Book of Abstracts

TRENDS IN MAGNETISM
VENICE 2022

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Peta Spin

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IUPAP Centenary YEARS 1922 - 2022

IEEE MAGNETICS

Qnami the quantum wave

AIMagn - Associazione Italiana di Magnetismo

Welcome to the 2nd TMAG Conference, the flagship event of Petaspin Association!

Trends in Magnetism (TMAG) is a multidisciplinary forum to share the latest advancements in magnetism, with a particular focus on trending topics. TMAG 2022 is the second event in a series of international conferences initiated by the Petaspin association, which started with TMAG 2020 in Cefalù. The location of the next edition will be announced in Venice. TMAG2022 is a Satellite Meeting of the IUPAP centenary celebration.

The main theme of TMAG 2022 will be "Antiferromagnetism and Light" where we want to create a chance for the experts in these two broad fields to meet and move the scientific community forward. "Light" (from terahertz to Xrays) offers a chance to measure many of the properties of antiferromagnets in time and space. Asides the main theme, TMAG 2022 will give space to trending topics in all the areas of magnetism, such as: biomagnetism, modeling of magnetic materials, novel magnetic materials and multilayers, spin torque switching, spin torque nano-oscillators and detectors, spin waves and magnonics, spintronics for neuromorphic and unconventional computing, topological magnetism.

The conference will be opened by a Nobel Lecture given by Nobel Laureate Prof. Albert Fert, and will take place in the beautiful historical centre of Venice, near the Canal Grande and Ca' Foscari University of Venice.

«We hope to see you in Venice!!»
Stefano, Vito and Jairo

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Trends in Magnetism

4th-9th September 2022, Venice

Program at a glance

September 4th			September 5th			September 6th			September 7th			September 8th			September 9th		
			09:00 - 09:30	keynote	Axel Hoffmann		keynote	Alessandra Lanzara		keynote	Alice Mizrahi		keynote	Tomas Jungwirth	Magnetism and correlated systems II	speaker 1	Yuriy Mokrousov
			09:30 - 10:00													speaker 2	Yves Acremann
			10:00 - 10:30	COFFEE BREAK			COFFEE BREAK			COFFEE BREAK			COFFEE BREAK			COFFEE BREAK	
			10:30 - 11:00	Antiferromagnetic materials I	speaker 1 Nicholas Kioussis		Ultrafast light sources	speaker 1 Laura Foglia		Unconventional computing	speaker 1 Shunsuke Fukami		Antiferromagnetic materials II	speaker 1 Antonio Caretta		speaker 3	Özhan Özatay
			11:00 - 11:30		speaker 2 Lucia Aballe			speaker 2 Myrta Gruening			speaker 2 Philipp Pirro			speaker 2 Andy Kent		speaker 4	Franca Albertini
			11:30 - 12:00		speaker 3 Helena Reichlova			speaker 3 Daniele Brida			speaker 3 Giovanni Finocchio			speaker 3 Matthias Althammer		discussion leader	Pallavi Dhagat
			12:00 - 12:30		discussion leader Olivier Klein			discussion leader Paolo Vavassori			discussion leader Burkard Hillebrands			discussion leader Mathias Kläui	TMAG 2022 awards and closing		
			12:30 - 15:30	FREE TIME			FREE TIME			FREE TIME			FREE TIME				
			15:30 - 16:30	Poster Session I			Poster Session II			Poster Session III			Poster Session IV				
16:00 - 18:00	TMAG 2022 registration		16:30 - 17:00	Dynamics in antiferromagnets I	speaker 1 Peng Yan		Dynamics in antiferromagnets II	speaker 1 Davide Bossini		Magnetism and correlated systems I	speaker 1 Romain Lebrun		Magnetic X-ray imaging	speaker 1 Peter Fischer			
18:15 - 18:30	TMAG 2022 opening		17:00 - 17:30		speaker 2 Takahiro Moriyama			speaker 2 Jean-Y. Chauleau			speaker 2 Fiona Forte			speaker 2 Claire Donnelly			
18:30 - 19:30	Nobel lecture	Albert Fert	17:30 - 18:00		speaker 3 Jean-Eric Wegrowe			speaker 3 Michael Först			speaker 3 Chiara Ciccarelli			speaker 3 Lucas Caretta			
			18:00 - 18:30		discussion leader Andrei Slavin			discussion leader Alexey Kimel			discussion leader Gaspare Varvaro			speaker 4 Erick Burgos-Parra			
			18:30 - 19:00											discussion leader Nicolas Jaouen			
				20:30 VISIT Groups A&B			21:30 VISIT Group C			19:00 SOCIAL DINNER							

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Trends in Magnetism TMAG 2022
4-9 September 2022, Venice (Italy)

Invited sessions

Sunday, Sept. 4

Nobel Lecture - h.18:30

presenting author		title
Fert	Albert	Switching greener with spintronics (and going beyond with orbitronics, skyrmionics etc.)

Monday, Sept. 5

Keynote presentation - h.9:00

presenting author		title
Hoffmann	Axel	Spin Currents with Antiferromagnets

Invited session - Antiferromagnetic materials I - h.10:30
Discussion Leader: Olivier Klein

presenting author		title
Kioussis	Nicholas	Elasto-dynamical induced spin and charge pumping in bulk heavy metals
Aballe	Lucia	Direct X-ray detection of the spin Hall effect in CuBi
Reichlova	Helena	Spontaneous Hall effect in an uncoventional antiferromagent with vanishing magnetization

Invited session - Dynamics in Antiferromagnets I - h.16:30
Discussion Leader: Andrei Slavin

presenting author		title
Yan	Peng	Magnon frequency comb
Moriyama	Takahiro	Spin transport and dynamics in antiferromagnets
Wegrowe	Jean-Eric	Spin-Hall effect including screening: presence of longitudinal pure spin current

Tuesday, Sept. 6

Keynote presentation - h.9:00

presenting author		title
Lanzara	Alessandra	From excitons to topological excitons and their fingerprints on the electronic bandstructure

Invited session - Ultrafast light sources - h.10:30
Discussion Leader: Paolo Vavassori

presenting author		title
Foglia	Laura	Nanoscale transient magnetization dynamics: a comprehensive EUV TG study
Gruening	Myrta	Nonlinear and extreme nonlinear optics from first-principles
Brida	Daniele	Ultrafast electron transport at the nanoscale

Invited session - Dynamics in Antiferromagnets II - h.16:30
Discussion Leader: Alexey Kimel

presenting author		title
Bossini	Davide	Nonlinear coherent femtosecond spin dynamics in antiferromagnets
Chauleau	Jean-Yves	Observation and manipulation of antiferromagnetic distributions in magneto-electric multiferroics.
Först	Michael	Controlling magnetism through nonlinear phononics

Wednesday, Sept. 7

Keynote presentation - h.9:00

presenting author		title
Mizrahi	Alice	Multilayers of synaptic and neural operations in a magnetic tunnel junction network through rf-to-dc and dc-to-rf conversion

Invited session - Unconventional computing - h.10:30
Discussion Leader: Burkard Hillebrands

presenting author		title
Fukami	Shunsuke	Probabilistic spintronics – from device physics to computing
Pirro	Philipp	Novel spin-wave sources for hybrid magnonic circuits
Finocchio	Giovanni	Computing with spintronic devices and probabilistic bits

Invited session - Magnetism and correlated systems I - h.16:30
Discussion Leader: Gaspare Varvaro

presenting author		title
Lebrun	Romain	Detection and emission of coherent magnons in antiferromagnetic insulators
Forte	Fiona	Orbital mechanisms for novel phases in spin-orbit coupled Mott systems
Ciccarelli	Chiara	The importance of the interface for picosecond spin pumping in antiferromagnet-heavy metal heterostructures

Thursday, Sept. 8

Keynote presentation - h.9:00

presenting author		title
Jungwirth	Tomas	Emerging research landscape of altermagnetism

Invited session - Antiferromagnetic materials II - h.10:30
Discussion Leader: Mathias Klaui

presenting author		title
Caretta	Antonio	A novel x-ray polarimeter for femtosecond magneto dynamical studies
Kent	Andy	Spin-orbit torques in antiferromagnet insulator/heavy metal heterostructures
Althammer	Matthias	Observation of the magnon Hanle effect in antiferromagnetic insulators

Invited session - Magnetic X-ray imaging - h.16:30
Discussion Leader: Nicolas Jaouen

presenting author		title
Fischer	Peter	Recent advances with magnetic X-ray spectromicroscopy to investigate novel topological spin textures
Donnelly	Claire	Revealing three-dimensional spin textures with X-rays
Caretta	Lucas	Manipulating Excitations in Magnetic Oxides
Burgos Parra	Erick	X-ray magnetic circular dichroism as a tool to investigate magnetic nanostructures.

Friday, Sept. 9

Invited session - Magnetism and correlated systems II - h.9:00
Discussion Leader: Pallavi Dhagat

presenting author		title
Mokrousov	Yuriy	ORBITAL MAGNETISM OUT OF EQUILIBRIUM: DRIVING ORBITAL MOTION WITH FLUCTUATIONS, FIELDS AND CURRENTS
Acremann	Yves	Observation of spin voltage and -accumulation by spin resolved femtosecond photoelectron spectroscopy
Ozatay	Ozhan	Ultrathin Metallic Antiferromagnets spin current manipulation and thermal stability
Albertini	Franca	Exploiting magnetic and martensitic flexibility of metamagnetic Heusler thin films and nanostructures

Trends in Magnetism TMAG 2022
4-9 September 2022, Venice (Italy)

Poster sessions

Poster Session I - Monday, Sept. 5, h.15:30

presenting author		abstract code	poster title
Nemec	Petr	p-044	Voigt effect-based pump-probe studies of noncollinear antiferromagnet Mn3NiN thin film
Bialek	Marcin	p-095	Cavity-mediated magnon-magnon coupling at 0.3 THz
Gördes	Jendrik	p-085	Co-evaporation of Mn1-xAux on a Nb(100) substrate capped with a pseudomorphic Au layer
Lahoubi	Mahieddine	p-121	Unusual thermal properties and field induced weak ferromagnetic phase in the exchange-frustrated antiferromagnet PrBCO at low temperature
Ruta	Sergiu	p-090	Ab-inito and atomistic spin dynamics characterisation of antiferromagnetic materials Mn2Au and CuMnAs
Dolgikh	Irina	p-047	Ultrafast emergence of ferromagnetism in antiferromagnetic FeRh in high magnetic fields
Ślęzak	Michał	p-116	Memory of frozen and rotatable antiferromagnetic spins in epitaxial CoO(111)/Fe and NiO(111)/Fe bilayers.
Wittmann	Angela	p-076	Role of substrate clamping on anisotropy and domain structure in the canted antiferromagnet α-Fe2O3
Grzybowski	Michał Jacub	p-102	Growth and characterization of semiconductor low-dimensional structures with antiferromagnetic MnSe
Pradhan	Gajanan	p-157	Local magnetization reversal in FeGa magnetic nanostructures
Graczyk	Piotr	p-096	Inertial hopfion motion under magnetoelectric torque
Sala	Giacomo	p-113	Asynchronous current-induced switching of rare-earth and transition-metal sublattices in ferrimagnetic alloys
Gruszecki	Pawel	p-055	The influence of Dzyaloshinskii-Moriya interaction and perpendicular magnetocrystalline anisotropy on magnetization dynamics in spin spirals and stripe domain patterns
Mangold	Maximilian	p-078	Ferromagnetic resonance as a spectroscopic technique for topological surface states investigation
Finizio	Simone	p-037	Into the fourth dimension: time-resolved soft x-ray magnetic laminography
Unikandanunni	Vivek	p-073	Inertial spin dynamics in epitaxial cobalt films
Basini	Martina	p-003	Terahertz electric-field driven dynamical multiferroicity in paraelectric SrTiO3
Khatu	Nupur	p-067	Magnetization Dynamics in CoGd Induced by Transient Gratings
d'Aquino	Massimiliano	p-111	Magnetization switching in the inertial regime
Malvestuto	Marco	p-093	The MagneDyn beamline at the FERMI free electron laser

Poster Session II - Tuesday, Sept. 6, h.15:30

presenting author		abstract code	poster title
Gubbiotti	Gianluca	p-122	Spin-wave edge and cavity modes in a moiré magnonic crystal
An	Kyongmo	p-053	Bright and dark states of two distant macrospins strongly coupled by phonons
Ngouagnia	Igor	p-143	Dynamic instability in high power FMR of a BiYIG nanodisk
Bhardwaj	Richa	p-099	Optically induced ultrafast magneto-dynamics in ferromagnetic alloy
Kanai	Shun	p-124	Electric-field induced collective spin dynamics in nanomagnet revealed by 30-ps single-shot measurements
Srivastava	Titiksha	p-142	Nonlinear interactions between spin-wave modes probed by parametric excitation in YIG microstructures

Szulc	Krzysztof	p-039	Spin-wave dynamics in the system of coupled waveguides
Cucini	Riccardo	p-008	Spin wave excitation via magnetoelastic coupling by transient grating experiments
Girardi	Davide	p-011	Three-dimensional nanoscale imaging of propagating spin waves via time-resolved X-Ray Laminography
Rickhaus	Peter	p-098	Scanning NV Magnetometry for Magnetic Memory Devices
Montoncello	Federico	p-123	Spin wave dispersion in bilayer hybrid systems composed of artificial spin ice and thin film: Brillouin light scattering measurements and simulations
Kadlec	Filip	p-120	Study of nonlinear absorption by electromagnons in multiferroic hexaferrites
Lu	Zhiwei	p-139	Influence of non-local damping on magnon properties
Wojewoda	Ondřej	p-138	Observing high-k magnons with Mie-resonance-enhanced Brillouin light scattering
Metzger	Thomas	p-084	Propagation of nearly single cycle terahertz pulse in antiferromagnetic CoF2
Blank	Thomas	p-043	Ultrafast laser-induced dynamics in ferrimagnetic Gd/FeCo multilayers
Gareev	Timur	p-083	Laser-induced THz coherent dynamics of rare-earth magnetic moments in DyFeO3
Carrion Ruiz	Francisco	p-081	Spin-, time- and angle-resolved photoemission spectrometer
Laterza	Simone	p-082	All-optical spin injection in silicon revealed by element specific time-resolved Kerr effect
Mentink	Johan	p-103	Supermagnonic propagation in 2D antiferromagnets

Poster Session III - Wednesday, Sept. 7, h.15:30

presenting author		abstract code	poster title
Perez	Lucas	p-061	In-vitro Real-Time Magnetic Recording of Neuronal Activity on Spinal Cord Slices
Vicentini	Marta	p-134	Simulation of in vivo tests of magnetic hyperthermia
Cuccurullo	Simone	p-154	Engineered magnetic plucking for frequency up-conversion in energy harvesters
Ruiz-Gomez	Sandra	p-016	Magnetization in cylindrical nanowires: the role of chirality
Mazalski	Piotr	p-091	Magnetic domains in W(dW)/Co(dCo)/Pt ultrathin epitaxial layers
Fernández González	Claudia	p-066	Scale-up the electrodeposition of magnetic nanowires for the application in composite bonded magnets
Jedryka	Ewa	p-027	Origins of magnetic anisotropy in Mn5Ge3Cx films studied by NMR
Wójcik	Marek	p-028	Magnetic interactions in Mn2GaC films studied by NMR
Du	Wei	p-034	Effect of buffer and cap layer on the thermally stable perpendicular magnetic anisotropy in buffer/CoFeB/MgO/cap structure
Mandru	Andrada	p-114	Tuning the coexistence regime of incomplete and tubular skyrmions in thin film heterostructures
Brondin	Carlo Alberto	p-101	Tuning magnetic coupling via defects formation at graphene/ferromagnet interface
Varvaro	Gaspare	p-074	Flexible thin film heterostuctures based on Co/Ni synthetic antiferromagnets: towards shapeable and sustainable spintronics
Bardziński	Piotr	p-030	Magnetocaloric response of quasicrystal-forming Al-Cu-Fe-B alloy improved by self-ordering of orthorhombic Fe2AlB2 phase
Shreya	Sonal	p-147	Memory and Communication Logic (MCL) in Magnetic Tunnel Junctions
Aykin	Ahmet	p-048	Stable antivortex nucleation and spin-orbit torque driven dynamics
De Vita	Alessandro	p-060	Evidence of magnetism-induced topological protection in the antiferromagnetic topological insulator EuSn2P2
Mook	Alexander	p-089	Topological hybrids of magnons and magnon bound pairs
Rozhansky	Igor	p-100	Topological Hall effect in ferromagnetic and antiferromagnetic chiral spin textures

Poster Session IV - Thursday, Sept. 8, h.15:30

presenting author		abstract code	poster title
Kozioł-Rachwał	Anna	p-117	Insight into chemical and magnetotransport properties of epitaxial α-Fe2O3/Pt bilayers
Wagner	Kai	p-144	Surface magnetization and antiferromagnetic domain walls in Cr2O3
Brambilla	Alberto	p-086	Preparation of Cr2O3 nanostructures for the application in organic antiferromagnetic spintronics
Kamba	Stanislav	p-054	THz-field-induced transient magnetization and ferroelectric polarization in quantum paraelectric KTaO3
Garg	Priyanka	p-129	Spin Hall magnetoresistance in 3D antiferromagnet insulator, Ho0.5Dy0.5FeO3|Pt heterostructure
Selvi	Ege	p-105	Characterization of Finite-Size Effects in Antiferromagnetic Films Using Spin Pumping Effect
Schmoranzerová	Eva	p-079	Antiferromagnetic-like optical transition in thin YIG films as seen by quadratic magneto-optics
Sánchez-Tejerina	Luis	p-056	Antiferromagnetic THz oscillations excited by sub-picosecond structured laser pulses
Kadlec	Christelle	p-119	How THz circularly polarized ligth can be used to determine the mass of vortices in superconductors submitted to a magnetic field
Pancaldi	Matteo	p-057	Light and magnetic vortices: the experimental evidence of magnetic helicoidal dichroism
Leliaert	Jonathan	p-065	Thermoplasmonic nanomagnetic logic gates
Holt	Sam	p-131	Mag2exp: simulating experimental techniques from micromagnetic simulations
Stansill	Sean	p-040	The quantum thermodynamics of exchange stiffness
Alho	Bruno	p-109	Mean-field modelling of magnetocaloric effect of antiferromagnetic compounds
Manzin	Alessandra	p-136	Modelling design of magnetic nanomaterials for hyperthermia applications
Martín-Hernández	Rodrigo	p-051	Highly isolated femtosecond magnetic fields driven by azimuthally polarized laser beams in apertured nanoantennas.
Yeh	Tien-Tien	p-007	Robust phase retrieval method for broadband THz reflection spectroscopy
Jatkar	Kasturie	p-009	Terahertz spectroscopy of bulk InSb and SrTiO3 in reflection geometry
Pournaghavi	Nezhat	p-164	Transport properties in CrI3-Bi2Se3-CrI3 heterostructure

Nobel Lecture

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Albert Fert, Unité CNRS/Thales, Université Paris-Saclay, France

Switching greener with spintronics
(and going beyond with orbitronics, skyrmionics etc.)

My presentation will be a more general lecture than those that we, my colleagues physicists and me, generally present in conferences. I want to show how spintronics can not only push the technical limits of conventional electronics but also be crucially useful to reduce the worrying huge increase of energy consumption induced by the today explosion of digital data transfer. Two steps: switching greener with the today spintronic devices for the information technologies and, beyond, novel roads for the future with skyrmionics, orbitronics and terahertz emission, nanoscale components for neuromorphic computing etc.

Invited Talks

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Spin Currents with Antiferromagnets

Axel Hoffmann[a]

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Harnessing spin currents is a promising pathway towards low-power electronics. Towards this end, it recently has been recognized that antiferromagnetic materials can play an active role as conduits for spin currents, and that they can enable spin current generation and detection [1,2]. With respect to the later, we demonstrated spin current generation both via spin Hall effects in conducting antiferromagnets. We showed that CuAu-I-type metallic antiferromagnets (PtMn, IrMn, PdMn, and FeMn) have significant spin Hall effects, which in the case of PtMn become comparable to the ubiquitously used Pt [3]. The spin Hall angles increase for the alloys with heavier element; consistent with first-principle calculations of the spin Hall conductivities based on intrinsic spin Hall effects. Furthermore, the calculations suggest pronounced anisotropies of the spin Hall conductivities, which we verified using epitaxially grown antiferromagnetic films [4]. One peculiar aspect of antiferromagnets is that the antiferromagnetic spin structures can give rise to additional symmetry breaking, which in turn enables the generation of spin currents with novel geometries. Towards this end, we detected the magnetic spin Hall effects in $IrMn_3$ via the spin-orbit torques exerted on an adjacent ferromagnetic layer [5]. Furthermore, we explored spin-orbit torques in FeRh and discovered that in the antiferromagnetic state FeRh exhibits unusually strong spin-orbit torques with exotic symmetries [6].

This work was supported as part pf the Quantum Materials for Energy Efficient Neuromorphic Computing, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Materials Sciences through Award # DE-SC0019273, the National Science Foundation through the University of Illinois at Urbana-Champaign Materials Research Science and Engineering Center under Grant No. DMR-1720633 and was, in part, carried out in the Materials Research Laboratory Central Research Facilities, University of Illinois.

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[1] J. Železný, P. Wadley, K. Olejník, A. Hoffmann, and H. Ohno, Nature Phys. **14**, 220 (2018).

[2] S. A. Siddiqui, J. Sklenar, K. Kang, M. J. Gilbert, A. Schleife, N. Mason, and A. Hoffmann, J. Appl. Phys. **128**, 040904 (2020).

[3] W. Zhang, M. B. Jungfleisch, W. Jiang, J. E. Pearson, A. Hoffmann, F. Freimuth, and Y. Mokrousov, Phys. Rev. Lett. **113**, 196602 (2014).

[4] W. Zhang, M. B. Jungfleisch, F. Freimuth, W. Jiang, J. Sklenar, J. E. Pearson, J. B. Ketterson, Y. Mokrousov, and A. Hoffmann, Phys. Rev. B **92**, 144405 (2015).

[5] J. Holanda, H. Saglam, V. Karakas, Z. Zhang, Y. Li, R. Divan, Y. Liu, O. Ozatay, V. Novosad, J. E. Pearson, and A. Hoffmann, Phys. Rev. Lett. **124**, 087204 (2020).

[6] J. Gibbons, T. Dohi, V. P. Amin, F. Xue, H. Ren, J.-W. Xu, H. Arava, S. Shim, H. Saglam, Y. Liu. J. E. Pearson, N. Mason, A. K. Petford-Long, P. M. Haney, M. D. Stiles, E. E. Fullerton, A. D. Kent, S. Fukami, and A. Hoffmann, arXiv:2109.11108.

Elasto-dynamical induced spin and charge pumping in bulk heavy metals

Farzad Mahfouzi[a], Nicholas Kioussis[a]

[a] Department of Physics, California State University Northridge, USA

One of the primary objectives in the field of spintronics is the development of efficient means to generate pure spin current, which can be in turn used to manipulate the magnetization configuration and damping rate in magnetic based memory bits, spin transistors, and sensors. Various approaches have so far been proposed to generate spin current, which include; spin Hall effect (SHE), spin pumping from a precessing ferromagnet into an adjacent normal metal, the spin Seebeck effect, and spin current pulses produced by ultrafast laser induced demagnetization process.

