed atoms, leading to diffusion and aggregation, is a significant obstacle to using single-atom magnetic bits at technologically relevant conditions. A promising solution to this problem is to anchor the RE atoms within the insulating lattice's surface or bulk. For this purpose, we have grown thin films of several insulating oxides doped with rare earths by Pulsed Laser Deposition. Doping is achieved either within the surface or within the bulk. Here we discuss the structural and magnetic properties of Dy- and Er-doped thin films of $SrTiO_3$, $BaTiO_3$, and ZnO, with RE doping at around 1%. These three hosts were selected for their potential to manipulate the magnetic state of the RE atoms with electric fields. Evidence of hysteresis opening, reproduced from [8].



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Re-entrant spin glass behaviour, nonlinear magnetodielectric coupling and multicaloric effect in $Fe_2(MoO_4)_3$ multiferroic

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We report a comprehensive study of the hidden magnetism, nonlinear magnetodielectric coupling, and large multicaloric effect in the multiferroic L-type ferrimagnetic (L-FIM) compound $Fe_2(MoO_4)_3$ [1]. The materials show multiferroic properties below T_{N1} (12 K). Through temperature- and field-dependent ac and dc magnetic susceptibility measurements, we identify two distinct metamagnetic transitions at critical fields H_{C1} = 0.5 T and H_{C2} = 2 T, revealing the presence of re-entrant spin-glass-like (RSG) behavior below T_{N2} with a critical temperature (T_{g0}) of 6.2 K. These findings indicate a complex interplay between antiferromagnetic and ferrimagnetic domains, pointing to the emergence of hidden magnetic phases not previously observed in this material [2].

Our study also reveals a strong nonlinear magnetodielectric (MD) effect, where sharp anomalies in the dielectric constant correspond to these metamagnetic transitions. A magnetoelectric (ME) coupling coefficient of 0.56 ps/m is observed, which is comparable to that of magnetoelectric materials such as $NdCrTiO_5$ and $MnGa_2O_4$ demonstrating robust interaction between the magnetic and electric orders. The temperature dependent adiabatic temperature change (ΔT_m) due to the contribution of magnetic spin entropy exhibits a small value (0.8 K) with an oscillatory-like magnetocaloric effect. Remarkably, the large multicaloric effect exhibited by $Fe_2(MoO_4)_3$ is characterized by a total adiabatic temperature change (ΔT_{total}) of up to 5.2 K under a 7 T magnetic field, driven by a combination of magnetocaloric and magnetoelectric effects. The tunability of T_{N2} with temperature and magnetic field strength represents a unique multicaloric medium whose temperature and field parameters can be easily adjusted for potential cryogenic applications near liquid – helium temperatures.

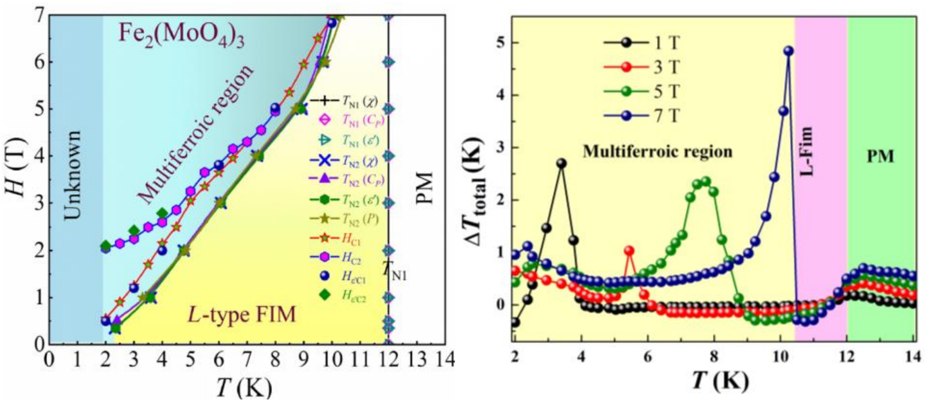

Figure 1: (a) H-T phase diagram of $Fe_2(MoO_4)_3$ and (b)temperature dependent total adiabatic temperature change (ΔT_{total}) for different H values in various temperature regimes.

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The role of domain walls in magnetization reversal of 2D periodic ferrimagnetic heterostructures

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In our previous paper [1], we have demonstrated how He^+ ion bombardment of ferrimagnetic Tb/Co multilayers produces two dimensional periodic patterns composed of Co dominated (Co^+) squares embedded in a Tb^+ matrix. Applying a magnetic field perpendicular to the surface of such heterostructures we can switch between two configurations: (1) a monodomain state with an interfacial domain wall situated on the borders between the Co^+ squares and the Tb^+ matrix; and (2) a multidomain state without domain walls (Fig.1). In the experiment presented in [1], the switching field of the squares (H_S^S) was smaller than the switching field of the matrix (H_S^M) $H_S^S < H_S^M$.

In Fig. 1a the full and minor magneto-optical hysteresis loops are shown for a structure similar to that described in Ref. [1], however, in the present case $H_S^S > H_S^M$, therefore the minor loop (dotted line in Fig. 1a) corresponds to the reversal of the matrix. The switching fields of the matrix are different for the transition between state (1) and (2) and for the transition between state (2) and (1) ($H_S^{M(1\rightarrow2)} < H_S^{M(2\rightarrow1)}$). The origin of the difference is related to the existence of a domain wall in state (1). As can be seen in Fig. 1b, the magnetic reversal from (1) to (2) takes place by the propagation of an already existing domain wall. However, for the reversal from (2) to (1), the creation of reversed domains starts from nucleation centers and is followed by domain wall propagation. Thus, $\Delta H_S^M = H_S^{M(2\rightarrow1)} - H_S^{M(1\rightarrow2)} = 80$ Oe determines the difference between magnetic fields necessary for creation of a reversed domain and the magnetic field required for domain wall propagation, respectively.

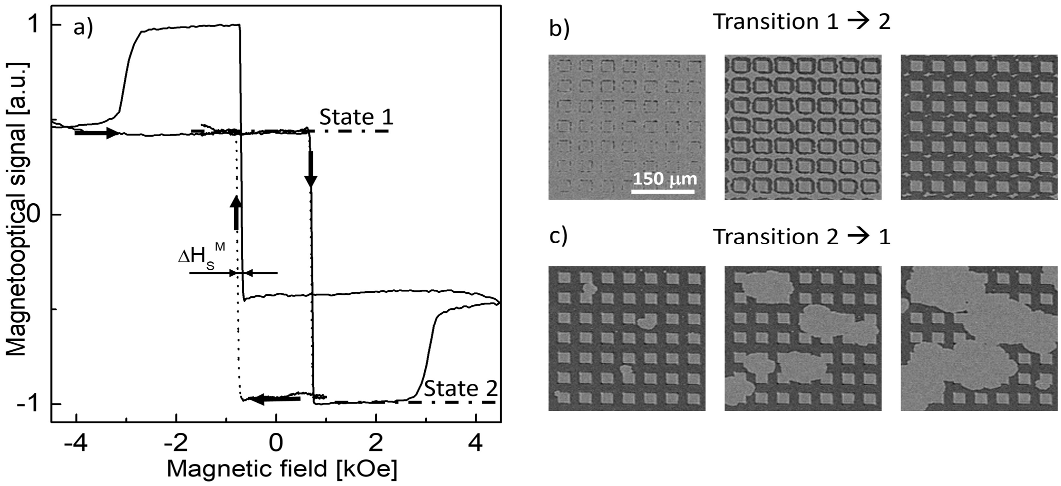

Fig. 1: Magnetization reversal of Tb/Co multilayers measured using magneto-optical Kerr microscope. a) full and minor hysteresis loop (solid and dotted line, respectively) calculated from magnetic domain structure changes with magnetic field oriented perpendicular to the surface. b), c) representative domain structure evolution during the reversal of the matrix, b) and c) correspond to the transition between states: 1 → 2 and 2→1, respectively.