Recently, a different approach to generate spin current was demonstrated experimentally in X/CoFeB/MgO (X=W,Pt,W) heterostructures where the spin current emerges from the lattice dynamics in strong spin-orbit nonmagnetic metals (Pt, W), and flows transverse to the propagation direction of the surface acoustic wave[1]. This is similar to the conventional SHE where the spin current propagates orthogonal to the electrical current. However, to date, the underlying atomistic mechanism for spin pumping in response to the elastic wave propagation remains unresolved.

Using ab initio based electronic structure calculations we reveal the emergence of a dc charge (spin) current in response to acoustic phonons in heavy metals (Pt), shown schematically in Fig.1 (a, where the spin current flows transverse to the phonon propagation direction. The numerical calculations are carried out using Floquet approach, as depicted in Fig. 1(b), within Density-Functional Theory, where we have calculated the elastodynamical-induced charge and spin pumping in bulk Pt and demonstrate that: (i) the phonon-induced charge (spin) current saturates (diverges) in the limit of ballistic transport regime, signifying its intrinsic (extrinsic) origin. This is in sharp contrast to the electric field-induced charge (spin) current where the corresponding longitudinal (transverse) conductivity is extrinsic (intrinsic).; (ii) The longitudinal charge current is of nonrelativstic origin, while the transverse spin current is a relativistic effect that to lowest order scales linearly with the spin-orbit coupling strength; (iii) Analogous to the SHE, the spin polarization orientation is orthogonal to both the spin current and phonon propagation directions; and (iv) both charge and spin pumped currents have parabolic dependence on the amplitude of the elastic wave.

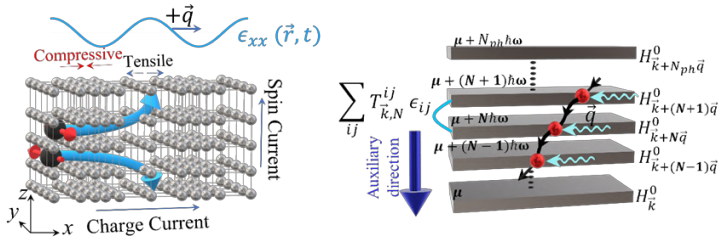

Figure 1: Left: Schematic of the elastodynamical-induced charge and spin current in bulk heavy metal under a time- and position-dependent strain. Right: Floquet space representation of the combined electron-phonon system.

[1] Takuya Kawada et al, *Acoustic spin Hall effect in strong spin-orbit metals*, Sci. Adv. **7** : eabd9697 (2021).

Direct X-ray detection of the spin Hall effect in CuBi

S. Ruiz-Gómez[a,b*], R. Guerrero[c+], M. W. Khaliq[b], C. Fernández-González[a,c], J. Prat[b], S. Finizio[d], P. Perna[c], J. Camarero[c,e], L. Pérez[a,c], L. Aballe[b], M. Foerster[b]

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[c] IMDEA Nanociencia, 28049 Madrid, Spain.
[d] Swiss Light Source, Paul Scherrer Institut, 5232 Villigen, Switzerland.
[e] Universidad Autónoma de Madrid, Campus de Cantoblanco, 28049 Madrid, Spain.

The spin Hall effect and its inverse are important spin-charge conversion mechanisms widely investigated due to their fundamental importance in the development of spintronic devices. Their measurement is typically done by electrical detection schemes involving an interface with other magnetic materials and thus, a combination of the properties of both materials as well as the interface are measured. Optical detection schemes have been successfully used for the determination of SHE in semiconductors. This approach is, however, challenging for metallic systems, due to their considerably shorter spin diffusion lengths. Only recently, optical measurements for Pt and W have been reported [1].

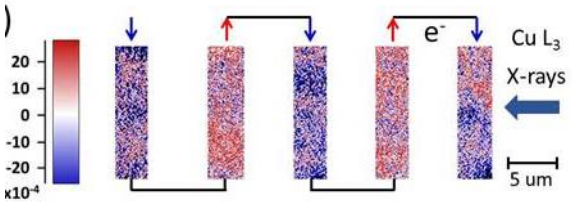

Figure 1: visualization of the spin accumulation in a $Cu_{95}Bi_5$ electrode

On the other hand, x-ray magnetic circular dichroism (XMCD) has become a reference tool for precision measurement of small or diluted magnetic signals. We thus propose the use of XMCD-PEEM microscopy for direct, interface-free determination of SHE in metals. In particular, we report the observation of spin separation due to SHE in a single layer of Bi-doped Cu ($Cu_{95}Bi_5$), a material in which giant SHE has been reported [2,3]. We performed interface free x-ray spectro-microscopy measurements at the Cu $L_{3,2}$ absorption edges while applying electrical current to the sample. As expected for SHE, the sign of spin accumulation depends on the direction of the current and the amplitude of the XMCD signal scales with the current density and has different sign at the L_2 and L_3 absorption edges. We measured an induced magnetic moment of $(2.7 \pm 0.5) \times 10^{-12} \mu_B A^{-1} cm^2$ per Cu atom averaged over the probing depth, which is of the same order as for Pt measured by magneto-optics. Our results constitute the proof of concept for the direct, interface free and element-selective measurement of the SHE in a single material by means of X-ray spectro-microscopy, and highlight the potential of CuBi for spin-charge conversion applications [4]. This method can be directly applied to antiferromagnetic materials thanks to X-ray magnetic *linear* dichroic contrast.

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Spontaneous Hall effect in an uncoventional antiferromagent with vanishing magnetization

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Spontaneous Hall effect has long been studied in ferromagnets and used to be commonly associated with magnetization. More recent developments of the intrinsic spontaneous Hall effect have predicted the phenomenon in systems with suppressed magnetization. It has been subsequently observed in antiferromagnetic crystals with geometrically frustrated lattices and/or typically exotic and rather strongly relativistic elements [1]. The family of materials that can exhibit spontaneous Hall effect has been significantly expanded by unconventional antiferromagnets with opposite spin sublattices coupled by crystallographic rotations [2]

In this talk, we present our observations of the spontaneous Hall effect in an unconventional antiferromagnetic candidate - Mn_5Si_3 epilayers [3]. We studied Mn_5Si_3 thin films grown on Si(111) substrate. Epitaxial constraints stabilize a hexagonal unit cell in the magnetic state distinct from previously described phases in bulk crystals [4]. We observe a sizable spontaneous Hall conductivity of 5-20 S/cm with large remanence (Fig.1 left) and negligible net magnetization (Fig.1 right). The Hall signal can be explained by an unprecedented type of the unconventional antiferromagnetic metallic band structure with time-reversal symmetry breaking spin-polarized valleys. Our results demonstrate the possibility of studying the topology of bands with broken time-reversal symmetry in crystals with unfrustrated lattices and weakly relativistic abundant elements.

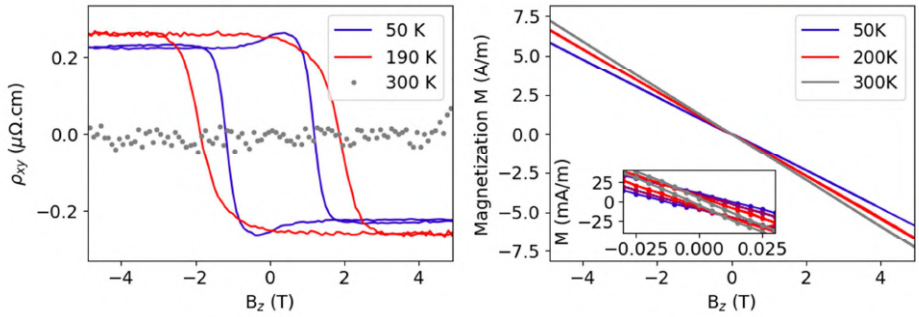

Figure 1: Left: anomalous hall effect in a Mn_5Si_3 film. Right: magnetization measurements in Mn_5Si_3 films. Inset: Detail of magnetization loop in small magnetic fields.

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Magnon frequency comb

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Abstract: We theoretically study the magnon-skyrmion interaction and predict a magnonic frequency comb (MFC) generated above a threshold driving amplitude, where the nonlinear scattering process involving three magnons prevails. The mode spacing of the MFC is equal to the breathing-mode frequency of the skyrmion and is thus tunable by either electric or magnetic means. The threshold of the driving amplitude and the excitation window of the driving frequency are well modeled by the Hamiltonian formalism involving the sum-frequency and difference-frequency processes of three magnons. Theoretical predictions are verified by micromagnetic simulations, and the essential physics can be generalized to a large class of magnetic solitons, such as domain walls and vortices. Terahertz frequency combs induced by nonlinear magnon-solition interaction in antiferromagnets are also an interesting issue. Our results open a novel avenue to study the frequency comb physics in magnetic systems combining the advantages of magnons and general magnetic textures.

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Reference

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Spin transport and dynamics in antiferromagnets

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In antiferromagnetic spintronics where manipulation of the antiferromagnetic spins is a central technological challenge [1], it is important to understand the spin transport and dynamics properties in antiferromagnets. We have recently explored a spin transport in insulating antiferromagnets as well as the antiferromagnetic dynamics in THz range.

The frequency-domain THz spectroscopies of antiferromagnet led to detail quantitative analysis of the antiferromagnetic damping [2], observation of the THz spin pumping effect in NiO/Pt and NiO/Pd and determination of the spin mixing conductance [3], and control of the antiferromagnetic resonance properties by various cation substations of antiferromagnetic oxides [4, 5].

We showed a long-distance spin current transport in crystalline antiferromagnets with a particular crystalline orientation [6] and also showed the spin transport in the THz range [7]. It was found that the spin polarization rotates associating with the Néel vector orientation. The results not only revealed the high-speed spin transport in the antiferromagnet but also the transient interaction between the spin current and the Néel vector.

The talk will focus on our recent investigations on spin transport and dynamics in antiferromagnets including abovementioned results.

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Spin-Hall effect including screening: presence of longitudinal pure spin current

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Spin-accumulation can be produced at the edges of a conducting bar by injecting an electric current into a non-magnetic material with high spin-orbit coupling. This effect is called Spin Hall Effect (SHE).

One of the main difficulty for the description of the SHE is the same as for the classical Hall effect: it is due to the fact that the values of the charge and spin accumulation at the edges of the Hall bar are not directly imposed by the external constraints (the boundary conditions) but by the system itself, in reaction to the spin-orbit effective magnetic field and the current injection. As a consequence, the determination the solution of the spin-dependent drift-diffusion equations at stationary state - that necessitates the knowledge of the boundary conditions - is problematic.

It is however possible to take into account the non-equilibrium nature of the electric screening on the basis of the least dissipation principle [1-4]. The global constraints are used instead of the local boundary conditions. The minimization of the dissipation functional - under the approximation of both weak and strong spin-flip scattering - leads to analytical expressions of the spin-currents and the spin-accumulation. It is shown that the spin-accumulation can reach 1% of the density of charge carriers in semiconductors. The spin-accumulation is found to be linear from one edge to the other, as observed in the experiments reported in reference [5].

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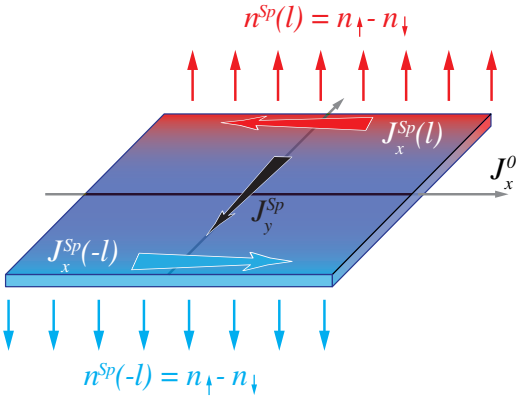
$n^{Sp}(l) = n_{\uparrow} - n_{\downarrow}$
$J_x^{Sp}(l)$
J_x^0
J_y^{Sp}
$J_x^{Sp}(-l)$
$n^{Sp}(-l) = n_{\uparrow} - n_{\downarrow}$

From excitons to topological excitons and their fingerprints on the electronic bandstructure

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Here I will discuss some recent work where, by using the ultrafast angle resolved photoemission spectroscopy exciton formation in semiconductors and in the presence of topology are discussed. Coulomb-bound electrons and holes forming excitonic quasi-particles and induced by coherent light-matter interactions in semiconductors, have attracted significant interest given their critical roles in both fundamental science and applications. Whether these excitonic state can be driven in the presence of topological invariants, what properties of the topological state persists and what are their fingerprints in the material's band structure are all open questions. Here I will discuss some recent work where, by using the ultrafast angle resolved photoemission spectroscopy we study and reveal under which conditions exciton state can be driven in a topological insulators and we discuss the differences with respect to semiconductor excitons and their fingerprints on the electronic structure.

Nanoscale transient magnetization dynamics: a comprehensive EUV TG study

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[a] Elettra Sincrotrone Trieste, Trieste, Italy

The manipulation of magnetization on nanometer length- and femtosecond time-scale is paramount for light-controlled ultrafast magnetic data processing and storage applications.

To date, however, the wavelength limitations of optical radiation have restricted the capability of manipulating and studying magnetic phenomena on such a length scale. The advent of extreme ultraviolet (EUV) and X-ray free electron lasers (FELs) has opened up the possibility of extending laboratory-based, non-linear optical techniques to the short wavelength regime.

Here, we use crossed coherent femtosecond EUV pulses to produce transient sinusoidal gratings of magnetization with a period in the tens of nanometers range controlled by the wavelength and crossing angle of the excitation pulses. The dynamics of the magnetization gratings is then monitored via diffraction of a time-delayed EUV probe pulse.

This technique, which is the EUV extension of transient grating (TG) spectroscopy, has been pioneered at the EIS-Timer beamline of the free-electron laser (FEL) FERMI in Trieste, Italy.

In this talk, we review the most recent advances on the TG-based investigation of nanoscale transient magnetization dynamics.

First, we show how EUV-TG is capable of inducing transient magnetization gratings which appear on a subpicosecond time scale as the sample is demagnetized at the maxima of the EUV intensity and then decays on the time scale of tens of picoseconds via thermal diffusion [1].

Building upon this first demonstration, we investigate the transition from ultrafast demagnetization to all-optical switching (AOS) by looking at the ratio between the first and the second order of diffraction as a function of excitation fluence. Indeed, the non-linear fluence dependence of AOS induces a non-uniform spacing of the magnetization pattern that results in the appearance of even diffraction orders [2].

Finally, we compare the magnetization dynamics induced by intensity gratings with those launched by polarization gratings, obtained when the two excitation beams have orthogonal polarization. Here, the intensity distribution on the sample is uniform and ultrafast the formation of transient magnetization gratings has to be associated to the coupling of majority and minority spins with the electric field polarization.

Summarizing, EUV-TG is a promising tool for the ultrafast manipulation of magnetism Moreover, this approach can be applied also to the investigation of spin diffusion, magnons or skyrmions on length-scales comparable to electron diffusion length.

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Nonlinear and extreme nonlinear optics from first-principles

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In the past decades, many-body approaches based on the GW approximation and the Bethe-Salpeter equation have become state-of-the-art for calculating optical absorption in solids and nanostructures. In this talk, I'll first present a real-time approach derived from the non-equilibrium Green's function, that allows extending the GW+BSE approach beyond the linear regime.[1,2] Using this approach, I'll address the importance of many-body effects and in particular of excitonic effects for nonlinear optical properties.[3] For example, I'll look at the case of single-layer monochalcogenide whose strong Second Harmonic Generation cannot be reproduced within the independent-particle approximation.[4] In the second part of the talk, I'll then apply this approach to high-harmonic generation in solids. The latter seems to escape explanations through "simple" models: a first-principles approach can help to clarify the role and interplay of the "various ingredients" in the models proposed so far (e.g. intraband, interband, Berry's curvature).

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Ultrafast electron transport at the nanoscale

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Recently, we demonstrated that single-cycle pulses of minute energy content may result in extremely nonlinear optical phenomena at the nanoscale by exploiting an electronic circuit with a few-nanometre gap between the tips of an optical antenna. The strong electrical bias provided by the field contained in ultrashort optical pulses was harnessed to drive tunnelling and ballistic acceleration of electrons to generate a current through the free-space gap with PHz bandwidth [1]. This non-perturbative process is fully coherent with the driving radiation and occurs within a half-cycle of the near-IR carrier wavelength. In addition, we further explored this concept by gaining direct temporal information via interferometric autocorrelation measurements with two identical replicas of truly single-cycle driving pulses.

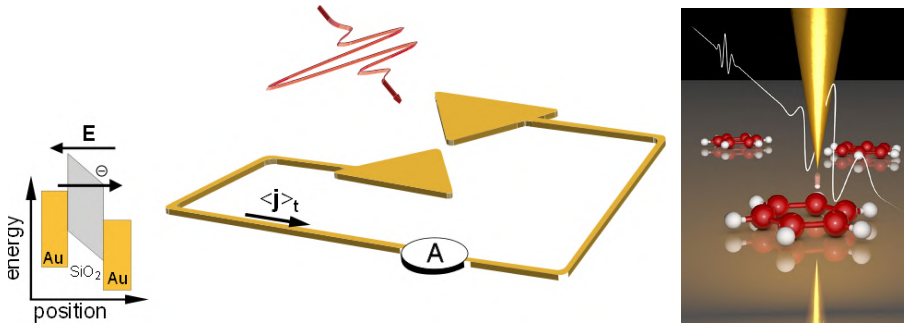

Figure 1: Conceptual sketch for ultrafast electron transport at the nanoscale. The optical field biases the junction between two metal thus inducing tunnelling and transport on a sub-cycle timescale. Left panel: experiments in a metallic junction made by a bowtie plasmonic antenna with the electron transport occurring in its feedgap. Right panel: same concept applied to a scanning tunnelling microscope with atomic resolution.

These experiments exploit the electric currents coherently driven at the gap of a single nanodevice by optical pulse with pJ energies. The full width at half maximum of the current autocorrelation amounts to less than one femtosecond, demonstrating that we can transfer individual electrons between the two contacts on an attosecond time scale. These concepts are currently being applied, with promising results, to a scanning tunnelling microscope with the bias provided solely by the optical field. In the future, we are aiming at a regime where the Coulomb interaction between electrons becomes important at truly atomic time and length scales. In addition, by a careful selection of the tip material, it will be possible to access the spin degree of freedom in the characterization of electronic wavefunctions.

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Nonlinear coherent femtosecond spin dynamics in antiferromagnets

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The wildly growing field of antiferromagnetic spintronics is currently addressing several fundamental questions. A major topic of investigations concerns the possibility to drive and manipulate coherent magnons on the ultrafast timescale. The proposition that driving such magnon modes, in a strongly nonlinear regime, could even result in switching coherently the order parameter on the femtosecond timescale needs to be considered. Optical experiments are usually performed focussing the beams into a single domain, whose size can be increased in several materials by annealing. Domains are usually perceived as a nuisance, occurring in the ground state of antiferromagnets, to be avoided for an efficient control of spins. In my talk I will discuss recent results, which experimentally disprove this commonly accepted wisdom. Relying on a spectroscopic opto-magnetic investigation of the femtosecond spin dynamics in the archetypal antiferromagnet NiO in a multidomain state, I will demonstrate: i) the excitation and a novel mechanism to arbitrary amplify a THz magnon mode via the exciton-magnon transition [1]; ii) nonlinear femtosecond spin dynamics, in the form of coupling between the different magnon modes, typically orthogonal in a single-domain state; iii) the microscopic nature of the coupling between modes, which is due to the presence of domain walls. This last point was supported by a phenomenological model [2] and, most importantly, by means of a control experiment performed in a single domain of the material. This experiment confirms that the coupling between the modes requires domain walls, as it is not observed in a single domain [3]. This experimental evidence is a manifestation of nonlinearity of the coherent femtosecond spin dynamics in magnets.

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Observation and manipulation of antiferromagnetic distributions in magneto-electric multiferroics.

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Antiferromagnets (AF) are currently in the limelight thanks to recent breakthroughs demonstrating the efficient effect of spin currents in interacting with the AF order parameter. So far, due to the lack of net magnetization, controlling AF distributions has been rather challenging. Current-induced AF control also opens new perspectives in Terahertz magnetization dynamics. On the materials side, antiferromagnets represent most magnetic materials and some of them show several simultaneous coupled ordered phases. They are commonly called 'multiferroics'. As a result, when the AF order is coupled to a net polarization, it may be controlled by applying a voltage. Multiferroic materials [1] are the focus of an intense research effort due to the significant technological interest of multifunctional materials as well as the rich fundamental physics lying in the coupling of various order parameters. Among all multiferroics, $BiFeO_3$ (BFO) is a material of choice because its two ordering temperatures (ferroelectric FE and AF) are well above room temperature, in addition of showing one of the largest magnetoelectric coupling. One difficulty in handling multiferroics lies in the challenging assessment of their coupled FE/AF textures, with characteristic sizes often in the hundreds of nanometers range. Optical second harmonic generation (SHG) has proven to be a powerful and elegant way to image complex multiferroic textures and to disentangle the different contributions at play and in particular to image the silent AF order [2]. In this presentation, after discussing the SHG imaging of AF domains distributions in BFO epitaxial thin films and their quasi-static actuation via different types of stimuli [3], we will address their ultrafast dynamics by assessing the time evolution of these multiferroic texture when subjected to intense femtosecond light pulses. Their efficient manipulation by the internally optically rectified sub-picosecond electric fields will be discussed, paving the way to an all-optical terahertz control of the AF order, independently of the electric polarization, but still using the magnetoelectric effect. We now aim at tackling these issues at typical scales below 100 nm in order to fully grasp their intrinsic mechanisms. In this goal, we will present our latest advances in near-field SHG imaging.

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Controlling magnetism through nonlinear phononics

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Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany

Optical excitation with intense light pulses has emerged as a powerful tool for the dynamical control of modern materials, in which functionality is determined by the intertwined physics of charges, orbitals, spins and the crystal lattice. In contrast to linear optical spectroscopy, which interrogates the collective properties of a material at equilibrium, the nonlinear excitation represents a radically new approach for the control of its properties away from thermodynamic equilibrium. This field has become a rich playground for fundamental research but may also be relevant for technical applications requiring ultrafast switching capabilities [1].

Strikingly, light pulses at mid-infrared and THz frequencies can dynamically tailor the atomic structure via the resonant excitation of phonons. The atomic displacements easily exceed those accessible by static structural engineering, driving materials into a nonlinear regime [2], with unprecedented dynamical symmetry breaking possibilities casted in the term *nonlinear phononics* [3].

In this talk I will focus on the application of this technique to induce a transient magnetization in the prototype antiferromagnet CoF_2, which is also known to be piezomagnetic [4]. I will show that the essential features of piezomagnetism can be reproduced with optical phonons alone. Nonlinear phononics is exploited to prepare the desired crystal field distortions that induce a ferrimagnetic moment of 0.2 μB per unit cell, nearly three orders of magnitude larger than achieved previously with mechanical strain.