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Manipulation of quantum metric in a topological chiral antiferromagnet at room temperature

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The quantum metric and Berry curvature are two fundamental and distinct factors that describe the geometry of quantum eigenstates. While the role of the Berry curvature in governing various condensed-matter states has been investigated extensively [1,2], the quantum metric, which was also predicted to induce topological phenomena of equal importance [3], has rarely been studied. Recently, breakthrough has been made in observing the quantum-metric nonlinear Hall effect in a van der Waals magnet [4,5], but the effect is limited at cryogenic temperature and is tuned by strong magnetic fields of several teslas. In our study [6], we demonstrate room-temperature manipulation of the quantum-metric structure of electronic states through its interplay with the interfacial spin texture in a topological chiral antiferromagnet/heavy metal Mn_3Sn/Pt heterostructure, which is manifested in a time-reversal-odd second-order Hall effect (ScHE) (Figs. 1a and 1b). We also show the flexibility in controlling the quantum-metric structure with moderate magnetic field and verify the quantum-metric origin of the observed ScHE by theoretical modeling. Our results open the possibility of building applicable nonlinear devices by harnessing the quantum-metric structure.

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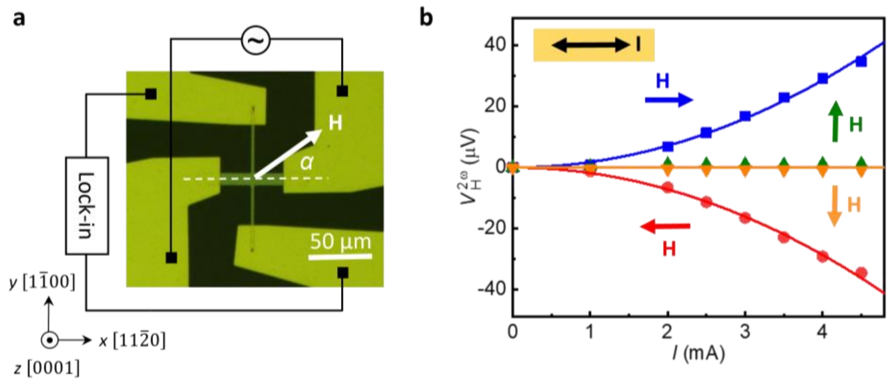

Figure. 1 **a**, Optical image of a Hall bar device and measurement setup for proving ScHE. **b**, ScHE as a funcation of applied current when the magnetic field of 0.4 T was applied along α = 0° (blue), 90° (green), 180° (red) and 270° (orange).

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Terahertz-driven magnetoelectric torque in the collinear antiferromagnet Cr_2O_3

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Magnetoelectric effect, facilitating a control of spins in magnets with the help of electric field, has long been seen as a cornerstone for future energy efficient and nano-scalable technologies for magnetic writing and processing of magnetically stored information. In contrast to spin-polarized currents, a control of spins with the help of electric fields promises much lower dissipations and in contrast to magnetic fields, electric fields are easier to apply to a nanoscale bit. Understanding temporal evolution of the magneto-electric effect, revealing how fast spins respond to an electric field is thus crucial for revealing the fundamental limit on the operational frequency of magnetoelectric devices. Here we report on ultrafast magnetoelectric effect in antiferromagnetic Cr_2O_3.

We studied Cr_2O_3 response, which is known as a prototypical magnetoelectric antiferromagnet (Néel temperature T_N=307.6 K), on the broadband THz excitation. The studied sample in the form of a thin plane plate cut such that the antiferromagnetically ordered spins of Cr^{3+} ions lie in the sample plane $(10\bar{1}0)$ parallel to crystallographic *c*-axis of the crystal.

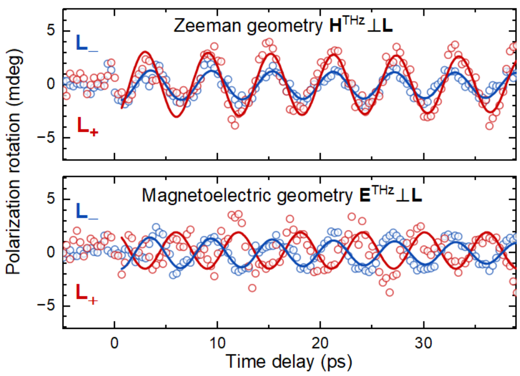

Figure 1: THz-induced spin dynamics measured for domains with oppositely oriented Néel vectors $\mathbf{L}_+$ and $\mathbf{L}_-$ for Zeeman and magnetoelectric geometries.

We have demonstrated that antiferromagnetic resonance at 0.165 THz [1,2] in Cr_2O_3 can be driven using nearly single cycle THz electromagnetic pulse. It is shown that the electric component of the THz pulse takes part and plays in the excitation significant role that exert a magnetoelectric along the Zeeman torque [3]. Hence, our experiments also reveal a fundamentally new mechanism for ultrafast control of spins in antiferromagnets.

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Visualisation of a triangular Ising antiferromagnet with two-dimensional lattices of non-magnetic fullerenes

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On-lattice frustration is not restricted to magnetic systems, and was in fact introduced about 90 years ago when Pauling provided an explanation for water ice's extensive entropy at 0 K. There, the relevant degree of freedom was structural, namely the position of H atoms between two O atoms. Several, however few, other examples exist of geometrical frustration whereby neighbouring objects (e.g. an atom, a molecule) cannot simultaneously minimise the different interactions they are subjected to. With this perspective in mind, we recently investigated the corrugation disorder encountered in two-dimensional (2D) triangular lattices of fullerene molecules self-assembled on a Cu(111) surface. Magnetic imaging is then replaced by standard scanning tunneling microscopy, wich reveals the structural (rather than magnetic) state of each individual molecule (up or down [1]) over assemblies of thousands of molecules. Applying a correlation analysis developed to characterise artificial frustrated spin systems, we unveiled the nature of the correlated disorder in this molecular system [2].

This allowed us to demonstrate that the system is well-described by an Ising frustrated spin Hamiltonian with interactions extending up to the third neighbours. In this framework, molecular islands can be considered at thermal equilibrium at a well-defined, low effective temperature [2]. We also detected signs of emerging order, and more recently managed to observe the dynamical evolution of the molecular lattice, which is fluctuating at the timescale of minutes following concerted changes of state of clusters of molecules [3]. The presentation will address these different aspects.

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The arctic square ice

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The square ice is a two-dimensional spin liquid hosting a Coulomb phase physics [1]. When constrained under specific boundary conditions, the so-called domain wall boundary conditions [2,3], a phase separation occurs leading to the formation of a spin liquid confined within a disk surrounded by magnetically ordered regions. Remarkably, the ordered regions are not just confined along the edges, but rather extend deep into the lattice, conferring to the spin liquid an average spin texture resembling that of an antivortex. In other words, the highly fluctuating central region of the lattice is not purely liquid-like, but is dressed by a static, curling spin texture. As a consequence, a monopole segregation also occurs, and monopoles are 'spontaneously' sorted according to the magnetic charge and magnetic moment they carry, without the application of an external driving force [4]. Counter-intuitively, monopoles carrying the same magnetic charge move in opposite directions!

Here, we numerically characterize the ground state properties of this spin liquid, coined the arctic square ice in reference to a phenomenon known in statistical mechanics. Our results reveal that both the vertex distributions and the magnetic correlations are inhomogeneous within the liquid region, and exhibit a radial dependence. If these properties resemble those of the conventional square ice close to the center of the disk, they evolve continuously as the disk perimeter is approached. There, the spin liquid orders. As a result, pinch points, signaling the presence of algebraic spin correlations, coexist with magnetic Bragg peaks in the magnetic structure factor computed within the disk. The arctic square ice thus appears as an unconventional Coulomb phase sharing common features with a fragmented spin liquid, despite the absence of magnetically charged defects [5].