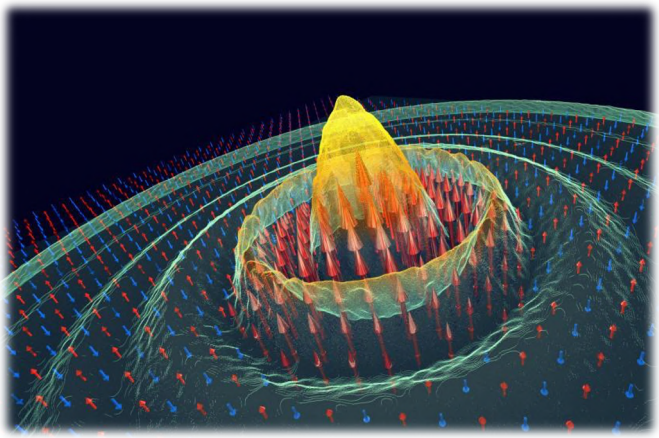

Figure 1: Illustration of the formation of a net magnetization in the antiferromagnet CoF_2 under resonant optical phonon excitation. The red and blue arrows denote the original AFM-ordered spins. Intense terahertz light pulses change the crystal structure to polarize the spins in the optically excited region.

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Multilayers of synaptic and neural operations in a magnetic tunnel junction network through rf-to-dc and dc-to-rf conversion

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One of the main challenges of neuromorphic computing is to replicate on-chip the hierarchical structure of deep neural networks, which use multiple successive layers of synapses and neurons to build meaningful representations of inputs and achieve high accuracy. This task is particularly complicated when nanodevices are used for their compactness to implement synapses and neurons, as the signals they generate are often complex, unstable, and need to be strongly reshaped before feeding other nanodevices. For example, while the connection of a nano-synapse array to nano-neurons has been demonstrated in memristive networks, the connection of nano-neurons to nano-synapses is still missing.

Here we take advantage of the multifunctionality and stability of magnetic tunnel junctions to implement synaptic operations by RF-to-DC conversion and neural operations by DC-to-RF conversion. The devices used for synapses and neurons are identical, and the transmitted signals, either sinusoidal or constant, are well controlled, providing a simple way to string the layers. We assemble a proof-of-concept neural network composed of nine magnetic tunnel junctions with the structure: RF inputs (2)/RF-to-DC synapses (4)/DC-to-RF neurons (2)/RF-to-DC synapses (2)/DC-to-RF neuron (1). We show that it solves nonlinear tasks with an accuracy drop of less than 2% compared to software. We show, through physics-based simulations, that a scaled network classifies real-world RF inputs with accuracy matching that of software for a drone identification task. Our work lays the foundation for deep spintronic neural networks at the nanoscale.

Probabilistic spintronics – from device physics to computing

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[b] Center for Science and Innovation in Spintronics, Tohoku Univ., Japan
[c] Center for Innovative Integrated Electronic Systems, Tohoku Univ., Japan
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Probabilistic, or stochastic, behavior is usually a cause of trouble in conventional electronics. In 1981, Richard Feynman gave a suggestion of an unconventional computing scheme, so-called the probabilistic computing, where probabilistic behavior of physical systems is effectively used for computation [1]. Probabilistic bit (p-bit) is a fundamental unit of the probabilistic computer, whose output fluctuating in time between 0 and 1 is controlled by external input. Recent studies have revealed that spintronics has a great potential to realize the p-bit [2]. In this talk, I will show two examples of the proof-of-concept of probabilistic computing using spintronics p-bit. Stochastic magnetic tunnel junction (MTJ) with a perpendicular easy axis is designed to constitute the p-bit. The first example of the proof-of-concept addresses a combinatorial optimization problem. Using eight p-bits, integer factorization is demonstrated with an algorithm developed for quantum annealing [3]. In the second example, I will show a capability of the spintronic probabilistic computer for Boltzmann machine learning. Using five p-bits and 15 RC elements, in-situ learning of weights and biases of the Boltzmann machine is demonstrated [4]. I will also discuss device physics and technology for high-performance probabilistic bit and computer [5-7].

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Novel spin-wave sources for hybrid magnonic circuits

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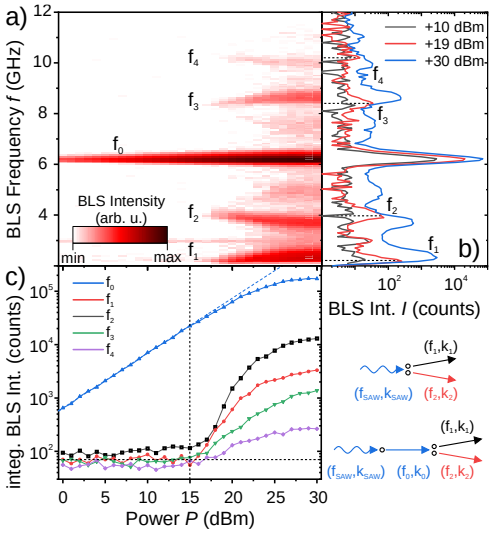
Coherent spin waves are ideal candidates for wave-based computing since they offer pronounced nonlinear properties, wavelengths scalable to the nanometre range and GHz clock rates compatible with CMOS-based circuits. In the last years, numerous linear and nonlinear magnonic building blocks have been demonstrated [1]. However, a technologically competitive implementation of magnonic circuits requires novel magnon sources with higher excitation efficiencies, the capability to excite short wavelengths, and an efficient way to create normalized signals. In this context, I discuss two routes towards novel magnon sources.



Parametric phonon-to-magnon instability in a CoFeB film excited by SAW at frequency f_0. (a) and (b) BLS spectra (c) intensity of the involved modes as a function of SAW power.

The first route is magneto-elastic excitation, where mechanical strain is used to create effective magnetic fields which in turn can excite spin waves. First, I present the generation of spin waves by coherent surface acoustic waves (SAW) in a thin metallic ferromagnetic film of CoFeB. Micro-focused Brillouin light scattering spectroscopy (µBLS) proves that the magneto-elastic excitation can efficiently drive the spin waves into the nonlinear regime (see Figure) [2]. Analytical modelling combined with micromagnetic simulations is used to reveal the different phonon-magnon instability processes by identifying the involved mechanisms and magnon modes. As a further step towards nanoscaled magneto-elastic spin-wave emitters, I present results on magnon-phonon-interaction in multiferroic nano devices composed of piezoelectric elements with lateral dimensions down to 80 nm which are mechanically coupled to magnon waveguides.

The second route for novel sources is the use the spin-wave nonlinearity itself in the excitation process. Using µBLS, we demonstrate an unprecedented nonlinear frequency shift of more than 2 GHz for spin waves in out-of-plane magnetized nano-waveguides. This shift enables the excitation of exchange spin waves of wavelength down to tens of nanometers. Moreover, the amplitude of the excited spin-wave is independent of the input microwave power due to self-locking by the nonlinear shift. This nonlinear method removes the wavelength limitations imposed by the size of inductive antennas, increases the excitation efficiency of short-wavelength spin waves, provides a way to robustly set the output amplitude to a fixed value, and enables direct on-chip integration.

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Computing with spintronic devices and probabilistic bits

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Spintronic technology, which takes advantage from the simultaneous use of charge and spin of the electron, has recently grown attention because of its success stories, starting from the hard disk read heads to the spin-transfer-torque MRAMs, in solid-state devices. A key building block of spintronic devices is the magnetic tunnel junction (MTJ). The fundamental element of a MTJ is a tri-layer composed by two ferromagnets separated by a thin isolating material. The resistance of this tri-layer depends on the relative orientation of the magnetization vector of each ferromagnet. In general, one of the two is designed to be fixed while the other can be manipulated easily with field, current and/or voltage. Together to the switching, it has been shown that in presence of a dc spin-polarized current it is possible to excited self-oscillation of the magnetization having the so called spin-transfer-torque oscillator while with an ac input it is achieved the diode effect. In this talk we will review the fundamental properties of spintronic devices and their applications as hardware building block in neuromorphic computing, in particular for the realization of neurons and synapses. Depending of the MTJ physical and geometrical parameters, it is possible to reproduce sigmoid and ReLU activation functions (most used so far at software level). we also show a possible use of spintronic diodes to implement analog multiplication, which is a key operation in convolutional neural networks (CNN), introducing the concept of degree of rectification (DOR). We will also discuss antiferromagnetic devices for implementation of synapses and memristive systems for computing applications. In the last part of the talk, I will review our recent results on Ising machines (IMs) and their potential hardware implementation with spintronic technology focusing on oscillator-based IMs and IMs built with p-bits (probabilistic computing). This computing paradigm is very promising to solve combinatorial optimization problems (COPs), which are a class of mathematical problems that have important applications in a variety of industrial and scientific fields, which span from logistics to geoscience, from water distribution network design to job scheduling. Many of these, such as maximum cut (Max-Cut), maximum Boolean satisfiability (max-SAT) or the travelling salesman problem, are NP-complete or NP-hard, meaning in their worst-case instances they have no polynomial-time solution. We show how the probabilistic computing can be used to solve max-sat instances (the other problems can be mapped on them) beating state-of-the art solvers having a time-to-solution to 95% at least one order of magnitude smaller.

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Detection and emission of coherent magnons in antiferromagnetic insulators

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Antiferromagnetically ordered materials are the most common class of magnetic materials with several crucial advantages over ferromagnetic systems. In contrast to the latter, antiferromagnets are stable and impervious to external fields, and can be operated at THz frequencies which makes them ideal candidates for a next generation of ultra-fast magnonic and spintronic devices[1]. Recent works highlighted how uncoherent magnons can propagate spin-information over long-distances insulating antiferromagnets[2–4]. However, efficiently excitation and detecting coherent magnons remains key challenging tasks to develop antiferromagnetic magnonic.

In this talk, I will first discuss how one can efficiently detect the magnetization dynamics of antiferromagnets through spin-pumping in an adjacent heavy metal layer[5]. I will highlight that canted antiferromagnets represent promising candidates to obtain large inverse spin-Hall voltage whilst conserving THz magnon modes. Using hematite as a model system, we measure at room temperature the antiferromagnetic resonance and an associated inverse spin-Hall voltage and observe that the sign of the inverse spin-Hall voltage provides direct information about the mode handedness as expected from coherent spin-pumping. Beyond these promising results, we also evidenced in the same AFM materials, that these antiferromagnetic magnons can hybridize strongly couple with microwave photons[6] which also opens perspective antiferromagnetic spin-cavitronics. In a second part, I will then discuss how one can generate coherent magnon modes in antiferromagnetic thin films. Whilst most theoretical studies focused on exciting magnetization dynamics in AFMs by spin-orbit torques, I will discuss some of our recent results evidencing that one can achieve narrow band THz emission from antiferromagnetic thin films using bulk optical torque or interfacial thermo-magneto-elastic process[7]. These promising results highlight strong perspectives to potentially tune THz narrowband emission of antiferromagnetic systems via the use of ultrafast magneto-strictions.

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Orbital mechanisms for novel phases

in spin-orbit coupled Mott systems

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In transition metal oxides, quantum phases marked by strong electron correlations are prone to dramatic reconstructions due to the interplay of multiple internal degrees of freedom and external perturbations. One of the best examples is the paradigmatic 4*d* insulator Ca_2RuO_4 (CRO), where comparable energy scales related to spin-orbital magnetic exchange, spin-orbit coupling, and structural distortions lead to a near degeneracy between different magnetic/orbital ground states and unconventional collective modes, which makes it highly sensitive to external stimuli [1].
Particularly, the insulating antiferromagnetic and orbital ordered ground state of CRO is prone to magnetic reconstruction by either applying temperature, doping or pressure. Notably, a moderate electric field can also be used to control the conducting properties, leading to novel phases that are absent at equilibrium, marked by a spatial reconstruction involving magnetic, orbital and lattice degrees of freedom.
In this talk, I will present recent results of a comprehensive theoretical analysis of the CRO, which focuses on the prominent role played by the orbital degree of freedom and its interplay with charge, spin and lattice degrees of freedom, when equilibrium and out of equilibrium forces are exerted. The first results concern the effect on magnetic ordering induced by partial substitutional doping of Ru d^4 with orbitally inactive d^3 Mn ions [2]. Orbital degrees of freedom are known to set out the character of the magnetic exchange in complex oxides. It will be shown that a transition between two symmetrically distinct antiferromagnetic A and B phases can be generally obtained by orbital reconstruction with a small concentration of Mn dopant [3].
In the second instance, I will discuss how the spin-orbital correlations in the Mott phase are dramatically affected by the application of a static electric field, showing an amplitude modulation in time, with reduction of the antiferromagnetism, and the possibility of having a collapse of the orbital order [4]. This result goes beyond the standard equilibrium view of superexchange mechanisms for spatially ordered patterns for both spin orientations and orbital occupations, thus opening novel paths for switching spin and orbital orders in the Mott phase through nonequilibrium electrical stimuli.

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The importance of the interface for picosecond spin pumping in antiferromagnet-heavy metal heterostructures

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Interfaces between heavy metals (HMs) and antiferromagnetic insulators (AFIs) have recently become highly investigated and debated systems in the effort to create spintronic devices able to function at terahertz frequencies. Such heterostructures have great technological potential because AFIs can generate sub-picosecond spin currents which the HMs can convert into charge signals. In this work we demonstrate an optically induced picosecond spin transfer at the interface between AFIs and Pt using time-resolved THz emission spectroscopy. We select two antiferromagnets in the same family of fluoride cubic perovskites, KCoF3 and KNiF3, whose magnon frequencies at the centre of the Brillouin zone differ by an order of magnitude. By studying their behaviour with temperature we correlate changes in the spin transfer efficiency across the interface to the opening of a gap in the magnon density of states below the Néel temperature. Our observations are reproduced in a model based on the spin exchange between the localized electrons in the antiferromagnet and the free electrons in Pt.

Emerging research landscape of altermagnetism

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Magnetism is one of the largest, most fundamental, and technologically most relevant fields of condensed-matter physics. Traditionally, two basic magnetic phases have been considered - ferromagnetism and antiferromagnetism. The breaking of the time-reversal symmetry and spin splitting of the electronic states by the magnetization in ferromagnets underpins a range of macroscopic responses in this extensively explored and exploited type of magnets. On the other hand, antiferromagnets have attracted significantly less attention because of their vanishing net magnetization. This talk will reflect on recent predictions of materials with an intriguing ferromagnetic-antiferromagnetic dichotomy, in which spin-split spectra and macroscopic observables, akin to ferromagnets, are accompanied by antiparallel magnetic order with vanishing magnetization, typical of antiferromagnets. An unconventional non-relativistic symmetry-group formalism offers a resolution of this apparent contradiction by delimiting a third basic magnetic phase, dubbed altermagnetism. We will start with an overview of the emerging unique phenomenology of the phase, and of the wide array of altermagnetic material candidates. We will then illustrate how altermagnetism can enrich our understanding of overarching condensed-matter physics concepts, ranging from Kramers theorem, Fermi-liquid instabilities and electron quasiparticles, to Berry phase. We will conclude by discussing potential impact of altermagnetism in fields including spintronics, magnonics, or superconductivity.

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A novel x-ray polarimeter for femtosecond magneto dynamical studies

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While in the visible range there are several polarimeters that can detect the polarization state of light waves, in the EUV (Extreme Ultraviolet) range polarimeters are lacking, slow and not very efficient. For this reason, we developed a polarimeter capable of single-pulse linear polarization angle detection in the EUV energy range. The WollasTON polarImeter for X-ray FEL sources (TONIX) is currently installed at the MagneDyn beamline at FERMI FEL, and it is available for users. In Fig. 1a we show the design and describe the mechanical realization of the TONIX.

Motivated by the rapidly growing field of femtomagnetism, we focus on time-resolved element-specific magnetic experiments. In particular, we study the magnetic dynamics of Ni atoms in a Ni_{80} Fe_{20} permalloy, by probing the RMOKE (Resonant Magneto-Optical Kerr Effect) at the $M_{2,3}$ Ni edge (67 eV) with the TONIX polarimeter. A schematic of the experiment is shown in Fig. 1b. A laser pump pulse excites the magnetic sample while a second time-delayed EUV pulse probes the same spot. The EUV reflected pulse is collected by the TONIX in order to measure its polarization state. As shown respectively in Fig. 1c and Fig. 1d, it is possible to reconstruct the reflectivity (ΔR/R) and the magnetic (ΔM/M) response of the material after the laser pump excitation.

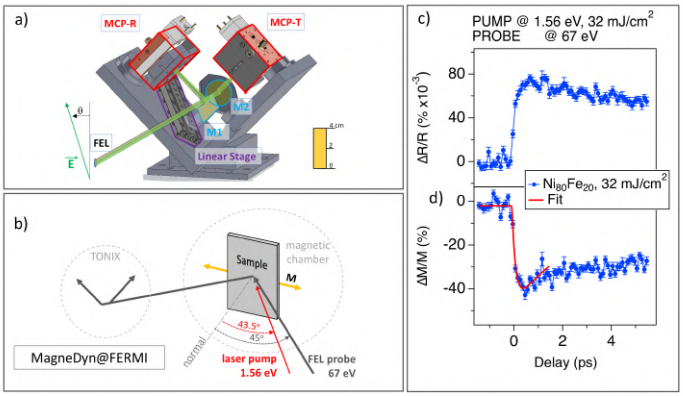

Figure 1: (Copyright 2020, AIP Publishing LLC [1]) a) TONIX polarimeter. The incoming FEL beam (green) is split by the first mirror M1 that reflects the radiation to MCP-R, the MCP (Multi Channel Plate) detector. The transmitted beam is reflected by the mirror M2 onto MCP-T. The TONIX estimates the polarization angle q of the FEL. b) Magnetic experiments on $Ni_{80}Fe_{20}$ performed at the Ni $M_{2,3}$ edge (67 eV); Pump-probe reflectivity DR/R (c) and magnetization changes DM/M (d) as a function of the time delay between the FEL and the laser pulse.

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Spin-orbit torques in antiferromagnet insulator/heavy metal heterostructures

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The effect of spin currents on the magnetic order of insulating antiferromagnets (AFMs) is of fundamental interest and can enable new applications. In this talk I will highlight our experimental studies of the effect of current pulses and spin-orbit torques on AFM order. We conducted two types of experiments: (1) Direct x-ray imaging of electrical switching of antiferromagnetic Néel order [1] and (2) Harmonic Hall effect measurements that make it possible to determine the form and magnitudes of the spin-torques that act on the Néel vector [2]. In both cases we have studied c-axis oriented α-Fe_2O_3 films, a predominantly easy-plane AFM, with an interface to Pt, where the Pt was patterned into the shape of a Hall cross. X-ray photoelectron emission microscopy shows that current pulses lead to reversible and repeatable switching with the current direction determining the final state. However, current pulses also produce irreversible changes in domain structure, in and even outside the current path, showing the thermal effects are important to the switching. We then used harmonic Hall signals to determine the amplitudes of field-like and damping-like spin orbit torques. Out-of-plane field scans were shown to be essential to determining the damping-like component of the torques. In contrast to ferromagnetic/heavy metal heterostructures, our results demonstrate that the field-like torques are significantly larger than the damping-like torques, which we correlate with the presence of a large imaginary component of the α-Fe_2O_3/Pt interface spin-mixing conductance. Our experiments highlight some of the significant differences between current-induced torques and switching of ferromagnetic and antiferromagnets.

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Observation of the magnon Hanle effect in antiferromagnetic insulators

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The spin-1/2 of an electron makes it an archetypal two-level system and inspires the description of other two-level systems using an analogous pseudospin. The quantized spin excitations of an ordered antiferromagnet represent pairs of spin-up and -down magnons and thus can be characterized by a magnonic pseudospin. The similarity between electronic spin and magnonic pseudospin has triggered the prediction of exciting phenomena like emergent spin-orbit coupling and topological states in antiferromagnetic magnonics. In the last years, first experimental observations of the associated dynamics of antiferromagnetic pseudospin have been reported [1,2,3]. Based on these findings, we will expand the concept of magnon pseudospin and the description of magnon pseudospin dynamics [4,5] and discuss the influence of dimensionality on the magnon Hanle effect. Additionally, we show our recent experiments demonstrating control of magnon spin transport and pseudospin dynamics in thin films with varying thickness of the antiferromagnetic insulator hematite (α-Fe2O3) utilizing two Pt strips for all-electrical magnon injection and detection [3]. We observe an oscillation in polarity of the magnon spin signal at the detector as a function of the applied magnetic field, which we quantitatively explain in terms of diffusive magnon transport. In particular, we observe a coherent precession of the magnon pseudospin caused by the easy-plane anisotropy and the Dzyaloshinskii-Moriya interaction. Moreover, we find peculiar changes in the magnon spin signal for thicker hematite layers indicating contributions from low energy magnons possessing finite spin. The finite spin signal from low energy magnons exhibits a dependence on the external magnetic field and can be included in our antiferromagnetic pseudospin theory. Our results are paramount in unlocking the high potential of antiferromagnetic magnonics towards the realization of electronics-inspired phenomena.

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Recent advances with magnetic X-ray spectromicroscopy to investigate novel topological spin textures

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Spin textures and their dynamics hold the key to understand and control the properties, behavior and functionalities of novel magnetic materials, which impact the speed, size and energy efficiency of spintronics technologies. Topology, frustration, and tailored geometries that impact spin textures have recently attracted significant scientific interest and led to intense research addressing a broad spectrum of challenging scientific and technological questions in novel spin textures, such as vortices, skyrmions, Hopfions, etc.[1]

Advanced characterization tools that provide magnetic sensitivity to spin textures, disentangling the role of individual components in heterogeneous material at high spatial resolution, ultimately at buried interfaces and in all three dimensions and at high temporal resolution to capture the spin dynamics across scales, are required to address those questions, and are therefore of large scientific interest. [2]

Various magnetic soft X-ray spectro-microscopies using polarized soft x-rays provide unique characterization opportunities to study the statics and dynamics of spin textures in magnetic materials combining X-ray magnetic circular dichroism (X-MCD) as element specific, quantifiable magnetic contrast mechanism with spatial and temporal resolutions down to fundamental magnetic length, time, and energy scales. [3]

In this talk, I will review briefly current achievements and future opportunities with magnetic x-ray spectro-microscopies. I will show our recent studies on the statics and dynamics of magnetic Hopfions, which are spin textures that can only exist in 3D. In addition to the topological winding number which are characteristic for magnetic skyrmions, they exhibit an additional topological linking number and can be viewed as twisted skyrmion tubes. Using a combination of soft x-ray magnetic microscopies we confirmed the creation of Hopfions in tailored magnetic multilayers [4], with target skyrmions [5] being precursors as predicted from theory [6]. Micromagnetic simulation using high performance computing tools on the field dependence of Hopfion structures showed characteristic dynamics including a transition to a toron state around 60mT [7].

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Revealing three-dimensional spin textures with X-rays

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Three dimensional magnetic systems promise significant opportunities for applications, for example providing higher density devices and new functionalities associated with complex topology and greater degrees of freedom [1,2].

In recent years, the development of magnetic tomographic techniques have opened up the possibility to map both the three-dimensional magnetic structure [3,4,5,6], and its dynamical response to external excitations [4,7]. In this way, both the static configuration, and dynamical behaviour, of topological structures within the bulk of a system [3,4,8], as well as in nanoscale structures [6,7,11] have been revealed.

Armed with these new experimental capabilities, we gain insight into a variety of magnetic systems. Within the bulk of a ferrimagnet, we observe 3D magnetic solitons which we identify as nanoscale magnetic vortex rings [8,9].

As well as naturally existing within the bulk, 3D spin textures can be introduced and controlled via the patterning of complex 3D magnetic nanostructures [10]. In a highly coupled curvilinear model system, consisting of cobalt double helices, we observe highly coupled domain walls that imprint textures in the magnetic stray field [11]. These new experimental capabilities for 3D magnetic systems open the door to complex three-dimensional magnetic structures, and their dynamic behaviour.

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Manipulating Excitations in Magnetic Oxides

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Excitations in magnetic materials, such as domain walls, skyrmions, cycloids, and spin waves, provide a rich playground for studying intriguing physical phenomena like chirality, topology, and spin-orbit interactions. Additionally, these excitations hold vast technological potential. For example, domain walls and skyrmions, which can be nucleated, annihilated, and translated by electrical stimuli, provide a promising approach to encode bits of information for next-generation memory and logic. Additionally, magnons, which can be generated by electrical or thermal mechanisms, can carry information with low losses. One technological and scientific challenge is to stabilize these magnetic excitations and manipulate them efficiently. This is critical for dense, power efficient, and fast beyond-CMOS memory and logic. However, in traditional metallic ferromagnetic materials, current-driven spin texture dynamics face an intrinsic "speed limit" and room-temperature-stable magnetic skyrmions are an order of magnitude too large to be useful in any competitive technologies. Furthermore, the energy requirements for current-driven manipulation of magnetism are orders-of-magnitude too large for practical devices. By synthesizing and engineering new classes of magnetic oxide materials systems, we show a pathway to overcome these fundamental limitations. Specifically, by using a combination of epitaxial growth techniques, interface design, and magnetic sublattice engineering, we drive magnetic domain walls to velocities over 4,300 m/s, demonstrate low-power electric-field control of magnons, and provide pathways for energy efficient spin-to-charge interconversion. Moreover, by using advanced electrical and optical techniques (and developing new ones), we show that these systems provide a new platform to study complex fundamental phenomena like inversion symmetry-breaking and even relativistic dynamics.

X-ray magnetic circular dichroism as a tool to investigate magnetic nanostructures.

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Chiral magnetic structures induced by Dzyaloshinskii-Moriya interaction (DMI) [1] have been proposed as the cornerstone of new technology applications such as high-density data storage devices or neuromorphic computing [2], due their room temperature stability and efficient current induced motion. Given the size and the in-depth complexity of these structures, techniques such as MFM or MOKE are often not enough to study and characterize them completely. In this sense, X-ray magnetic circular dichroism (XMCD) is a powerful tool to study chiral magnetic structures, with element specificity, nanometric resolution, and with access to the magnetism buried underneath the surface.

In this talk we present the use XMCD as a tool to investigate the properties of chiral magnetic structures by using two experimental setups: x-ray holography, HERALDO, in transmission mode and X-ray resonant magnetic scattering in reflection mode. In one hand, we use HERALDO to image and study the out-of-plane field dependence of a skyrmion array hosted in a ferromagnetic (FM) multilayer with perpendicular magnetic anisotropy (PMA) engineered to obtain skyrmion sizes down to 20 nm. In the other hand, we use small angle reflectivity XRMS to directly reveal the chiral properties of FM multilayers with tailored magnetic chiralities driven by spin-orbit-related effects at interfaces [3,4]. We show that it can straightforwardly and unambiguously determine the main characteristics of chiral magnetic distributions in perpendicularly magnetized multilayers [3]: its chiral nature, the quantitative winding sense (clockwise or counterclockwise), and its type, i.e. Néel (cycloidal) or Bloch (helical). Moreover, we prove that this approach combined with micromagnetic simulations reveals hybrid chiral spin texture in multilayers [4]. Finally, we studied the in-plane field dependence intensity of the dichroism and the appearance of second order diffraction peaks, usually forbidden on these systems. We have performed XRMS simulations on micromagnetic simulations to better understand the asymmetric change of the intensity of the magnetic asymmetry lobes the hysteretic behavior of these ones with the external field. By these means we were able to obtain a 3D characterization of the spin textures (HCDW) that are stabilized in these multilayers. It is worth noting that our approach of comparing observed XRMS data with simulations from a proposed 3D magnetic structure [5] can be applied to any other complex spin textures such as columnar hybrid skyrmions, magnetic bobbers or magnetic hopfions, both in static and dynamic experiments.

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ORBITAL MAGNETISM OUT OF EQUILIBRIUM: DRIVING ORBITAL MOTION WITH FLUCTUATIONS, FIELDS AND CURRENTS

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In modern spintronics properties of non-equilibrium orbital polarization and orbital currents start to attract significant attention. In this talk we will review the theory of orbital magnetism in low-symmetric crystals and corresponding current-induced orbital magnetization. We will in particular show that applied electrical currents and optical pulses can drive non-equilibrium orbital magnetism and currents of orbital angular momentum. These orbital currents can be used to transmit angular momentum over large distances in solids, and can be utilized to exert sizeable orbital torques on magnetization thus enabling magnetic switching even in light materials with weak spin-orbit interaction. Moreover, we will underline that in fluctuating magnets spin excitations can mediate a significant orbital response which can be coupled to temperature gradients so as to ignite thermal orbital currents. We will thus attempt to promote a paradigm that unleashing non-equilibrium orbital physics and entanglement of spin and orbital degrees of freedom in diverse classes of materials can lead to much richer physics than previously expected, and might provide a key to realization of novel properties of matter out of equilibrium as well as energy-efficient applications.

Observation of spin voltage and -accumulation by spin resolved femtosecond photoelectron spectroscopy

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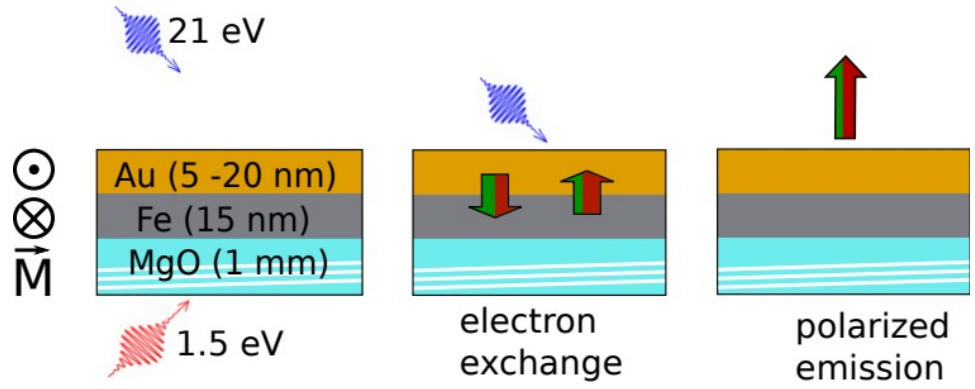
The generation of spin current pulses by laser-driven demagnetization links the field of ultrafast magnetism to spintronics. So far, this spin transport and its cause could only be observed indirectly. We demonstrate that femtosecond spin injection can be observed on the femtosecond time scale by spin and time resolved photoemission experiments.

We study thin, epitaxial iron films which are excited by a 800 nm pump laser beam. Photoemission by a higher harmonic generation source (photon energy: 21 eV) in combination with an electron spin polarimeter is used to measure the chemical potentials of the minority- and majority electrons. This way, we observe the spin voltage [1], which acts as the driving force for the spin current.

If we deposit a thin gold film onto the iron sample and excite the iron film through the transparent substrate, we can study spin injection and accumulation. The spin polarization in Au rises on the femtosecond time scale and decays within < 1ps [2]. The decay time depends on the Au film thickness. This thickness dependence can be described by a “spin capacitance” [3], which is similar to the capacitance in charge-based electronics.



Experimental setup for measuring the spin accumulation in a gold film. The ferromagnetic film is excited from the backside through a transparent substrate. Due to the ultrafast demagnetization effect a spin current is injected into the gold cap layer. The spin polarization in the gold layer is detected by spin-resolved photoelectron spectroscopy.

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Ultrathin metallic antiferromagnets

spin current manipulation & thermal stability

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Antiferromagnetic spintronics is currently regarded as a promising technology as a potential replacement for the ferromagnetic counterpart due to many benefits including superior scalability, lack of neighboring bit cross talk in memory devices, high radiation endurance and THz frequency dynamics. A technological realization of such devices necessitates a solid understanding of the behaviour of antiferromagnetic thin films in the ultrathin limit including thermal stability and susceptibility to torque applied by spin currents for easy manipulation of the Neel vector. However, this is quite challenging since conventional characterization techniques for ferromagnets such as reversal with a magnetic field application in practical limits and magnetic imaging in a university lab environment do not work. One needs to resort to more advanced techniques such as X-ray Magnetic Circular Dichroism or neutron diffraction for proper probing of the spin sublattices in a central lab environment.

Here we discuss our characterization of ultrathin antiferromagnetic metallic films including IrMn, PtMn, NiMn, PdMn and FeMn using two different techniques: one in which we rely on a pure spin current generated at the interface with Pt to momentarily reorient the spin sublattices following a field cooling procedure with three different orientations [1] where we study the effect of increasing the number of repetitions in heavy metal/ antiferromagnet bilayers for enhancement of spin torque from multiple interfaces and two in which we do temperature dependent ferromagnetic resonance of NiFe/ AFM bilayers [2] and correlate with exchange bias obtained from hysteresis measurements to uncover the blocking temperature-Neel temperature relationship (see fig. 1).

We will discuss the strategy for engineering antiferromagnetic ultrathin films for device applications based on the experimental results.

We acknowledge support from TUBITAK under project numbers 118F116 and 118F431 and Bogazici University Research Fund BAP under project number 17161.

Figure 1: Left: Exchange bias field as a function of temperature for different antiferromagnet ic film Right: Vector Network Analyzer- measurements of the resonance frequency as a function of temperature.

[1] Han et. al. Sci. Rep. **6**, 31996 (2016).

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Exploiting magnetic and martensitic flexibility of metamagnetic Heusler thin films and nanostructures

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Metamagnetic Heusler compounds display a first order structural transformation associated by large changes in magnetization and/or magnetic order. Their properties can be tuned by suitable changes in composition making them a versatile class of multifunctional materials thanks to the strong interplay between thermal, mechanical and magnetic degrees of freedom. In addition, their hierarchically interrelated twin-with-twin microstructure, in the low temperature martensitic phase, and the strong spin-lattice coupling allow to control their magnetic and multifunctional properties from the atomic to the micro-scale by tuning growth conditions and applying external fields.

In my talk I will report on our recent results on nano/microscale materials obtained by different fabrication methods (e.g. epitaxial thin films, patterned and free-standing structures) [1, 2]. Thin films and micro/nanostructures are of particular interest not only for the realization of new-concept devices, but also for providing insights into the magnetostructural coupling at the different length scales. The talk will focus, in particular, on microstructure engineering and microstructure related effects on the martensitic transformation, also in view of the possible exploitation of this class of materials in energy related and smart applications.

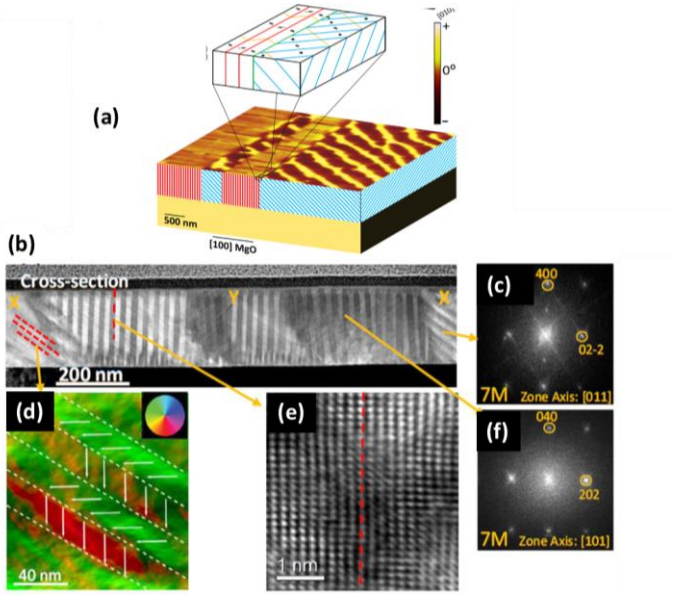

Figure 1 (a) Schematic representation of the twinning and magnetic configuration of Ni-Mn-Ga epitaxial films on (001) MgO: 3D slice of X- and Y-type twins including the direction of the easy magnetization axes. The resultant MFM signal is shown on the surface; (b) cross-section HAADF-STEM image and (c, f) corresponding FFT plots; (d) magnetic induction color map by electron holography for X- type twin variants in cross section; (e) HRTEM image of the marked twin boundary in Y-type microstructure.

[1] M. Takhsha Ghahfarokhi, Appl. Mater. Today **23** (2021), 101058.

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Voigt effect-based pump-probe studies of noncollinear antiferromagnet Mn_3NiN thin film

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[b] Blackett Laboratory, Imperial College, London, United Kingdom
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Recent breakthroughs in electrical detection and manipulation of antiferromagnets have opened a new avenue in the research of non-volatile spintronic devices. Antiferromagnetic ordering leads to a reduced sensitivity to magnetic field perturbations, multi-level stability and ultra-fast spin dynamics. However, these features also make the characterization of antiferromagnetic materials, in particular of thin metallic films suitable for spintronics, a major challenge [1]. One from a few available experimental approaches is to use magneto-optical effect which depends quadratically on the sublatice magnetization, the Voigt effect [1]. The applicability of pump-probe experimental technique based on Voigt effect for the investigation of magnetic anisotropy was demonstrated in compensated antiferromagnetic metal CuMnAs, where antiparallel ordering of two spin sublattices is present [2]. Very recently, the presence of Voigt effect was predicted [3] and experimentally observed [4] in non-collinear antiferromagnet Mn_3Sn, where triangular ordering of three magnetic sublattices exists. In this contribution we report on Voigt effect-based pump-probe studies of 50 nm-thick film of non-collinear antiferromagnet Mn_3NiN [5]. In particular, we show that using this approach changes of magnetic domain structure induced by external magnetic field in triangular antiferromagnets can be studied experimentally.

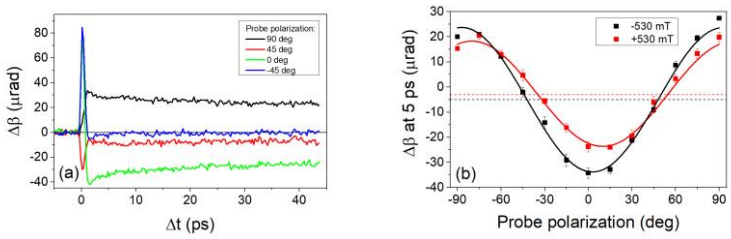

Figure 1: (a) Time-resolved pump-induced change of polarization rotation ($\Delta\beta$) measured by probe pulses with different orientation of linear polarization in 50 nm-thick Mn_3NiN on MgO substrate; magnetic field -530 mT, sample temperature 25 K, wavelength of pump and probe pulses 800 nm and 400 nm, respectively. (b) Probe-polarization dependence of $\Delta\beta$ measured at Δt = 60 ps for two opposite directions of external magnetic field (points); lines are fits by Eq. (2) in Ref. 1.

[1] P. Němec, M. Fiebig, T. Kampfrath, and A. V. Kimel, Nature Physics **14**, 229 (2018).

[2] V. Saidl, P. Němec et al., Nature Photonics **11**, 91 (2017).

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Cavity-mediated magnon-magnon coupling at 0.3 THz

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In the regime of strong light-matter coupling, polariton modes are formed that are hybrid light-matter excitations sharing properties of both, a cavity mode and a matter mode. Recently, magnon-polaritons are intensively researched in ferromagnetic materials in the microwave range, motivated mostly by applications for quantum devices. However, magnon-polaritons can be also obtained in the THz range with the antiferromagnetic resonance (AFMR) [1].

Here, we report on cavity-mediated magnon-magnon coupling in a system consisting of two parallel-plane crystals forming a Fabry-Perot type cavity. A crystal of yttrium ferrite ($YFeO_3$) is kept at room temperature, while a crystal of hematite (α-Fe_2O_3) is fixed on a copper mirror placed on a heater. We used a monochromatic continuous-wave spectrometer based on frequency extenders to a vector network analyser operating in the range of 0.2-0.35 THz. To detect cavity modes coupled to different matter modes, we performed spectroscopic measurements under modulation three parameters. This allows us to extract modes coupled to each of the crystals.

Reflection spectra measured as a function of hematite temperature *T* (Fig.1a) show a series of cavity modes that form avoided crossings with AFMR in hematite, frequency of which is rising with *T*. By measuring temperature-differential (Fig.1b) of these spectra, we reveal only cavity modes coupled to the AFMR in hematite, because AFMR in $YFeO_3$ does not depend on temperature of hematite. Differential to external magnetic field *H* (Fig.1c) reveals only cavity modes coupled to the AFMR in $YFeO_3$, since *H* is applied in a direction that does not change the AFMR in hematite. Differential to a gap *d* between the two crystals (Fig.1d) reveals the cavity modes. Under certain distance between the crystals, at about 0.3 THz where there is AFMR in $YFeO_3$, we can observe cavity modes that are strongly coupled to AFMR in both crystals.

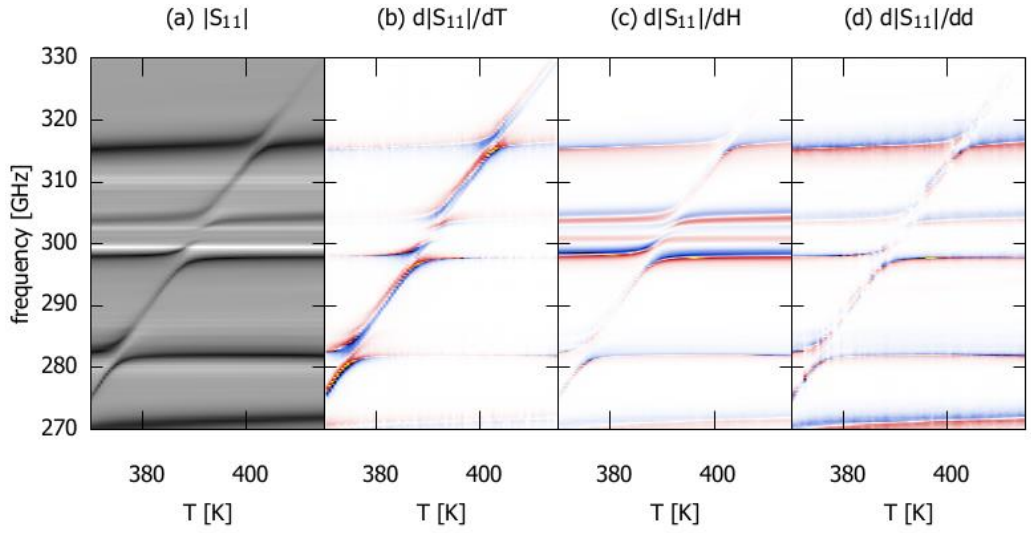

Figure 1: (a) Reflection magnitude, (b) temperature differential, (c) magnetic field differential, (d) differential to gap between the crystals.

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Co-evaporation of $Mn_{1-x}Au_x$ on a Nb(100) substrate capped with a pseudomorphic Au layer

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The exponentially increasing demand for fast and energy-efficient data storage requires new materials as Moore's law is reaching its limits. Antiferromagnetic materials are promising candidates for future data storage devices due to their absence of magnetic stray field and spin dynamics in the THz range. One promising material is Mn_2Au which can be electrically switched [1] by Néel spin-orbit torque without an additional heavy metal layer.

Here, we report on the co-evaporation of $Mn_{1-x}Au_x$ on a Nb(100) substrate capped by a pseudomorphic monolayer of Au via flash annealing. This keeps the long-range crystallographic order and periodicity of Nb [2] while preventing the substrate surface from oxidizing. Layer growth of $Mn_{1-x}Au_x$ is monitored in-situ via medium-energy electron diffraction (MEED). Structural analysis is carried out by Auger electron spectroscopy (AES) and low-energy electron diffraction (LEED).

The presented research highlights the feasibility to expand the range of available substrates to metal single crystals for the growth of Mn_2Au layers.

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Unusual thermal properties and field induced weak ferromagnetic phase in the exchange-frustrated antiferromagnet PrBCO at low temperature

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The linear thermal expansion α(T) and specific heat C_p(T) data obtained on nonsuperconducting ceramics of $PrBa_2Cu_3O_{6+x}$ ($PrBCO_{6+x}$ or PrBCO) with x = 0.44 (UN) and 0.95 (OP) are reported. From the low-temperature dependences of Δα(T)/T and ΔC_p(T)/T, with Δα(T) = [α($PrBCO_{6+x}$) – α($YBCO_{6.9}$)](T) and ΔC_p(T) = [C_p($PrBCO_{6.95}$) – C_p($YBCO_7$)](T), the Pr antiferromagnetic (AFM) contribution is observed at the Néel temperature T_N = 9 and 14 K, respectively. There is also an almost visible anomaly at the spontaneous spin reorientation temperature T_2 = 6.75 and 10.25 K for the UN and OP states respectively, and a change of slope close to the same low-critical point T_{cr}(x) = 4-5 K.

The curves of α(T)/C_p(T) and the effective Grüneisen parameter Γ_{eff}(T) show a nearly similar behaviour which is enhanced for the UN state. They increase monotonically below a quite visible rounded anomaly at T_N but exhibit a strong increase in slop below T_{cr}(x).

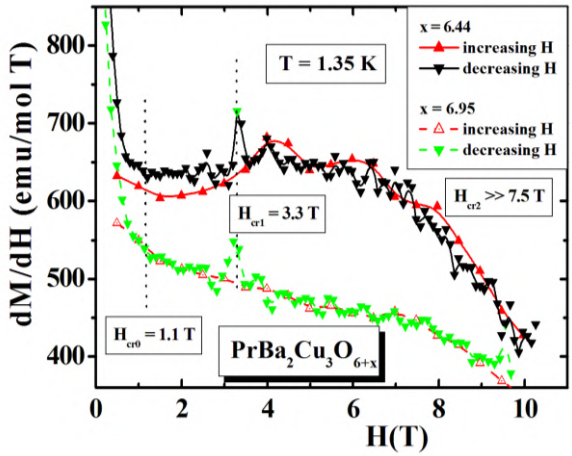

Figure 1: Curve dM(H)/dH versus H at 1.35 K for $PrBCO_{6+x}$ with x = 6.44 and 6.95.