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Thermally superactive artificial kagome spin ice structures

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Artificial spin ices are lithographically defined magnetic metamaterials, which are engineered to mimic various phenomena occurring in complex materials or theoretical models. The real space imaging of arrays of dipolar-coupled nanomagnets has led to the observation of cooperative phenomena such as emergent magnetic monopoles, magnetic correlations, and phase transitions [1]. An open challenge is the direct imaging of the low temperature phases in artificial kagome spin ice. Due to the high frustration associated with the kagome lattice, for nanomagnet sizes that allow x-ray microscopy investigations, the critical temperatures are lower than the blocking temperature, so that the moments freeze before the low temperature phases can be reached.

An effective mechanism to lower the blocking temperature, which was implemented at our Laboratory, is to exploit the Dzyaloshinskii-Moriya interaction (DMI) [2]. This interaction gives rise to a canting of the spins at the edge of the nanomagnets, effectively reducing the energy for magnetization switching. While this approach proved to be effective, the relatively modest DMI at the Pt/Py interface led to only a partial blocking temperature reduction.

We have now probed the properties of CoFeB and Co based artificial kagome spin ices, with and without a Pt underlayer, using the Magneto-optic Kerr effect (MOKE) and magnetic force microscopy (MFM). Longitudinal and polar MOKE hysteresis loops recorded for different magnetic layer thicknesses revealed the possibility to obtain superparamagnetic CoFeB and Pt/CoFeB nanomagnets at room temperature, which is essential for the observation of thermally-induced dynamics. In contrast, the magnetization in Co and Pt/Co based nanomagnets went from in-plane to out-of-plane on decreasing the magnetic layer thickness before any superparamagnetic behaviour was observed. The effective temperature of the artificial kagome spin ice was determined from MFM images for the different material systems, and we found a lower effective temperature for the CoFeB-based artificial kagome spin ices compared to that of the Py-based ones, indicating greater ordering towards the ground state. This can be explained by the larger saturation magnetization and low coercivity of CoFeB, implying a stronger coupling between the nanomagnets and a low energy barrier to switching, respectively.

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Current-induced magnetization switching in the presence of ferromagnetic interlayer exchange coupling and Dzyaloshinskii-Moriya interaction in Co/Pt/Co multilayers

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Spin-orbit torque-induced current magnetization switching (SOT-CIMS) provides an energy-efficient way of manipulating the magnetization in the ferromagnetic layers. We present a detailed study of the magnetization switching in the presence of the interlayer exchange coupling (IEC), Dzyaloshinskii-Moriya interaction (DMI) in multilayered Ti(2)/Co(1)/Pt(0-4)/Co(1)/MgO(2)/Ti(2) (thicknesses in nanometers) micrometer-sized Hall-bar devices. Here, the Pt acts as a source of the spin current and a nonmagnetic spacer whose thickness controls the magnitude of the IEC [1]. From anomalous Hall effect (AHE), anisotropic magnetoresistance (AMR) and spin Hall magnetoresistance (SMR) measurements, we found that the increase in Pt thickness (t_{Pt}) leads to the reorientation of both Co magnetizations: from the in-plane direction to the perpendicular-to-the-plane direction at $t_{Pt} \approx 1.3$ nm. For Pt thicknesses over 3 nm, the IEC weakens, causing the Co layers to become magnetized orthogonally to each other. The Brillouin light scattering (BLS) measurements (Fig.1a) allowed us to quantify the effective DMI (Fig. 1b), and explore its role in magnetization dynamics and switching. Experimental findings show four distinct resistance states under an external magnetic field and spin Hall effect related spin current (Fig.1c). We explain the result by the asymmetry between Pt/Co and Co/Pt interfaces and the interlayer coupling, which, in turn, influences the DMI [2]. The numerical simulations supported the experimental observations and helped uncover the underlying mechanisms. Furthermore, magnetic domain observations using polar magneto-optical Kerr microscopy provided insights into both the spatial distribution of magnetization and its dynamics for different IECs as well as its interplay with the DMI.