From the magnetization and differential susceptibility measurements performed below T_N under high DC magnetic fields up to 16 T, a weak ferromagnetic (WFM) phase is revealed at 1.35 K between two critical fields: H_{cr0} = 1.1 T and H_{cr1} = 3.3 T (Fig. 1). Above H_{cr1}, the WFM phase is suppressed whereas the initial AFM phase is wholly restored and the transition to the paramagnetic state may occur at H_{cr2} well above 7.5 T. The results are compared with those reported earlier [1]-[3] and discussed in terms of the Pr-Cu(2) interactions [4] and the Schottky anomaly due to crystal field splitting of the ground state of the Pr^{3+} ions.

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Ab-inito and atomistic spin dynamics characterisation of antiferromagnetic materials Mn2Au and CuMnAs

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[2] *STFC Scientific Computing Department, Daresbury Laboratory, UK*

Antiferromagnetic (AFM) materials are magnetically ordered systems with parallel magnetisation in sub-lattices and a net-zero overall magnetisation. Discovered by Louis Néel [1] in 1948, AFMs have become of interest due to the high frequency antiferromagnetic resonance mode, which is often in the THz domain, resulting in fast magnetisation dynamics. As a result of these high frequency dynamics, AFMs have been proposed for information transport applications via electrons (spintronics) [2] or spin waves (magnonics) [3]. Exciting AFM systems with an electric current or ultra-fast laser pulse can lead to a fast response of the system, emitting THz signal or even switching the magnetic configuration [4].

In this work, we characterise two promising AFM materials Mn2Au and CuMnAs. Both have in-plane AFM ordering that is maintained at room temperature, with an Néel temperature (T_N) above 300K ($\sim$550K for CuMnAs and $\sim$ 1500K for Mn2Au). First, we parametrize the Heisenberg Hamiltonian using ab initio density functional theory, which is used as the basis for the atomistic spin dynamics modeling. The ab-initio calculations were done using 1) quasiparticle self-consistent GW (QSGW) via the full-potential linearised muffin-tin orbital (FP-LMTO) code Questaal [5] and 2) the fully-relativistic Korringa-Kohn-Rostoker package SPR-KKR [6]. For the SPR-KKR method, the inter-atomic magnetic interactions (Heisenberg exchange integrals) are evaluated using the magnetic force theorem independently for ferromagnetic, antiferromagnetic (the true ground state) and paramagnetic configurations. The results indicate comparable exchange parameters and to some degree independent of the configuration used.

In the second part, we use atomistic spin dynamics to determine the Néel temperature T_N and the spin waves for different parametrisation mentioned above. The Néel temperature is in the experimental range of about 1500K, with the mention that the atomic configuration becomes unstable just below 1000K and direct measurement of T_N is not possible. An alternative way to validate the exchange parameters is via spin wave (SW) dispersion relations, which can be computed at any temperature. In figure 1, we show the SW and magnon density of state at 0K (similar results at 300K), indicating a very good agreement at a lower frequency (below 40 THz) and differences up to 10Thz at the high range.

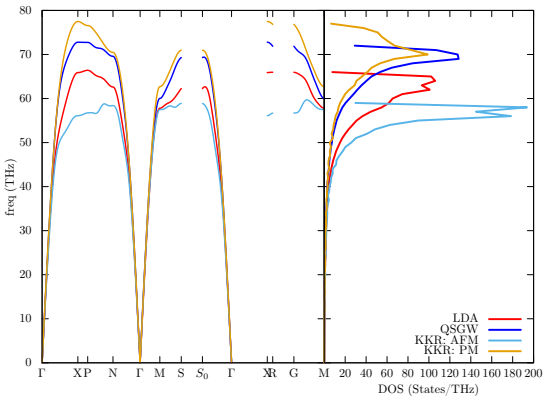

Figure 1: Spin-wave dispersion (left) and magnon density of state (right) for Mn2Au. The results are computed using AFM and PM exchange parameters from SPRKKR and AFM parameters from QSGW.

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Ultrafast emergence of ferromagnetism in antiferromagnetic FeRh in high magnetic fields

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The future of magnetic data storage crucially depends on our understanding of the mechanisms and fundamental limits on the speed of angular momentum transfer between lattice and spins. In the case of antiferromagnetic FeRh, this is a particularly interesting problem. Upon a temperature increase, the spins of Fe in FeRh suck angular momentum from the lattice - the medium becomes ferromagnetic, while the lattice expands [1].

Aiming to reveal the mechanism and the fastest possible time-scale of the magneto-structural phase transition resulted in a spin-and-lattice causality dilemma also known as a chicken-and-egg problem we carried out a time-resolved optical measurement in extreme conditions [2]. Here we resolve the problem by accelerating the spin dynamics in high (25 T) fields and observing both structural and spin dynamics with the help of time-resolved optical and magneto-optical measurements, respectively (see Fig.1). We observe that the fastest possible induction of ferromagnetism occurs on a time scale of the lattice expansion (3 ps). The regime implies that the laser excitation first modifies the exchange interaction on a sub-ps time-scale launching coupled magneto-structural spin dynamics such that the total spin-lattice angular momentum can be conserved.

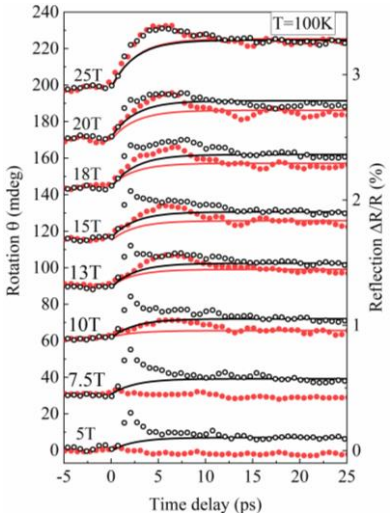

Figure 1: The polarization rotation induced by the magneto-optical Kerr effect (red) and reflectivity change (black) at 100 K and various magnetic fields. The open circles represent the experimental data and the solid lines are their respective fits. The curves are plotted with an offset.

[1] L. H. Lewis, C. H. Marrows, & S. Langridge. J. of Phys. D: Appl. Phys. **49** (2016), 323002.

[2] I. A. Dolgikh, T. G. H. Blank, G. Li, et al. *Prepr*. arXiv:2202.03931 (2022).

Memory of frozen and rotatable antiferromagnetic spins in epitaxial CoO(111)/Fe and NiO(111)/Fe bilayers.

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We combined XMLD, XMCD and in-situ MOKE techniques to follow the magnetic properties of epitaxial CoO(111)/Fe(110) [1] and NiO(111)/Fe(110) [2,3] bilayers. We find that in both studied cases ferromagnetic (FM) sublayer plays a dominant role and determines the magnetic state of the neighbouring antiferromagnet (AFM), however different interaction mechanisms are involved. In CoO/Fe bilayers the AFM spins are frozen and their orientation is imprinted by magnetization of Fe layer when the system passes the Neel temperature of CoO. Once the Fe layer grafts the particular magnetic anisotropy (MA) into the CoO overlayer, it later remains frozen and insensitive to external factors like external magnetic field or Fe magnetization direction [1]. Specifically, choice of particular magnetic state of Fe sublayer, when passing Néel temperature of CoO, determines both the axis and direction of interfacial antiferromagnetic spins after the sample is cooled and allows for imprinting their +/- 90° and 0/180° alignment within the sample plane. For example, particular direction of frozen AFM spins determines the corresponding sign of the shift field of exchange biased magnetic hysteresis loop (Fig.1, left). For NiO/Fe bilayers, the AFM spins are rotatable and always follow the reorientation of Fe magnetization that can be controlled by external magnetic field or via the temperature and thickness driven SRT of Fe(110). In a uniform thickness NiO(111)/Fe(110) system, two magnetic states with orthogonal spin orientations can be stabilized in AFM NiO and field-free, reversible switching between these two AFM states was demonstrated [2]. Additionally, tuning the thickness of Fe sublayer allows to tailor the critical temperature of SRT in AFM NiO and provides possibility to cover wide temperature window ~ (250 – 380 K) for switching of AFM spins [3]. Nanoscale AFM vortex states in individual self-organized NiO/Fe nanostructures will be also presented (right panel of Fig.1).

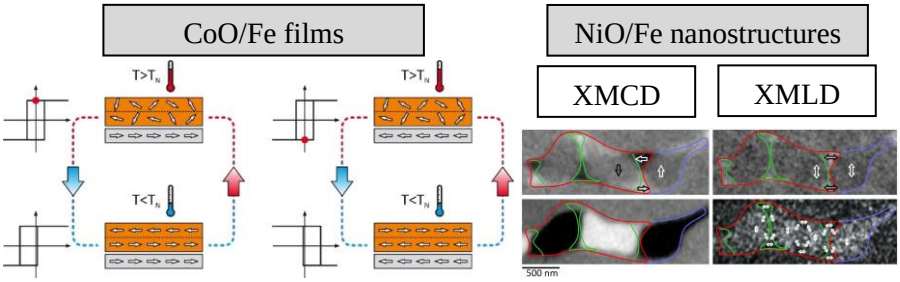

Figure 1: (left) Memory of frozen AFM spins in CoO(111)/Fe bilayer. (right) XMCD- and XMLD-PEEM images of NiO/Fe nanostructures for two sample geometries.

[1] M. Ślęzak et al., JMMM **545** (2022) 168783

[2] M. Ślęzak et al., Nanoscale **12** (2020) 18091

[3] M. Ślęzak et al., Phys. Rev. B **104** (2021) 134434

Role of substrate clamping on anisotropy and domain structure in the canted antiferromagnet α-Fe_2O_3

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Antiferromagnets are at the forefront of research in spintronics and demonstrate high potential for revolutionizing memory technologies. However, many of the underlying phenomena remain to be explored. In this work, we investigate the domain structure in a thin-film canted antiferromagnet α-Fe_2O_3.

We observe a strongly field-dependent domain structure of α-Fe_2O_3 thin films using x-ray magnetic linear dichroism (XMLD) (see Fig. 1a) and spin Hall magnetoresistance (SMR) measurements. Fig. 1b shows that the remanent resistance R_{rem} (dark) and the saturated resistance R_{sat} (light) follow the same symmetry. We find that the internal destressing fields driving the formation of domains do not follow the crystal symmetry of α-Fe_2O_3 but result in an overall equiprobable distribution of the orientations of the magnetic domain with locally fluctuating easy-axes. These long-range interactions qualitatively impact the domain structure and magnetization process.

The insights and the refined model developed in this work will allow for a more informed understanding of magnetic switching and complex spin textures in easy-plane antiferromagnets.

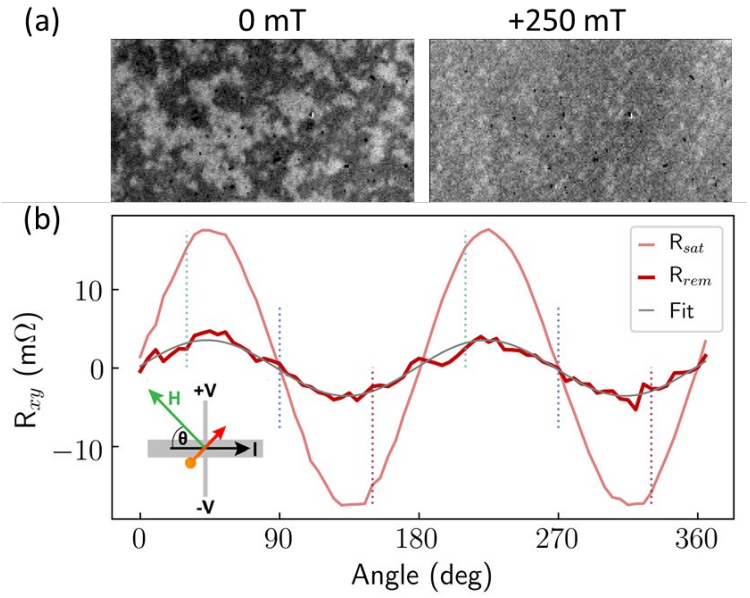

Figure 1: (a) XMLD image of the domain structure of α-Fe_2O_3 at 0 mT (left) and in 250 mT in-plane magnetic field (right). (b) Transverse remanent SMR signal R_{rem} (dark red) of α-Fe_2O_3/Pt Hall cross after H has been reduced from a saturated state R_{sat} (light red) to zero field as a function of angle of the applied magnetic field.

Growth and characterization of semiconductor low-dimensional structures with antiferromagnetic MnSe

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The array of experimental methods capable of unequivocal detection of the Néel vector state in thin-film antiferromagnets remains limited and dominated by complex surface sensitive techniques such as X-ray dichroism [1]. This hampers practical applications of these materials, even though they can exhibit numerous appealing properties such as reorientation of spins upon electrical current [2,3] or large magnon propagation lengths [4].

To address this important challenge in antiferromagnetic spintronics we propose that properties of an antiferromagnetic layer can be revealed by the observation of how low dimensional structures interact with the adjacent antiferromagnet. In this work, we show the design, MBE growth, and characterization of such low-dimensional structures comprising antiferromagnetic thin-films made of II-VI semiconductors. Firstly, we show the surface and the optical characterisation of the thin-film MBE-grown antiferromagnetic semiconductive MnSe on GaAs (111) substrate. Moreover, we present photoluminescence of low dimensional structures made of CdSe with adjacent barrier of wide band-gap MnSe. This approach aims at determining a quantum well or quantum dots photoluminescence dependence on the spin state of an antiferromagnetic barrier as a novel method of the Néel vector reorientation detection.

The research was funded by National Science Centre (NCN), Poland under Grant 2021/40/C/ST3/00168.

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[2] P. Wadley et al., Science **351** (2016), 587.

[3] H. Meer et al., Nano Lett. **21** (2021), 114.

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Local magnetization reversal in FeGa magnetic nanostructures

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The recent advances in nanofabrication techniques have given a boost to the study of artificially patterned nanostructures for smart multifunctional systems. In case of magnetic nanostructures, the quest of the last two decades was to gain advances in high density magnetic storage, sensor technology and magneto-logic devices [1]. Large-area arrays of nanostructures are fabricated by several methods, either top-down or bottom-up techniques. Conventional top-down methods lead to highly ordered patterns suitable for use in devices. In this work, patterned FeGa nanodots have been produced exploiting either Laser writing lithography (top-down, Fig. 1(a)) [2] or using self-assembling nanospheres. Nanodots fabricated using laser lithography have a diameter between 1~2 µm and forms vortex-like magnetic textures at remanence as observed by magnetic force microscopy (MFM) as shown in Fig 1(b). The magnetic hysteresis curve along with domain images of the FeGa dots are recorded with MOKE (Fig. 1(c)). It is observed that magnetic vortices with opposite chirality are stabilized for majority of the dots at positive and negative remanence (Fig. 1(d) and 1(e)) which confirms good patterning quality. At saturation fields, single domain states are recorded with opposite contrast. Further, compositional change of FeGa dots are explored to discover new magnetic states reversal mechanism.

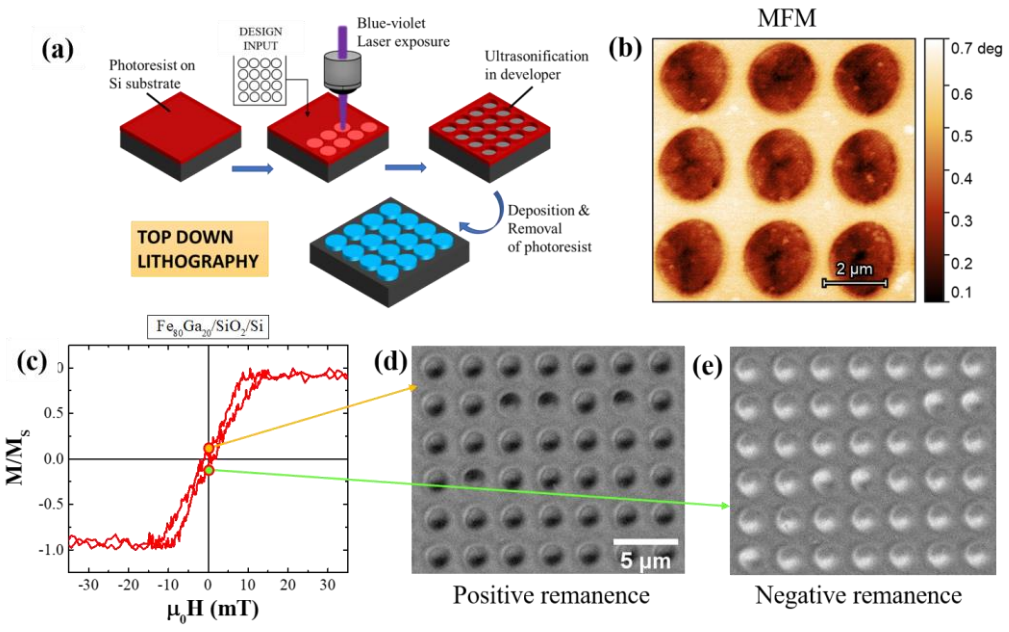

Figure 1: (a) Schematic of Laser writing lithography. (b) MFM image recorded at remanent state. (c) Magnetic hysteresis recorded with MOKE. (d) and (e) represent negative and positive remanent state, respectively.

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[2] Z. L. Wu, Y. N. Qi, X. J. Yin, et al. Polymers, 11.3, 553 (2019)

Inertial hopfion motion under magnetoelectric torque

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We theoretically investigated the motion of Bloch hopfion stabilized in the waveguide build from the multiferroic spiral-spin-ordered material exhibiting inhomogeneous magnetoelectric (flexomagnetoelectric) effect [1,2]. The Landau-Lifshitz-Gilbert equation has been solved numerically by finite-element method (Comsol Multiphysics) taking into account magnetoelectric torque. The gradient of the electric field applied perpendicular to the waveguide results in the torque acting on hopfion along the waveguide axis. The torque induces the motion of the hopfion in the waveguide. Unlike for skyrmions, where the uniform movement has been reported [3], the hopfion is constantly accelerating for small values of Gilbert damping constant, eventually collapsing (Fig. 1). For moderate values of Gilbert damping, the hopfion reaches steady-state motion of oscillatory character around particular value of velocity. For significant damping, the velocity of hopfion tends to zero.

The uniformly accelerated movement of hopfion indicates its inertial character, which may be quantified by the effective mass. We analyzed the hopfion dynamics via Thiele equation describing the dependence of the hopfion effective mass on the Gilbert damping coefficient. The velocities and effective mass of hopfion have been compared with those obtained for the skyrmion and toron. The electric-field induced motion of hopfions is an attractive energy-efficient alternative to other current- or magnetic-field-driven solutions.

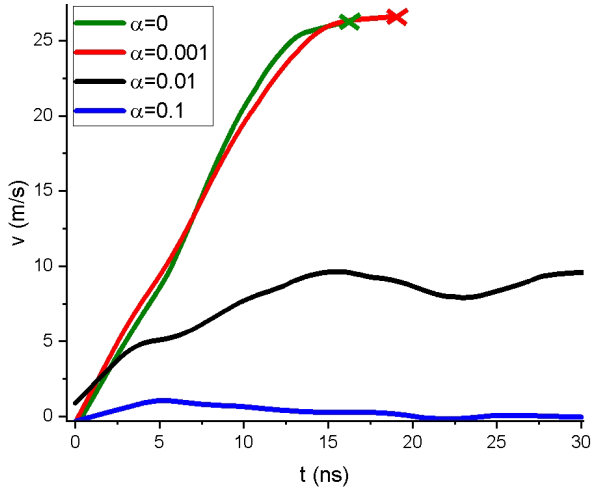

Figure 1: The time-dependence of hopfion velocity subjected to the inhomogeneous electric torque for different Gilbert damping coefficients. The crosses indicate hopfion collapse.

This work was conducted under grant no. 2018/28/C/ST3/00052 from National Science Centre in Poland and grant no. 2020/37/K/ST3/02450 from the Norwegian Financial Mechanism 2014-2021.

[1] S. Dong et al., National Science Review 6, 629-641 (2019)
[2] P. Graczyk and E. Coy, 'Single-phase multiferroics', in Nanostructured Multiferroics, R. Balakrishnan and P. M. Visakh, Eds. John Wiley and Sons, 2021, p. 38.
[3] X. Wang et al., Physical Review B, 9, 064426 (2019)

Asynchronous current-induced switching of rare-earth and transition-metal sublattices in ferrimagnetic alloys

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Rare-earth transition-metal (RE-TM) ferrimagnets have raised considerable interest because of their ultrafast laser-induced [1-2] and current-induced [3] magnetic dynamics. In particular, ferrimagnetic domain walls driven by spin-orbit torques can reach speeds that are inaccessible in ferromagnets and can be as high as several km/s [3-4]. In addition, the easier detection of the dynamics of ferrimagnets as compared to antiferromagnets provides a fertile ground to explore the behaviour of antiferromagnetically-coupled systems.

So far, the response of the individual RE and TM sublattices to electric currents has remained unexplored. Here we present the first study of the dynamics triggered by ns and sub-ns-long electric pulses in GdFeCo and TbCo that combines temporal (70 ps), spatial (35 nm), and elemental resolution [5]. We discover a variety of dynamics characterized by a variable degree of coupling between the two sublattices. While being antiferromagnetically coupled in equilibrium, the RE and TM sublattices can evolve asynchronously in time and inhomogeneously in space during and after the current pulses. This difference takes the form of a delay between domain walls in the two sublattices or, in the extreme case, of a transient ferromagnetic state that can last as long as 2 ns. Micromagnetic simulations and electron microscopy measurements identify the origin of the asynchronous dynamics with the weak antiferromagnetic exchange interaction between the RE and TM sublattices, which is a sensitive function of the atomic structure of amorphous alloys. Our results provide a novel and unique insight into the dynamics of antiferromagnetically-coupled systems and have practical implications for spintronic applications of ferrimagnets.

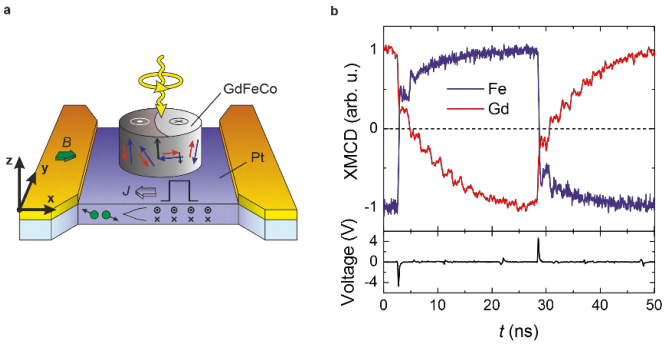

Figure 1. **a,** Schematic of the sample layout, which consists of a GdFeCo dot on a Pt current line. The current pulse *J* induces the switching of the RE and TM magnetizations by spin-orbit torques. **b,** Time-dependence of the X-ray magnetic signal (XMCD) proportional to the Fe and Gd magnetizations measured while applying 200-ps-long current pulses.