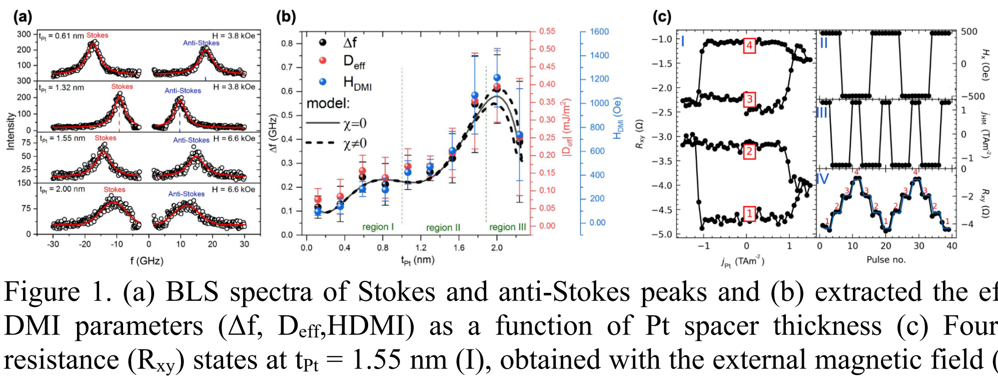

Figure 1. (a) BLS spectra of Stokes and anti-Stokes peaks and (b) extracted the effective DMI parameters (Δf, D_{eff},HDMI) as a function of Pt spacer thickness (c) Four stable resistance (R_{xy}) states at t_{Pt} = 1.55 nm (I), obtained with the external magnetic field (II) and current pulses (III). R_{xy} levels in (IV) correspond to the R_{xy} levels of CIMS loops in (I).

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Brillouin light scattering measurements of Dzyaloshinskii Moriya interaction: reproducibility and uncertainty

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Brillouin light scattering (BLS) is a well-established technique to measure spin waves (SWs) in magnetic materials due to its high sensitivity in a wide range of wave vectors and a relatively simple experimental apparatus and, over the recent years, it has become one of the most straightforward and reliable techniques to measure the DMI constant [1]. This is possible because SWs propagating in opposite directions have opposite chiralities, so the DMI contribution to the SW energy may either decrease or increase the SW frequency and results in an intrinsic nonreciprocity of the SW propagation which is revealed by BLS as a Stokes/Anti-Stokes peak asymmetry [2]. Nonetheless the problem of the measurement's reproducibility as well as the uncertainty on the determination of the DMI constant remains an open problem. As a matter of fact, in the scientific literature there are several examples of inconsistent results about DMI properties, obtained on nominally identical samples with different experimental techniques and, sometimes, even with the same experimental technique from different groups [3]. In the present study we investigated, by means of BLS, the DMI on ferromagnetic/heavy-metal multilayers, like Pt(3.0nm)/Co(0.8nm) as an example, with emphasis on the reproducibility of the measurements and on the uncertainty on the extracted value of the DMI constant. For this experimental analysis we repeated the BLS measurements on different regions of the same sample and we also repeated the measurements to obtain a reasonable statistic to extract the value of the DMI constant with a reliable uncertainty. The results of this study show how the DMI constant can sometimes vary even in regions of the sample which are very close to one another, like 1-2 mm, by a substantial amount. We point out the importance to understand if and how these fluctuations can be explained by statistical uncertainty or by an actual difference in the local sample properties. The final aim of this work is to try and establish good practices in the experimental determination of DMI constant by means of BLS.

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Micromagnetic simulations for the ML-based evaluation of the DMI parameter

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The determination of the DMI value can be challenging through experimental techniques. In this case, a Machine Learning (ML) approach can be useful, and it can rely on magnetic domain pattern obtained by micromagnetic simulations. The system, in fact, will be trained providing as input simulated bubble domains with known DMI value, and it should be able to reveal the DMI value of other simulated and experimental images.