[1] C. D. Stanciu, Phys. Rev. Lett. **99** (2007), 047601

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[3] K. Cai, Nat. Elec. **3** (2020), 37-42

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[5] G. Sala, Nat. Mat. (2022), in press

The influence of Dzyaloshinskii–Moriya interaction and perpendicular magnetocrystalline anisotropy on magnetization dynamics in spin spirals and stripe domain patterns

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Magnetic textures characterized by spatial periodicity can be used as a periodic medium for spin wave (SW), i.e., magnonic crystals that do not require nanostructuralization. An example of them are aligned stripe domain patterns[1,2]. Basic magnetic parameters determining the internal structure and chirality of domain walls are perpendicular magnetocrystalline anisotropy (PMA), film's thickness, and Dzyaloshinskii–Moriya interaction (DMI, *D*)[2,3]. These parameters together with the exchange constant and the saturation magnetization determine the periodicity of magnetization textures. This periodicity can be on the order of down to tens of nanometers.

Using micromagnetic simulations, we study how (i) the dynamic magnetic susceptibility Im$\chi(f)$, (ii) dispersion relation of SWs, and (iii) the equilibrium magnetic configuration in periodic magnetic textures in ultrathin films depend on the value of both DMI and PMA. We show that depending on the polarization of the microwave field, different resonant modes are excited (see Fig. 1). For propagation along the direction of the periodicity, we observe a bandgap that closes at a characteristic topological transition point, where two bands swap order. For waves propagating in the perpendicular direction to the periodicity, we classify modes depending on the region of their localization with respect to the out-of-plane component of the static magnetization. Interestingly, some of these modes can serve as unidirectional channels for spin waves.

We acknowledge the funding from the Polish National Science Centre projects No. UMO-2019/33/B/ST5/02013 and 2020/37/B/ST5/02299.

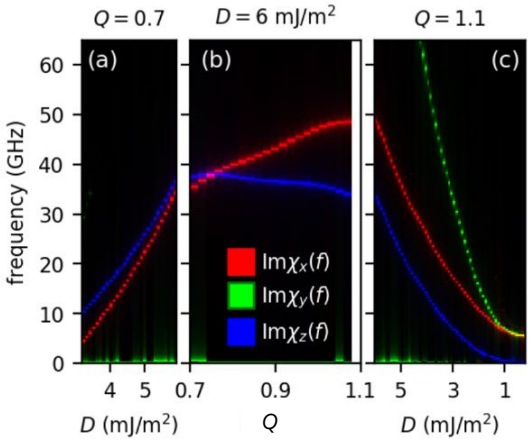

Figure 1: SW spectra in thin film (saturation magnetization M_S=1420 kA/m, exchange constant A_{ex}=13 pJ/m, thickness d=2 nm) in dependence (a) on D for Q=0.7, (b) on Q for D=6 mJ/m^2, and (c) on D for Q=*1.1*. Q [=$K_{PMA}/(½\mu_0 M_s^2)$] is the quality factor that linearly depends on value of PMA (K_{PMA}). The colors correspond to the intensities of the SWs excited by the microwave field of different linear polarization, i.e., the red color corresponds to microwave field polarized along the *x*-axis, the green to the polarization along the *y*-axis, and the blue color to polarization along the *z*-axis.

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[2] Gruszecki, et al. *Solid State Physics* 70 (2019), 79-132.
[3] Kisielewski et al. *New J. Phys.* 21 (2019), 093022.

Ferromagnetic resonance as a spectroscopic technique for topological surface states investigation

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Three dimensional topological insulators (TIs) [1] are characterized by a bulk bandgap and metallic surface states (TSSs) that are spin-momentum locked and are therefore predicted to be very efficient in spin-to-charge interconversion phenomena. In this work, following the p-n junction approach already proposed in [2] and [3], we use ferromagnetic resonance (FMR) as a spectroscopic technique to probe spin-pumping into TSSs.

The samples investigated are $SrTiO_3/Bi_2Se_3(1)/(Bi_{1-x}Sb_x)_2(Te_{0.1}Se_{0.9})_3(10)/NiFe(10)$ heterostructures, where the numbers in parenthesis are the thicknesses in nm. We vary the Sb concentration *x*: for low *x*, BSTS is n-type, for $x \geq 0.5$ the Fermi level (E_F) moves in the bandgap. We performed full film FMR measurements and extracted the Gilbert damping parameter α at different temperatures. Comparing these measurements with the temperature behaviour of the resistance allowed us to have a signature of spin-pumping into TSSs at low temperatures.

We then measured back-gated FMR on samples with Sb concentrations such that E_F is placed in the bandgap. The behaviour of α is shown in Fig. 1 for two different Sb concentrations. α is at minimum when E_F reaches the Dirac point and it increases away from this point due to an increase in TSSs DOS. When the applied gate voltage is high enough to shift E_F inside the conduction or valence bands, α saturates, due to the large bulk conductivity of the structure, that screens the electric field. The spectra for the two samples are shifted in energy, confirming that for lower Sb concentrations E_F lays closer to the conduction band.

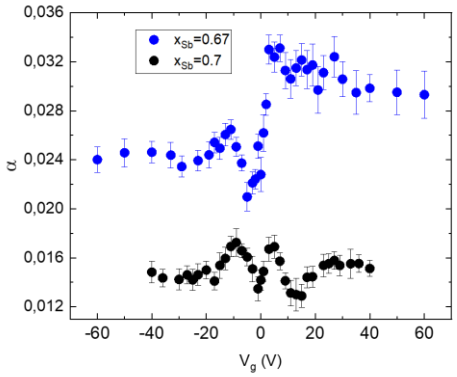

Figure 1: Gilbert damping dependence on backgate voltage for two samples with different Sb concentrations

[1] L. Fu, CL Keane, Phys. Rev. B, Vol 76, pp. 045302 (2007)

[2] T. Mayer, H. Werner, F.Schmidt et al., Phys. Rev. Mat., Vol 5, pp. 014202 (2021)

[3] S. Danilov, L. Golub, T. Mayer et al., Phys. Rev. Appl., Vol 16, 064030 (2021)

Into the fourth dimension: time-resolved soft x-ray magnetic laminography

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Until recently, most of the experimental research into magneto-dynamical systems has been focused on two-dimensional systems. Such systems exhibit a variety of phenomena that include, but are not limited to, magnetic vortex dynamics, domain wall motion, switching processes, skyrmion dynamics, and magnonic processes such as spinwave emission and propagation. The extension to the experimental investigation of fully three-dimensional dynamical processes has up to now only been possible through indirect methods and through comparison of two-dimensional data with micromagnetic simulations. One of the main reasons for this is that microscopy techniques that combine three-dimensional magnetic imaging with nanometric resolutions with the possibility to perform time-resolved investigations with sub-ns temporal resolutions are not widely available.

A first demonstration of time-resolved three-dimensional imaging was performed with hard X-ray magnetic laminography [1]. However, the technique exhibits limitations both in the sensitivity (due to the use of hard X-rays) and in the selection of accessible frequencies (due to the use of ptychography for imaging the magnetic samples), which has limited its applicability.

Here, we present first time-resolved measurements of magnetic vortex and spinwave dynamics fully resolved in all three spatial dimensions performed at soft X-ray energies, enabling us to obtain strong magnetic contrast at the 3d ferromagnetic elements ($L_{2,3}$ absorption edges). By combining the laminography imaging technique [1, 2] with time-resolved scanning transmission X-ray microscopy to acquire the angular projections, time-resolved three-dimensional imaging with free selection of the frequency of the electrical signals used to excite the dynamical processes is made possible. Here, we show the full three-dimensional characterization of two magneto-dynamical modes in a microstructured CoFeB element, namely a vortex gyration mode and a domain wall excitation mode [3].

A spatial resolution of about 40 nm in all three dimensions was demonstrated, with the possibility to perform measurements with temporal resolutions down to 30 ps if time-of-arrival detection methods are employed [4].

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Inertial spin dynamics in epitaxial cobalt films

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We investigate the spin dynamics driven by terahertz magnetic fields in epitaxial thin films of cobalt in its three crystalline phases. The terahertz magnetic field generates a torque on the magnetization which causes it to precess for about 1 ps, with a sub-picosecond temporal lag from the driving force. Then, the magnetization undergoes natural damped THz oscillations at a frequency characteristic of the crystalline phase (see fig. 1). We describe the experimental observations solving the inertial Landau-Lifshitz-Gilbert equation. Using the results from the relativistic theory of magnetic inertia, we find that the angular momentum relaxation time η is the only material parameter needed to describe all the experimental evidence. Our experiments suggest a proportionality between η and the strength of the magneto-crystalline anisotropy.

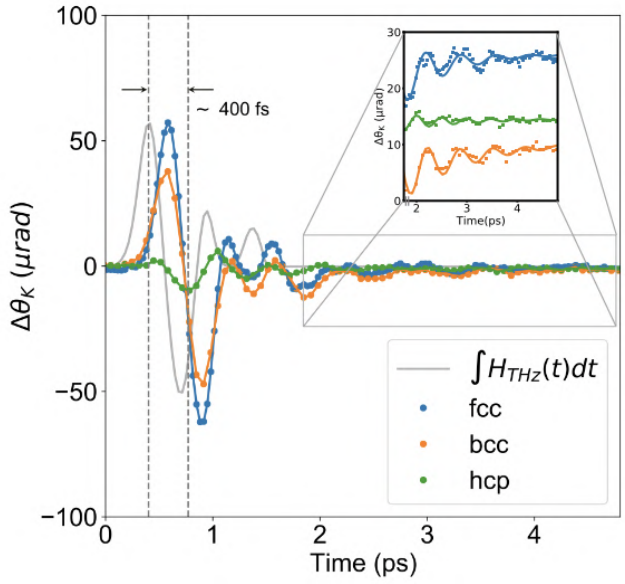

Figure 1: Solid symbols: time-resolved Kerr rotation measurements on fcc, bcc and hcp cobalt thin films. Dashed line: integral of the pump THz magnetic field H_{THz} . Inset: zoomed-in main panel data for t > 1.7 ps. The data is shifted vertically for clarity.

Terahertz electric-field driven dynamical multiferroicity in paraelectric $SrTiO_3$

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The emergence of collective order in matter is among the most fundamental and intriguing phenomena in physics. In recent years, the ultrafast dynamical control and creation of novel ordered states of matter not accessible in thermodynamic equilibrium is receiving much attention. Among those, the theoretical concept of dynamical multiferroicity has been introduced to describe the emergence of magnetization by means of a time-dependent electric polarization in non-ferromagnetic materials [1,2]. In simple terms, a large amplitude coherent rotating motion of the ions in a crystal induces a magnetic moment along the axis of rotation. However, the experimental verification of this effect is still lacking. Here, we provide the first evidence of room temperature magnetization in the archetypal paraelectric perovskite SrTiO3 due to this mechanism. To achieve it, we resonantly drive the infrared-active soft phonon mode with intense circularly polarized terahertz electric field, and detect a large magneto-optical Kerr effect. A simple model, which includes two coupled nonlinear oscillators whose forces and couplings are derived with *ab-initio* calculations using self-consistent phonon theory at a finite temperature [3], reproduces qualitatively our experimental observations on the temporal and frequency domains. A quantitatively correct magnitude of the effect is obtained when one also considers the phonon analogue of the reciprocal of the Einsten – de Haas effect, also called the Barnett effect, where the total angular momentum is transferred from the coherent phonon motion to the electrons. Our findings show a new path for designing ultrafast magnetic switches by means of coherent control of lattice vibrations with light.

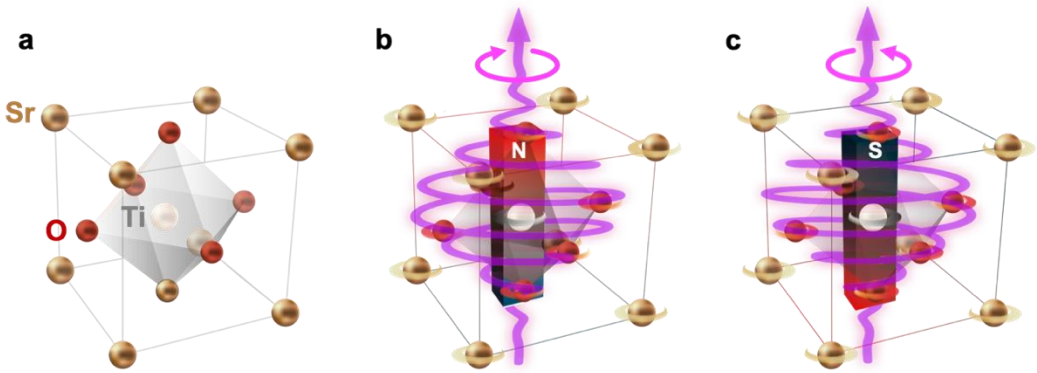

Figure 1 Schematic of the experimental realisation of dynamical multiferroicity. (a) $SrTiO_3$ unit cell in the absence of a terahertz electric field. When a circularly polarised terahertz field pulse drives a circular atomic motion, a net magnetic moment is created in the unit cell, which points (b) north for a pulse with left-handed and (c) south for a pulse which is right-handed.

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Magnetization Dynamics in CoGd Induced by Transient Gratings

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Four Wave Mixing (FWM) Transient Grating (TG) is a spectroscopy technique where coherent and high intensity LASER pulses coming from different incident angles are overlapped with each other on a sample. Their temporal and spatial overlap gives rise to the interference pattern having periodic modulations of intensity if they are polarized parallel to each other. If they are orthogonal, the polarization gratings are created with no modulation of intensity. Response of a fully magnetized sample to these gratings is a magnetization grating. Finally a third time-delayed pulse is diffracted off this grating to detect the TG signal. Such pump-probe studies give insights into the magnetization dynamics of the material.

FWM experiments of visible LASERs as well as Extreme Ultraviolet (EUV) pulses have been proven to be a sensible tool for studying the ultrafast magnetization dynamics in magnetic thin films [1,2]. Hard X-ray TG spectroscopy can also be used for studying magnetic systems [3]. However, the previous studies were done by using the transient intensity grating, where in addition to the excitation of spins, thermoelastic effects are also induced. When TG signals are studied in reflection geometry, the thermoelastic response dominates the total signal, hiding any magnetic contribution, as shown in Fig. 1. Therefore, in order to study purely the magnetization dynamics, transient polarization grating is a better choice for two reasons. First, there are no thermoelastic effects arising due to the absence of periodic modulations of intensity. Also there is a coupling between spins and the polarization states which is mediated by the angular momentum transfer. This allows us to have the control over spin waves by varying the spatial periodicity of the gratings. Fig. 2 shows data from a polarization grating experiment, with EUV pulses resonant with the M_2 absorption edge of Cobalt. It shows a non-sinusoidal feature with its maximum excitation time scale at around 2 ps. However, the tr-MOKE data from Fig. 3 shows the maximum demagnetization time of 0.5 ps. This effect cannot originate due to thermal grating due to absence of intensity grating and if it is a magnetic effect it must have shown the ultrafast timescale in a few Femtoseconds like the tr-MOKE measurements. Studying this effect in the visible regime is a promising experiment because the thermoelastic effect even due to the uniform heating of the sample will not be dynamic in the time scale where the magnetic effects are present. Also, we would be performing a FWM TG experiment in the EUV regime with the pulses resonant with the absorption edge of Gd. Hence, the study of ultrafast magnetization dynamics with these configurations will help us understand novel underlying mechanisms and offers the possibility of controlling the dynamics on the nanoscale.

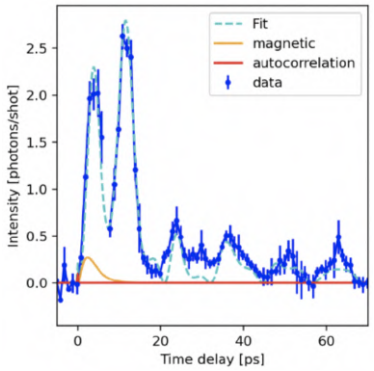

Fig.1

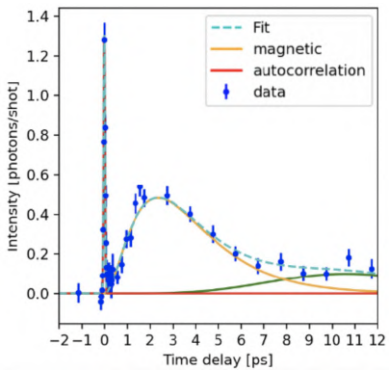

Fig. 2

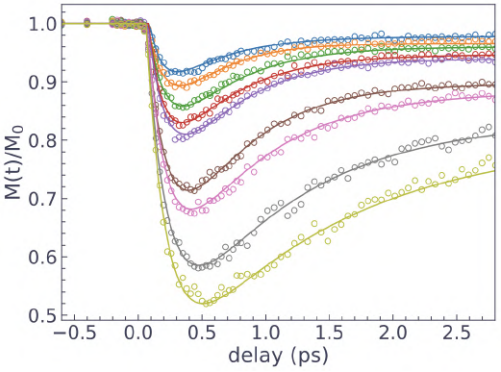

Fig. 3

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Magnetization switching in the inertial regime

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The traditional method of writing information to magnetic hard disk drives consists of reversing the magnetization direction via the application of magnetic fields produced by external currents and localized via a so-called "write-head." In order to achieve efficient switching, the magnetic field is applied nearly antiparallel to the direction of the initial magnetization state, and the switching process thus obtained is often referred to as "damping" switching [1–3]. The switching time in this process is limited by the macroscopic relaxation time of the magnetization of the order of 100 ps, and correctly described by the standard Landau Lifhitz Gilbert (LLG) equation [4]. Gerrits *et al.* [5] demonstrated instead a technique by which ultrafast magnetization reversal can be achieved using picosecond-long magnetic field pulses *transverse* to the magnetization direction. Such a switching technique was also reported in other studies [6,7]. The switching times reported in these works depend on the amplitude of the magnetic field and on the duration of the pulse, with a general trend that a pulse of larger amplitude will reduce the switching time. Coincidentally, at the same time, a series of experiments performed at the Stanford linear accelerator demonstrated the ultrafast switching of magnetization by intense magnetic fields created by relativistic electron bunches. In the paper published by Tudosa *et al.* [8], it was argued that deterministic magnetization switching cannot occur faster than 2 ps, setting this as the ultimate speed for magnetic reversal. However, due to the complexity of such an accelerator based experiment, direct observation of such an ultrafast switching in the time domain was not possible. A few years later, it was shown that a novel idea, i.e., using magnetic inertia, can greatly enhance the switching speed in antiferromagnets [9], up to 10 times faster than that reported in the above-mentioned studies. So far, nutation-type magnetization motions in ferromagnetic systems have been studied mostly theoretically, in the framework of classical LLG dynamics at GHz frequencies [10], as well as in other numerical studies considering the inertial version of the LLG [11–17], sometimes referred to as the iLLG equation. These works predicted the appearance of a spin nutation with an intrinsic resonance in the 10^{11}–10^{15} Hz range. The direct detection of spin nutation in ferromagnets recently achieved experimentally [18] has allowed us to narrow down the rather broad frequency range to the 10^{12} Hz one, i.e., in the THz region, for typical 3*d* ferromagnetic alloys such as NiFe and CoFeB.

In this work, we explore the role of inertia in the magnetization switching of a thin film ferromagnet triggered by magnetic field pulses in the picosecond range. Using macrospin simulations, we create a map of the magnetization dynamics as a function of the pulse duration and amplitude.

The dynamics is obtained and analyzed solving both the standard LLG equation and the iLLG equation[19]. We used realistic material parameters for an archetypal ferromagnet, namely $Ni_{81}Fe_{19}$ (permalloy), but they are valid for all thin film ferromagnets with similar characteristics. We show that the iLLG simulations predict a larger stability region than the LLG one for one of the two characteristic switching processes, and that the effect of the nutation resonance can be detected in switching experiments. We discuss our results analyzing the dynamics of the classical energy terms.

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The MagneDyn beamline at the FERMI free electron laser

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The beamline MagneDyn dedicated to magnetodynamic studies on solid samples at the FERMI free-electron laser, was opened to Users in 2020 and provides polarised extreme ultra violet (EUV) femtosecond pulses in the 50-300 eV photon energy range thus spanning the $M_{2,3}$ absorption resonances of 3d transition metals and $N_{4,5}$-edges of rare earth elements.
The beamline has been designed for time resolved magnetic dichroism experiments, both linear and circular, with high sensitivity, reproducibility, flexibility, user friendliness. The FEL beam is available in two experimental areas, one with a dedicated electromagnet, cryostat and EUV Wollaston-like polarimeter, the second area being open for User instruments.
Combined with the possibility to control and manipulate the intrinsically synchronized optical laser in a pump-probe scheme, MagneDyn provides state-of-the-art pump-probe tools enabling the experimental access to the transient magnetic states of matter, opening opportunities in the fields of femtomagnetism studies.
I will present recent results about time resolved EUV MOKE and RXES experiments at MagneDyn.

Spin-wave edge and cavity modes in a moiré magnonic crystal

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Two layers of two-dimensional lattices placed on top of one another with a small twist angle can generate a new periodicity much larger than the original lattice constant, referred to as a moiré superlattice. Moiré superlattices of 2D materials, such as twisted bilayer graphene [1] are found to exhibit superconductivity [2] and correlated insulator states [3], and therefore have attracted tremendous interest in the emerging field of twistronics based on van der Waals layered materials. To date, moiré physics in magnonic systems has only been studied theoretically. [4,5]

We report on the fabrication of nanostructured moiré magnonic crystals based on two low magnetic damping YIG antidot lattices forming a more superlattice. The existence of spin-wave (SW) edge modes and cavity modes are experimentally demonstrated in moiré magnonic crystals by micro-focused Brillouin light scattering technique (μ-BLS). The edge modes are observed at the boundary of a moiré unit cell (AB region) while the cavity modes are localized in the AA commensurate region.[6] By varying the twist angle and magnetic field intensity, the SW edge mode can be finely controlled. The edge mode becomes spatially best-defined at an optimal twist angle of 6° referred to as the "magic angle" of the moiré magnonic crystal.

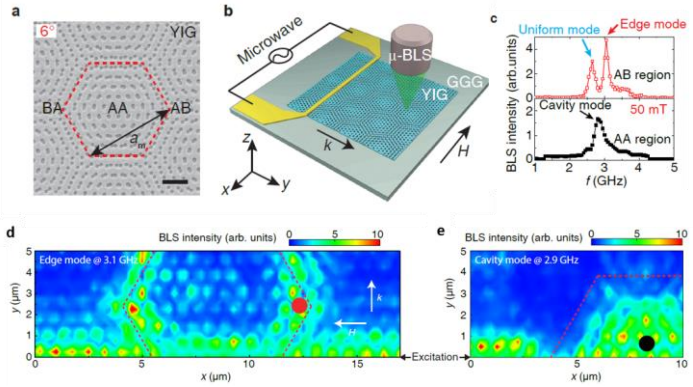

Figure 1: (a) Scanning electron microscope image of a moiré magnonic crystal based on yttrium iron garnet (YIG) with a twist angle of 6°. (b) Schematics of spatially-resolved spin-wave measurement on moiré magnonic crystals based on μ-BLS. (c) μ-BLS signals detected as a function of frequency at the AB region (red spot in d) and AA region (black spot in e). Two-dimensional spin-wave intensity maps measured by μ-BLS at 50 mT and (d) at the edge-mode frequency of 3.1 GHz and at the cavity-mode frequency of 2.9 GHz.