With this aim, we have followed two different strategies of micromagnetic simulations, which correspond to the field-driven expansion of two kinds of solitons: (1) skyrmions, characterized by a topological number equal to one; (2) bubbles, with topological number zero. The idea is to prepare a consistent dataset for the ML training consisting of images of both solitons. Strategy 1, based on the simulations of skyrmions, represents an easy way to obtain a large number of images, because skyrmions, that have diameters of tens to hundreds of nanometers, can be simulated in small devices, thus requiring low computational time for each simulation; moreover, skyrmions are strongly dependent on the DMI value. Strategy 2, on the other hand, is closer to the experimental achievements based on the MOKE analysis of bubble expansions. In this system, the domain is a magnetic bubble stabilized by the magnetostatic field and the DMI plays a less important role. However, such solitons have diameters on the order of hundreds of micrometers and, consequently, larger devices are necessary to appreciate the role of the DMI in the expansion driven by the external field.

The figure below shows some of the images obtained for the two strategies.

Considering these two strategies, we are working to obtain a dataset of about 5k images to train the ML network for the detection of the DMI value.

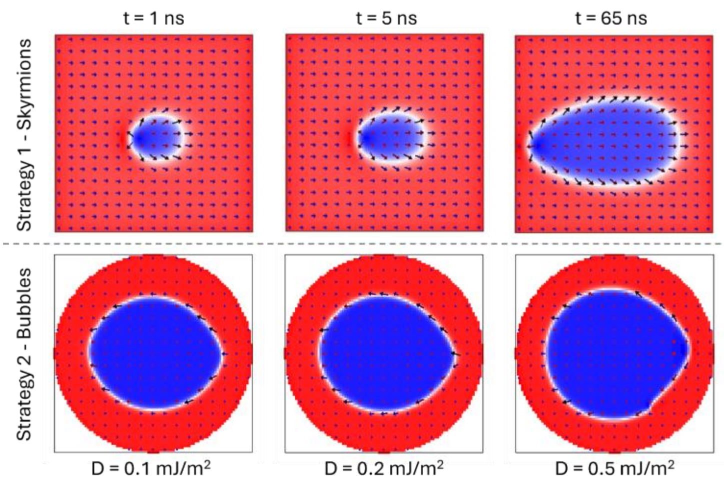

Figure 1: (Top) Snapshots of the skyrmion at different times during the expansion. (b) Snapshots of the bubble, at equilibrium, for different DMI values.

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Correlation of magnetic states in Magnetic Nanotubes with Ferromagnetic Resonance spectroscopy

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Magnetic nanotubes (NTs) have garnered immense attention for their potential in high-density magnetic memory, owing to their stable flux closure configuration and fast, reproducible reversal processes. Despite extensive research on the fabrication methods and magnetic properties of magnetic nanowires, magnetic nanotubes have been largely overlooked, even though they offer potential advantages over solid cylinders. For example, the ubiquitous curl magnetisation that wraps around a cylindrical crust is manifested in a variety of magnetic textures to reduce the energy required to reduce the demagnetization energy, leading to magneto-chiral properties [1]. However, characterizing their magnetic configuration through straightforward methodologies remains a challenge in both scope and detail. Here, we elucidate the magnetic state details using Remanence Field Ferromagnetic Resonance Spectroscopy (RFMR) for arrays of electrodeposited nanotubes. The NTs were created using a template-based method that allowed for precise control over their length and diameter [2]. Micromagnetic simulations revealed distinct spin configurations while coming from saturation, including the edge vortex, onion, uniform and curling states, with chirality variations depending on the preparation field direction. We identified individual spin configurations, as depicted in our micromagnetic simulations, through careful measurements of the RFMR spectra starting from both positive and negative saturation. The Observations revealed opposite RFMR spectra, indicating opposite magnetic spin configurations after removing the positive and negative saturating fields when the magnetic field was applied along ($\theta_H = 0^o$) and perpendicular ($\theta_H = 90^o$) to the nanotube axis. We observed a mixture of the non-uniform curling states with the end vortex state (onion-like curling state) at the end of the nanotubes for the $\theta_H = 0^o$ (90^o) and uniform magnetization states in the middle of the nanotubes for the $\theta_H = 0^o$configuration. Dynamic measurements in presence of the bias field, coupled with RFMR spectra analysis, provided insights into the evolution of individual modes. Additionally, our FMR analysis indicates nucleation within the edge vortex state, which was further corroborated by micromagnetic analysis and substantiated with First Order Reversal Curve (FORC) measurements.

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Magnetisation reversal in FeGa 3D nanostructures

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The manipulation of size and shape in nanostructures has been crucial to discover novel functionalities and applications across various scientific domains. Nanolithography has emerged as a versatile tool, enabling the precise manipulation of matter at the nanoscale and facilitating the creation of intricate three-dimensional materials with tailored properties [1].

In recent years, nanolithographic techniques have been extensively employed in the fabrication of three-dimensional magnetic materials. These advancements hold promise for significant contributions to various scientific and technological fields. Particularly to design magnetic materials, nanotechnology enables device miniaturization without compromising performance, and in some cases, even enhancing functional responses. This capability leads to novel applications in many diverse fields such as electronics, healthcare (e.g., miniaturized sensors for medical diagnostics), and data storage. Investigating magnetization processes in patterned magnetic structures, with respect to applied magnetic fields or electrical voltages, is crucial for understanding and optimizing their performance in such applications [2].

In this work, a bottom-up process used to design complex 3D structures, specifically nanowires with nanodots on one edge has been exploited as shown in Fig 1a. The process begins with the deposition of a thin film of magnetic material onto a substrate using techniques such as sputtering or chemical vapor deposition. Subsequently, a nanolithographic technique is employed to pattern the thin film into nanowires with desired dimensions. To create the nanodots on one edge of the nanowires, a modification of the bottom-up process is introduced. After patterning the nanowires, a selective etching step is performed using reactive ion etching (RIE). By carefully tuning the parameters of the RIE process, such as gas composition, pressure, and power, the length of the nanowires can be precisely controlled.

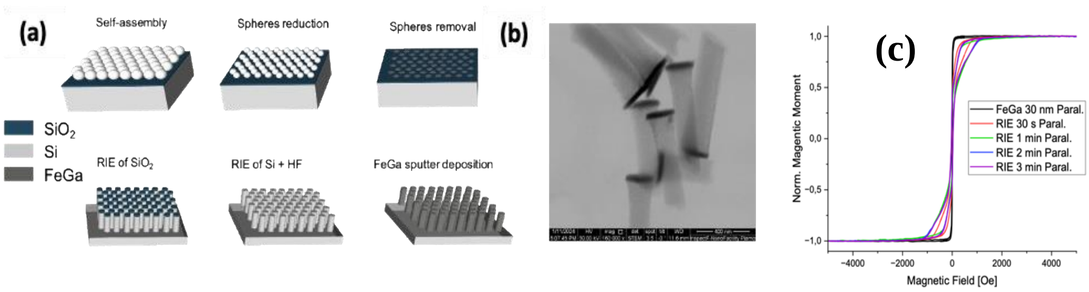

Figure 1: (a) Schematic of the process; (b) SEM micrograph of $Fe_{70}Ga_{30}$ nanowires by self-assembling of polystyrene nanosphere and (c) room-temperature hysteresis loops as a function of etching time.

This selective etching results in the formation of nanodots on one edge of the nanowires, with a typical diameter of around 250 nm. Room-temperature hysteresis loops of samples produced with different etching process are shown in Fig 1c. All the samples display the typical loop shape of vortex state configuration and the nucleation field is tuned by different etching times. The magnetic properties of the structures have been investigated by high-sensitive magnetometry. In addition to room-temperature magnetization curves, First-Order Reversal Curve (FORC) analysis has been employed to disentangle the contributions of the nanodisks and the nanowires to the overall magnetic behaviour. This analysis will support the refinement of the nanostructure designs to achieve desired magnetic functionalities.

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