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Bright and dark states of two distant macrospins strongly coupled by phonons

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We study the coupled dynamics of two magnets on both sides of a thick crystal spacer. The magnets communicate by acting as "speakers" as well as "microphones" for sound waves. The system can be tuned into tripartite hybridization by carefully tuning the two ferromagnetic resonance frequencies to a degenerate acoustic resonance of the crystal. Being in a regime where the interaction strength between the magnetic excitations is larger than their decay rate, the system is in the strong coupling regime in which the entire system of magnetization and lattice can only oscillate coherently. We show there that illumination of the bright and dark collective modes by a uniform microwave field depends on the parity of the phonon mode, which decides if the lattice displacement at the position of the two magnets is out-of-phase or in-phase. Depending on the parity of intermediate standing lattice waves, the interference is constructive or destructive, giving rise to the bright and dark collective modes [1].

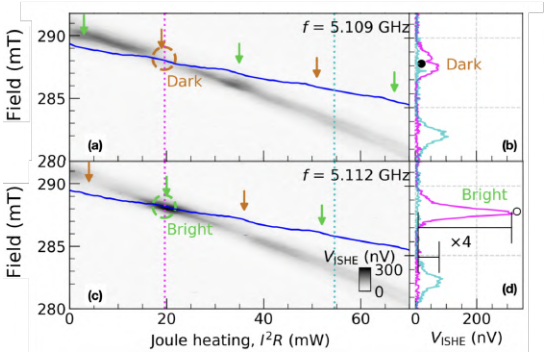

Fig. 1: Formation of bright and dark states mediated by odd and even phonons, respectively, under tuning two magnetic resonances with temperature gradient

[1] K.An et al., arxiv:2108.13272

Dynamic instability in high power FMR of a BiYIG nanodisk

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Spin waves (SWs), the eigenexcitations of an ordered magnetic material, become nonlinearly coupled at high amplitude. These nonlinear effects can be governed by several ingredients. On one side, nanopatterning leads to quantization of SW modes, thereby limiting the available nonlinear processes, which allows to reach large angle of magnetization precessions by conventional ferromagnetic resonance (FMR) [1]. On the other side, tuning the perpendicular magnetic anisotropy (PMA) allows to control the sign of the nonlinear frequency shift [2]. Recently, the growth of ultra-thin films of bismuth doped YIG (BiYIG) with tunable PMA and high dynamical quality has been achieved [3]. Greatly improved characteristics of SWs emitted by spin orbit torque [4] and spin current driven Bose-Einstein condensation of magnons [5] have been observed in BiYIG films where the PMA almost exactly compensates the shape anisotropy; this suggests very interesting effects in the nonlinear regime of FMR in nanostructures patterned from similar films.

Here, we study the magnetization dynamics in a nanodisk patterned from such a 30 nm thick BiYIG film. The static magnetic field is applied out-of-plane and the microwave field is in-plane. To detect the FMR, we employ a magnetic resonance force microscope. At high power, the dynamics becomes complex, with a rapid saturation of the signal amplitude and a splitting of the resonance line into several peaks (Fig. 1a). Micromagnetic simulations reproduce well these observations, revealing that a dynamic instability is responsible for the observed behavior. To experimentally probe this complex dynamics, we apply in addition to the main driving field at high power, a second, much weaker excitation field of varying frequency around the first one. The obtained frequency modulation spectrum (Fig. 1b) reflects rich low-frequency temporal variations in the magnetization dynamics. Mapping this spectrum through the resonance line as a function of power reveals an interesting bifurcation picture with a period-doubling route to this self-modulation regime.

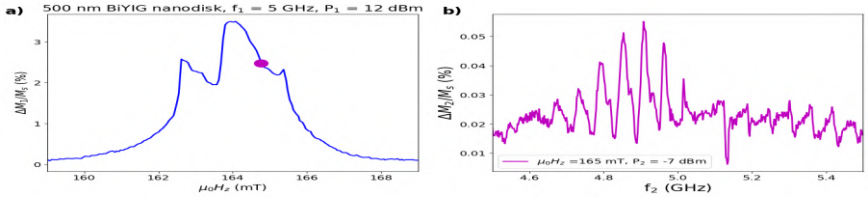

Figure 1: (a) Resonance line in the deeply nonlinear regime. (b) Two-tone spectroscopy performed inside the instability region, at $\mu_0 H_z$ = 165 mT.

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Optically induced ultrafast magneto-dynamics in ferromagnetic alloy

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The idea of using light to exploit magnetism, magnetic materials and regulating the magnetic order on ultrashort time scales is becoming vital for their direct applicability for next-generation magnetic devices which combines ultrafast data processing and data storage [1, 2]. This is however a challenge due to lack of understanding of the key parameters controlling magnetism on their fundamental time and length scales. In case of complex materials such as $Ni_{80}Fe_{20}$, it is reported that both elements exhibit same demagnetization time with in the experimental error at their M edges [3], while different dynamics observed at their respective L-edges [4]. In this work, we tried to understand how the exchange interaction can control the ultrafast dynamics of elemental spin subsystems in $Ni_{80}Fe_{20}$ by studying the magnetic dynamics of individual elements in permalloy. Time-resolved element-specific Kerr rotation experiment is performed in a pump-probe mode with the FERMI FEL pulses at MagneDyn beamline tuned at the Ni $M_{2,3}$ (67 eV) and Fe $M_{2,3}$ (54.55 eV) edges, respectively. The sample is excited with a laser pump pulse at 1.56 eV (794 nm) while a second time-delayed EUV pulse probes the same spot. The demagnetization dynamics, $\Delta M/M$, for both elements shows a sub-picosecond decay, followed by a slower recovery time and is further fitted using a double-exponential fit function to extract the intrinsic demagnetization times for Ni and Fe, respectively.

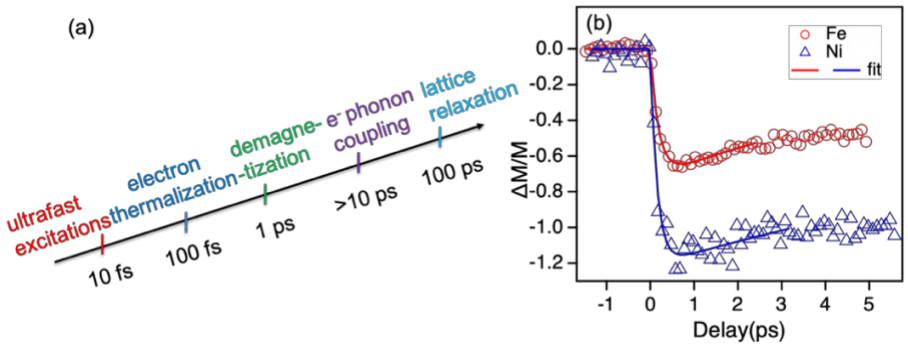

Figure 1: (a) Various scattering processes electrons undergo after rapid excitation by femtosecond laser pulse, (b) Element specific ultrafast demagnetization dynamics of the constituent magnetic moments in permalloy measured at the Fe and Ni $M_{2,3}$ edge. The solid lines are the double exponential fits to the data used to extract the intrinsic demagnetization times for Fe and Ni in the FeNi alloy.

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Electric-field induced collective spin dynamics in nanomagnet revealed by 30-ps single-shot measurements

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An electric-field pulse can induce magnetization switching in nanoscale magnetic tunnel junctions (MTJs) through the electric field effect on the magnetic anisotropy [1-4]. The switching probability oscillates with respect to the pulse duration, reflecting the magnetization precession in a free layer. While the electric-field induced magnetization switching has achieved an ultra-low-power and high-speed magnetization switching [5], the physical mechanism governing its thermal effect is unclear [6], hindering the way to improve the switching reliability. In this work, we measure real-time magnetization dynamics to elucidate the thermal effect on the magnetization dynamics induced by the electric field.

The stack structure, buffer layers /CoFeB(0.9 nm) /MgO(1.3 nm) /CoFeB(1.8 nm) /cap layers, is sputtered on a sapphire substrate and processed into an 80-nm-diameter MTJ. The resistance area product and tunnel magnetoresistance (TMR) ratio are 13 $\Omega\mu m^2$ and 84%, respectively. The top and bottom CoFeB layers are the free and reference layers with the perpendicular easy axis, respectively. We apply voltage pulses to induce the magnetization precession in the free layer about the in-plane component of an external magnetic field. The switching probability as a function of the pulse duration shows the clear oscillation, while the oscillation decays within the 5 periods as with our previous works [2-5].

The transmitted voltage measured by a high-speed oscilloscope reflects the magnetization precession due to the change in the junction resistance through the TMR effect. The transmitted voltage shows a clear oscillation, whose amplitude changes randomly due to the thermal agitation, but does not show significant decay up to 20 ns/ ~ 6 periods, indicating the precession lasts longer than the decay time of the switching probability. The oscillatory phase randomly changes with time as well, leading to the rapid decay in the switching probability after averaging over a number of events. We find that phase randomization is promoted by the oscillatory amplitude dependence of the precessional frequency. This dependence cannot be explained by a conventional macrospin model. On the other hand, the results of micromagnetic simulations, which include the spatial distribution of demagnetizing field, show a similar dependence in the single-domain like free layer. We develop a macrospin model to phenomenologically include this micromagnetic effect by including the dependence. The model successfully describes the experimental results of the switching probability vs. the pulse duration and has the potential to provide a guideline for improving the switching reliability of the electric field-induced magnetization switching.

This work was supported in part by Shimadzu Science Foundation, JSPS (16H06081, 19KK0130, and 20H02178), JST (JPMJPR21B2), and Cooperative Research Program of RIEC.

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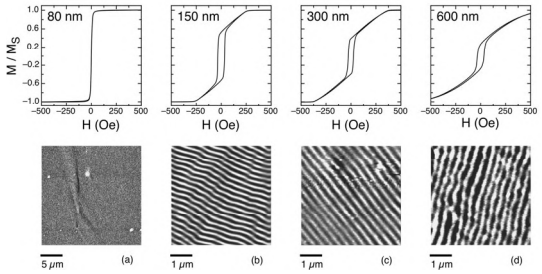

Figure 1: Top row: hysteresis loops of samples with different thickness. Bottom row: corresponding MFM images at remanence.

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Nonlinear interactions between spin-wave modes probed by parametric excitation in YIG microstructures

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Spin-wave (SW) dynamics exhibits a variety of nonlinear phenomena ranging from parametric instabilities to chaos. In confined structures, SW modes are quantized in wave-vector and energy, which limits the possible nonlinear processes due to conservation laws, but also open opportunities to understand and control them in more detail [1–3].

In this work, we use magnetic resonance force microscopy (MRFM) and micro-focused Brillouin light scattering (BLS) to probe parametric SWs in microdisks patterned from a 50 nm thick YIG film, excited by a pumping field parallel to the in-plane bias magnetic field. As expected and shown in Figure 1, the parametrically excited SWs are quantized [4,5].

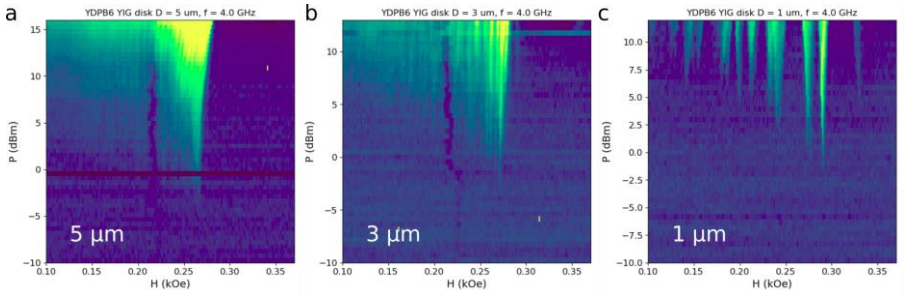

Figure 1: Intensity map of the parametrically excited modes in the field-power coordinates, measured by MRFM on disks with diameter 5 µm (a), 3 µm (b), and 1 µm (c). The parallel pumping field has the frequency f = 4 GHz.

Next, to study the nonlinear interactions between the SW eigenmodes, we simultaneously excite two of them by parametric pumping. Time-resolved BLS allows to evidence two main scenarios: indirect mode interaction and nonlinear phase locking of the modes. Two-tone MRFM spectroscopy demonstrates that each mode is coupled to all other modes, and shows that nonlinear interactions are complex, with enhanced or suppressed peaks, and the appearance of additional peaks in the spectrum. Micromagnetic simulations provide some insight into these nonlinear processes.

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Spin-wave dynamics in the system of coupled waveguides

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Magnonic waveguides are used to steer the spin waves. Due to their geometry, they are characterized in general with the multimodal spin-wave propagation, however, nanoscale waveguides can have a wide single-mode range of frequencies. The systems of multiple waveguides were investigated mostly in the planar structures, which are easy to prepare using lithographical techniques and they were used to design logic devices [1,2]. However, the development in the sample preparation makes the fabrication of complicated geometries possible [3].

We performed an in-depth study of the systems of magnetostatically-interacting waveguides of different sizes and in different geometries. We found that the nanoscale vertically-stacked waveguides are superior over the planar structures in terms of coupling strength due to significant increase of the interaction (Fig. 1a) and the possibility to reach smaller separation between the waveguides in the vertical direction. Vertically-stacked waveguides can have a dispersion crossing in the single-mode range (Fig. 1b), making the transmission of the spin wave between the waveguides impossible for the crossing frequency. By shifting one of the waveguides in its plane, one can play with the interaction between them, e.g., by shifting the crossing frequency and wavevector as well as achieving small transmission length of the spin wave between the waveguides [4] in wide frequency range (Fig. 1c).

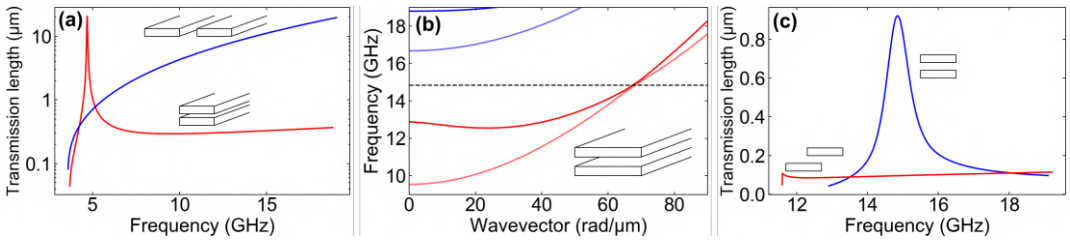

Figure 1: (a) Transmission length of spin waves [4] between the YIG waveguides of 10x50nm cross-section in horizontal (separation 25 nm) and vertical alignment (separation 5 nm). (b) Dispersion relation of vertically-stacked Py waveguides of cross-section 5x50nm. (c) Transmission length of spin waves between the Py waveguides of 5x50nm cross-section in vertical alignment (blue line) and with a 30 nm shift of the top waveguide (red line).

This study has received financial support from the NCN Poland project no. UMO-2021/41/N/ST3/04478.

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Spin wave excitation via magnetoelastic coupling by transient grating experiments

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The world-wide need for ever-increasing computing performances calls for new technologies for data storage and handling. Most prominently, in new-generation non-volatile magnetic memories the *write* operation through an external applied magnetic field is no longer possible, due to Moore-ruled scaling down of the magnetic bits. Instead, acoustic control of magnetism, often called magneto-acoustic, appears as an appealing route for low-energy-consumption operation, exploiting the magneto-elastic coupling (MEC), driven by inverse magnetostriction at micron-size wavelength [1]. Besides the technological relevance, much attention has been recently paid to fundamental investigation on interplay of spin degrees of freedom and coherent phonon excitation, without the intermediation of electronic excitation [2].

Here we propose an all optical approach for generation and detection of spin waves generated via magnetoelastic coupling, using a four-wave mixing approach, called transient grating. The elastic modulation, generated by the interference of two laser pump pulses, couples with magnetic degrees of freedom, generating a spin wave. Tuning an external applied magnetic field on magnetic thin films, we can reach the condition of acoustically-driven ferromagnetic resonance, in which the time-dependent magneto-elastic field balances the Gilbert damping, allowing the spin precession to last long after its intrinsic damping. A comparison with standard FerroMagnetic Resonance (FMR) spectroscopy measurements, and the extraction of magnetic parameters will be shown.

The proposed setup also allows to access directly to spin dynamics, using crossed polarized pump pulses. In this case, a polarization grating can be directly generated, overcoming the request of magneto-elastic coupling. Preliminary results on YIG thin films on GGG substrate and on the helimagnetic insulator bulk Cu2OSeO3 will be reported.

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Three-dimensional nanoscale imaging of propagating spin waves via time-resolved X-ray Laminography

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Spin waves are one of the most interesting candidates for the development of high-speed and low-power information carrier device and of systems for computing and signal processing [1]. Moreover, following the trend of nanoelectronics, harnessing the third dimension is one of the most desired capabilities [2]. Until now, however, spin waves have only been studied with 2D time-resolved techniques, and the visualization with nanoscale resolution of their 3D dynamical behavior still represents a major challenge [3,4].

In this framework, we exploit the innovative Soft X-Ray Laminography (SoXL) method, present at the PolLux beamline (X07DA) of the Swiss Synchrotron Light Source [5]. The SoXL is a synchrotron-based technique that allows to obtain the three-dimensional time-resolved reconstructions with nanoscale resolution of the magnetization dynamics of thin samples. To install the new Laminography setup, the two-dimensional STXM instrumentation present at the PolLux beamline was modified with an additional rotational stage, whose rotation axis is tilted respect to the incoming x-rays beam, as shown in Fig.1 (left). The projections obtained at the different Laminography rotation angles are analyzed with an iterative reconstruction algorithm, which allows to recover the components of the magnetization [6,7]. Here, we focused on CoFeB/NiFe-based synthetic antiferromagnetic (SAF) structures for the emission and propagation of spin waves, which are emitted from spin textures of magnetic Landau domains stabilized exploiting shape anisotropy in nanopatterned geometric features.

The SoXL technique allowed to reconstruct for the first time the sequence of 3D time-resolved images of propagating spin-wave modes inside the fabricated SAF samples and to study the variation of their localization in the z-direction. In Fig. 1 (right) an example of the 3D magnetic reconstruction for a single frame is reported, where the propagating spin waves for both top CoFeB and bottom NiFe layers are shown.

This work represents an important step towards the possibility to study and control three-dimensionally the spin waves emission and propagation for the development of innovative 3D nanomagnonic devices for the next generation computing architectures.

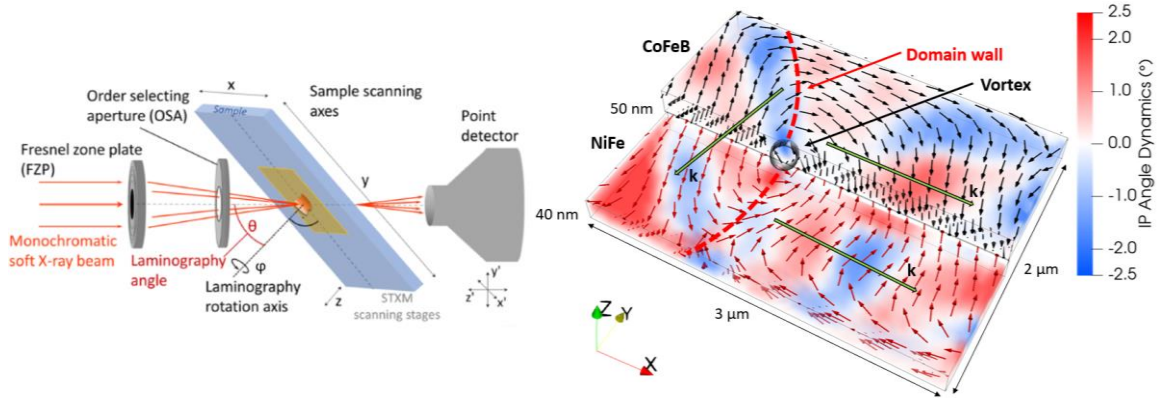

Fig. 1 Left: simplified scheme of the SoXL setup [4]. Right: 3D magnetic reconstruction of the investigated Landau domain. Only half of the top CoFeB and bottom NiFe layers are shown, to highlight the three-dimensionality of the sample. In black (red) the static in plane magnetization vectors for the CoFeB (NiFe) layer are represented, while the red and blue colors represent the maximum and minimum value of the angle between the in plane dynamic and static vectors of the magnetization.

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Scanning NV Magnetometry for Magnetic Memory Devices

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Scanning NV magnetometry (SNVM) is an emerging quantum sensing technique which allows to measure minute magnetic fields with nanoscale resolution. In the talk we will discuss the characterization of magnetic nanowires and nanomagnets for qubit. The former are among the essential building-blocks of contemporary spintronic devices [1] since their magnetic properties can be tuned by their geometry, and their fabrication is compatible with standard semiconductor fabrication schemes. While their topography and homogeneity can be well characterized with established techniques, it remains difficult to access their microscopic magnetic properties which are key to improve device performance. For the nanomagnets, a similar challenge appears. The stripes that we discuss are fabricated with FIB lithography and appear entirely homogenous in SEM imaging, however, their magnetic properties hold surprises. This is of relevance since their purpose is to generate a homogenous magnetic field gradient for spin quantum dot devices.

Here, we demonstrate magnetic imaging of these nanostructures by SNVM [2]. The imaging reveals the presence of several magnetic inhomogeneities that are largely undetectable with standard metrology. In this context, we will discuss the potential of SNVM for semiconductor device analysis.

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Spin wave dispersion in bilayer hybrid systems composed of artificial spin ice and thin film: Brillouin light scattering measurements and simulations

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We performed a joint experimental and theoretical study of the spin-wave dispersion in hybrid magnonic structures made of a NiFe artificial spin ice (ASI) layer deposited on top of a continuous (unpatterned) NiFe thin film. The ASI lattice consists of 20 nm thick ellipses with lateral dimensions of 260x90 nm^2 either in contact with the 20 nm thick NiFe film, or separated from the NiFe film by a 10 nm thick nonmagnetic spacer. The ASI is defined using electron beam lithography, electron beam deposition, and lift off [1]. We performed Brillouin light scattering measurements as a function of the light incidence angle (symbols in fig. 1 right panel), i.e., by varying the probed spin-wave wavevector, and hence the experimental dispersions $\omega(k)$ are obtained. Depending on the separation between the underlayer and the ASI nanostructure, we observe a rich mode spectrum that exhibits characteristics both spin waves in the extended film (Damon-Eshbach mode) and higher-order ASI modes. Among the latter, we experimentally reveal a weakly dispersive magnon mode. By means of mumax3 simulations [2], and by performing the space-resolved time Fourier transform, we calculated the spin-wave dispersions $\omega(k)$ (which we compared to the measured ones), the spatial profile of the spin mode cell functions, and the power spectra (k=0). We found a dynamic interplay between ASI and the film underneath. In particular, the ASI is forcing a nonuniform magnetization in the film layer [3], impressing its periodicity, and the film is found to increase the intensities of the ASI resonances and to alter the mode bandwidth. We finally draw important considerations of having a tuneable system which possesses different spin-wave modes that are either propagating or are stationary, as well as localized or extended.

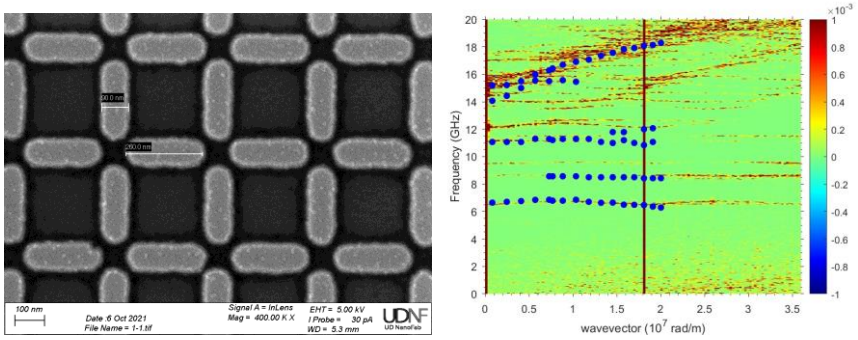

Figure 1: (Left panel) SEM micrograph of the fourfold ASI structure. (Right panel) Simulated dispersion (colormap, within two Brillouin zones) with experimental BLS points (full symbols) when ASI and film are in contact.

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Study of nonlinear absorption by electromagnons in multiferroic hexaferrites

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Numerous compounds with the hexaferrite structures exhibit magnetoelectric multiferroic properties, and their spin-lattice dynamics feature excitations called electromagnons; these are known to interact with the incident electromagnetic field. Additionally, the magnetic field – temperature phase diagrams of some hexaferrites show a rich variety of magnetic structures, indicating that a moderate excitation strength may be sufficient to achieve a phase transition of the spin system. In view of a potential use of hexaferrites as prototype media suitable for a novel type of magnetic data storage with electric-field switching, we performed an experimental study aiming at observing nonlinear properties of electromagnons in two *Y*- and *Z*-type hexaferrites, $Ba_{0.2}Sr_{1.8}Co_2(Fe_{0.96}\ Al_{0.04})_{12}O_{22}$ and $(Ba_{0.2}Sr_{0.8})_3Co_2Fe_{24}\ O_{41}$.

The equilibrium properties of electromagnons in these compounds, located in the THz range, were studied earlier [1,2]. In the present work, we used intense THz pulses generated by two different linear-accelerator-based sources. THz transmittance spectra of the samples for different radiation intensities and sample temperatures were measured and analysed.

In the *Y*-type hexaferrite single-crystal, we observed a weak shift in the electromagnon frequency after the THz irradiation. This might be possibly attributed to a transition from the alternating longitudinal conical magnetic structure to the transverse conical one. Based on simple calculations, the THz electric field induces spin tilts of ≈11° only; we conjecture that the magnetic component of the THz pulses should play a crucial role. The actual magnetic structure may be influenced, besides the temperature, magnetic and electric field, also by the history of sample irradiation by THz pulses.

In the *Z*-type hexaferrite ceramics, we observed no unambiguous signs of nonlinearity, and based on the instrumental parameters, we estimated the maximum THz-induced spin tilt as $\delta\mu < 4°$. By extending the model to a nonlinear one, assuming only a geometrical nonlinearity, we predicted that the nonlinearity would be observable for substantially higher THz intensities only.

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Influence of non-local damping on magnon properties

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Gilbert damping α is a key parameter in spintronics and low-power magnonics devices, which describes the rate of energy dissipation from the spin system to other degrees of freedom, like phonons. Experimentally, the Gilbert damping is typically measured using ferromagnetic resonance (FMR) techniques, but it is also accessible via magneto-optical Kerr effect measurements (MOKE). In the last decades, theory made efforts to predict the intrinsic part of the Gilbert damping by several methods [1]. Here, α is typically considered as a scalar parameter, but it has been recently observed that Gilbert damping is both anisotropic in terms of spin rotation [2] and non-local [1]. Based on these properties, the stochastic Landau-Lifshitz-Gilbert (SLLG) equation becomes:

$$\frac{\partial \mathbf{m}_i}{\partial t} = \mathbf{m}_i \times \left(-\gamma(\mathbf{B}_i^{\text{eff}} + \mathbf{b}_i) + \sum_j \frac{\boldsymbol{\alpha}_{ij}}{m_j} \frac{\partial \mathbf{m}_j}{\partial t} \right) \tag{1}$$

where $\boldsymbol{\alpha}_{ij}$ is the non-local damping tensor, $\mathbf{m}_i$ is the magnetic moment at site i, $\mathbf{B}_i^{\text{eff}}$ and $\mathbf{b}_i$ are effective field and stochastic thermal field, respectively. However, to the best of our knowledge, the impact of this non-local dissipation term on magnetic observables has not been shown.

We present our implementation of the non-local damping term into the UppASD software package[3]. Here, the effective field $\mathbf{B}_i^{\text{eff}}$ is related to a spin-Hamiltonian consisting of Heisenberg and Zeeman terms only and both the Heisenberg exchange parameters and the non-local damping are calculated from density functional theory (DFT). We traced the evolution of the magnetic moments and studied relaxation processes as well as magnon spectra and the respective magnon lifetimes.

In our study, we focus the application of this new implementation on bcc Fe, fcc Co and bcc $Fe_{50}Co_{50}$. It is found that the non-local damping has a pronounced effect on spin relaxation processes and magnons. Taking $Fe_{50}Co_{50}$ as an example, the non-local damping decelerates the spin relaxation process and increases the magnon lifetimes. We corroborate our numerical analysis of magnon lifetimes also with an analytical model from linear response theory. Observables of our studies can be linked to FMR and scattering experiments, which hopefully motivates experimental measurements of non-local damping in the future.

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Observing high-k magnons with Mie-resonance-enhanced Brillouin light scattering

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Advances in Brillouin light scattering (BLS) spectroscopy allowed us to study and develop first generation of magnon devices and are one of the main reasons why magnonics became one of the most promising candidates for "beyond CMOS" technology. However, further development and especially miniaturization is needed to bring spin-wave devices closer to real applications. Here, BLS has a fundamental limit in probing short wavelength magnons. This limit is given by the momentum conservation condition: $k_\mathrm{i} = k_\mathrm{r} + k_\mathrm{m}$ (for the Stokes process), where k_i (k_r) is 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 wavenumber of the incident light. Most BLS experiments utilize light from visible spectra, thus restricting state-of-the-art experiments to the approx. 300 nm wavelengths of spin waves.

To tackle this limitation, we propose a new way of detecting short-wavelength spin waves, beyond the fundamental limit of the BLS [Fig. 1 (a), (b)]. We employ Mie resonance-based dielectric nanoresonators to localize and amplify the incident electric wave [2]. We were able to increase the maximal detectable wavevector approx. three times [Fig. 1 (c), (d), (e)]. The results were also confirmed on coherent spin waves excited by microwave nanoantenna.

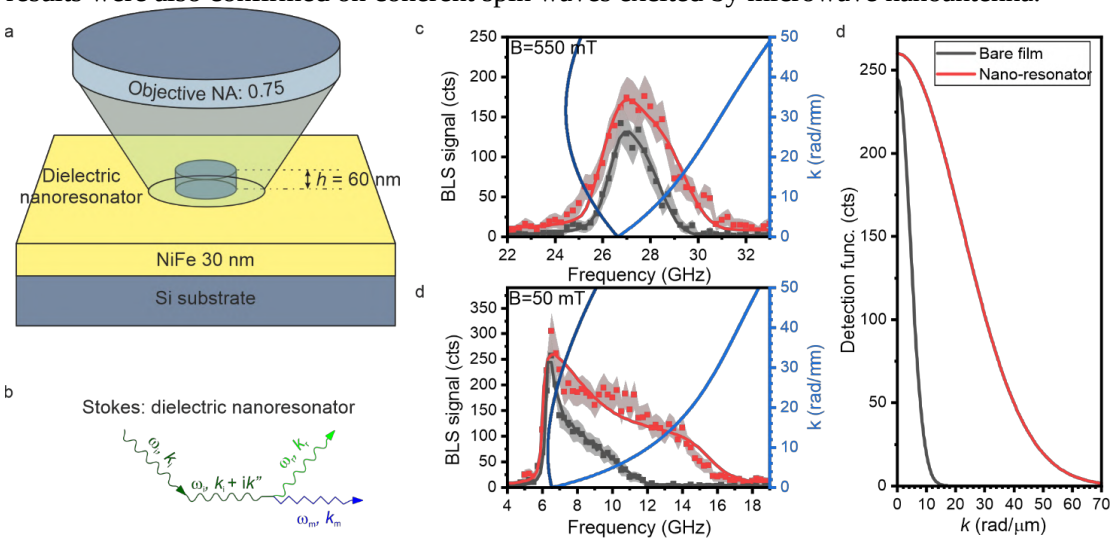

Fig. 1: (a) Schematics of the dielectric nanoresonator enhanced BLS. (b) Schematics of the Stokes processes during the BLS mediated by localized resonances. (c), (d) BLS experimental data for bare film (black dots) and dielectric nanoresonator (red dots) with corresponding fits (black and red lines). Blue lines with right axis show spin wave dispersion given frequency and wavevector range. (e) Dielectric nanoresonator enhanced detection function (red) compared to detection function for a bare film in the magnetic field of 50 mT

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Propagation of nearly single cycle terahertz pulse in antiferromagnetic CoF_2

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Antiferromagnets (AFM) have attracted tremendous attention in spintronics and magnonics because of their spin-wave resonances lying in the high-frequency terahertz (THz) range and unique functionalities when compared to conventionally used ferromagnets [1]. Excitation of such resonances requires THz sources of coherent radiation and thus can hardly be realized using traditional means, such as microstrip lines. Although much is known on how a THz pulse influences spin order, surprisingly little is known about the opposite. In fact, how interaction with the spins influences the THz pulse itself upon propagation inside of thick antiferromagnetically ordered media.

Here we study the archetypal low-temperature antiferromagnet CoF_2 (T_N = 39 K). In this easy-axis AFM, it has been recently shown that linearly polarized THz pulses can be used to coherently control both spin and lattice on the ultrafast timescale [2-3]. Using polarization-sensitive THz time-domain transmission spectroscopy, we explored how single-cycle linearly polarized THz pulse (Fig. 1 (a)) changes upon propagation through CoF_2. The changes are found to depend strongly on the sample temperature (Figure 1 (b)) and can be explained in terms of magnetic linear birefringence and dichroism. The ellipticity is showing a pronounced growth upon cooling below T_N and is accompanied by a giant rotation of the polarization plane. Although the magneto-optical effects in the THz spectral range are often considered to be relatively small, our experiments reveal that the polarization of the THz pulse substantially changes along with the pulse duration as shown in figures 1 (a, c). The pulse shape is further complicated by the emergence of pronounced beatings, indicative of the formation of magnon-polaritons highlighting a regime of strong coupling.

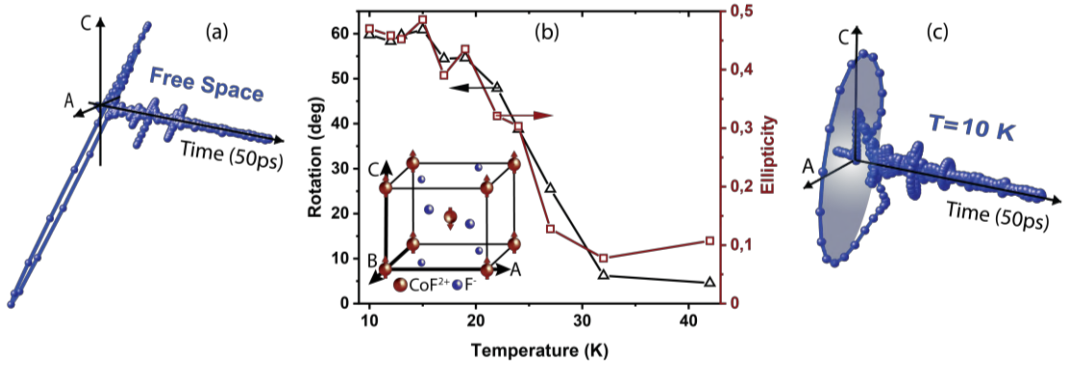

Figure 1: Linear polarized THz pulse before (a) and after (c) propagation through AFM CoF_2 (b) Extracted rotation and ellipticity as a function of temperature and CoF_2 unit cell.

Our findings demonstrate the importance of accounting for propagation effect in THz control of AFMs in spintronics and magnonics and thus help to develop methods for the fastest possible and the most energy-efficient logic operations based on AFMs.

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Ultrafast laser-induced dynamics in ferrimagnetic Gd/FeCo multilayers

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Ferrimagnetic Gd/FeCo multilayers were fabricated to mimic the properties of GdFeCo alloys and explore how all-optical-switching depends on strength of the exchange interaction and magnetic anisotropy. When performing ultrafast optical pump-probe experiments and laser-heating the medium above its compensation point (T_M = 320 K), we find a field-assisted sub-ns reversal of the magnetization as depicted in Fig. 1a. At lower fluences, the laser-excitation instead triggers spin precession with extraordinary large amplitudes reaching over 30 degrees (see Fig. 1b). Such a feature has not been reported in the alloy. The key to understanding these phenomena is hidden in the precessional motion, whose frequency slips in time $d\omega \approx 0.17$ GHz/period (see Fig. 1b) and also depends strongly on pump-fluence. From here, we argue that the ultrafast spin dynamics are triggered as a result of thermal transient dynamic behaviour of the anisotropy field $\boldsymbol{H}_A(t)$. These results are supported by simulations using the stochastic Landau-Lifshitz-Bloch (LLB) equations. We argue that the distinct laser-induced magnetization dynamics in the multilayers compared to the alloys can be due to the symmetry breaking at the numerous interfaces of the multilayer, giving rise to additional surface anisotropy, which alters the thermal transient behaviour of the net anisotropy field [1].

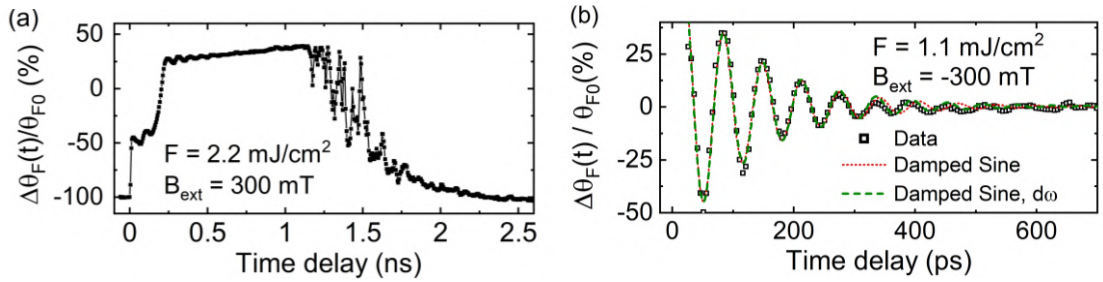

Figure 1: (a): Field-assisted sub-ns reversal of the magnetization. (b) Unusually large-amplitude oscillations of the magnetization triggered by a low laser-fluence. The data can only be fitted by assuming a linearly time-variable frequency.

Not only the anisotropy is altered by separating Gd and FeCo in different layers, also the inter- and intra-sublattice exchange coupling is modified. In particular, the reduced Gd-FeCo exchange allows a non-collinear configuration of the spins, known as "spin-flop", to occur for fields as low as 0.5 T [2]. Whereas previously in GdFeCo alloys, such a non-collinear orientation of the spins transition required at least several T. This allowed us to study the static and dynamic H-T phase diagram accurately by a table-top experiment, notably in the vicinity of the tricritical point where the phase-transition from non-collinear to collinear turns from 1st to 2nd order. Interestingly, while static measurements reveal three different magnetic phases, ultrafast laser excitation launches spin dynamics of four different types. Our analysis demonstrates that by varying magnetic field and temperature one can substantially modify both longitudinal and transversal magnetization dynamics in the ferrimagnetic multilayer.

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[2] D. Muis, T.G.H. Blank, *et al. (in preparation)*

Laser-induced THz coherent dynamics of rare-earth magnetic moments in DyFeO3

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Ultrafast laser control of magnetism is one of the most exciting and challenging topics in physics and technology, which provides a new route to control magnetic states with high speed and low energy consumption. To explore the mechanisms of ultrafast magnetization dynamics researchers frequently appeal to the rare-earth compounds, in which strong spin-orbit coupling results in the non-trivial spin dynamics [1].

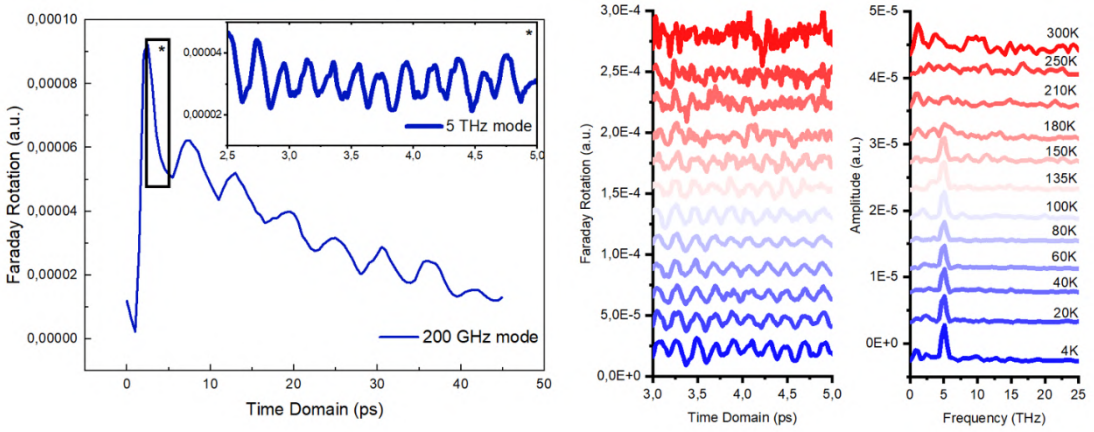

Figure 1: On left: Time-resolved ultrafast dynamics of the Fe3+ ions and the Dy3+ (inset) for circularly polarized light at the 4K temperature. On right: temperature dependence of crystalline lattice oscillations.

To probe and to control magnetic properties on a femto/picosecond timescale antiferromagnetic (AFM) rare earth orthoferrites are an interesting object to study due to the presence of two types of magnetic ions: transition metal iron (Fe3+) and rare-earth (R3+) ions. DyFeO3 is one of the most intriguing representatives of the orthoferrites family. The striking demonstrations of the ultrafast inverse Faraday effect [1], ultrafast spin-reorientation phase transition [2], generation of propagating coherent THz spin wavepackets [3] are to name a few. The collective dynamics of the rare-earth ions are addressed only indirectly and as consequence remains largely unexplored. Recent theoretical analysis [4] showed that magnetization dynamics triggered by an ultrashort laser pulse are owed due to the coherent oscillations of magnetic moments of Dy3+ ions in DyFeO3.

Using time-resolved pump-probe measurements of the magneto-optical Faraday effect we explore magnetization dynamics triggered in DyFeO3 by sub-10 fs laser pulses. The study reveals 5 THz mode which corresponds to an f-f transition in Dy3+ ions. The measurements reveal that the phase of the magnetization dynamics can be controlled by the helicity of the pump pulses. The results are explained in terms of the inverse Faraday effect on the rare-earth ions, where femtosecond laser pulses trigger magnetization dynamics composed of both spin and orbital degrees of freedom.

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Spin-, time- and angle-resolved photoemission spectrometer

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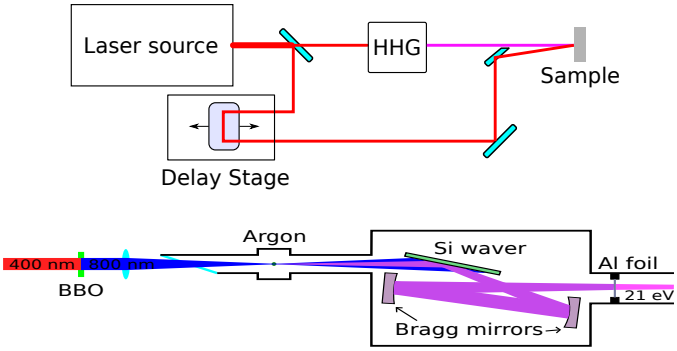
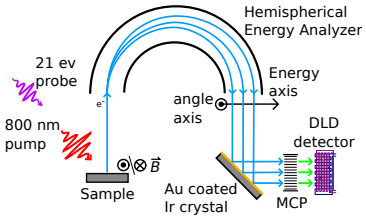
Femtosecond light sources enable us to study ultra-fast process in physics. Ultra-fast spin dynamics require accurate detection of electron behavior within the material. To deepen our understanding in this topic, a spin-, time- and angle-resolved photoemission spectrometer (STARPES) has been designed [1].

Time resolution is achieved with a Ti:Sapphire laser, which produces an 800 nm beam with ~25 fs pulse length. The beam is divided for a pump and probe scheme. The pump beam is directly focused onto the sample. High harmonic generation produces a probe beam with photon energy of 21 eV for photoemission from the sample.

After electrons are emitted, we get angle and energy resolution using a hemispherical energy analyzer (HEA). Then a Ir (100) crystal filters the electrons with a particular spin direction [2, 3]. After reflection of the Ir crystal, electrons are detected by a delay line detector (DLD). We can control the direction of the magnetization of the sample by applying microsecond field pulses using a coreless electromagnet in combination with a pulse generator. Spin resolution comes from comparing the detected filtered electrons for opposite magnetization directions of the sample.





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All-optical spin injection in silicon revealed by element specific time-resolved Kerr effect

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Spintronics aims at controlling both the charge and the spin carriers in solid-state devices. Semiconductor spintronics promises enhanced functionalities in terms of speed and energy consumption. The most promising mechanism to achieve spin currents in semiconductors is to inject spin-polarized hot electrons from a ferromagnetic film into the semiconductor substrate. Superdiffusive spin currents can be generated by the absorption of an ultrafast IR pulse by a ferromagnetic film. The excited electrons diffuse then ballistically inside the film but, as velocities and scattering times are bigger for spin majority electrons than spin minority ones, the excited electrons propagate then through interfaces as spin currents.

Silicon is an ideal material for spintronic applications due to both its role in the traditional electronics industry and its allowing long-lived spin currents. Nonetheless, the injection of spin currents in semiconductors still lacks direct evidence. To provide experimental evidence of spin injection, we studied a Ni/Si_3N_4/Si interface using the time-resolved resonant MOKE effect [1] both at the Ni $M_{2;3}$ and at the Si $L_{2;3}$ edges. The measurements were carried out at the MagneDyn beamline [2] at the externally seeded FERMI free-electron laser.

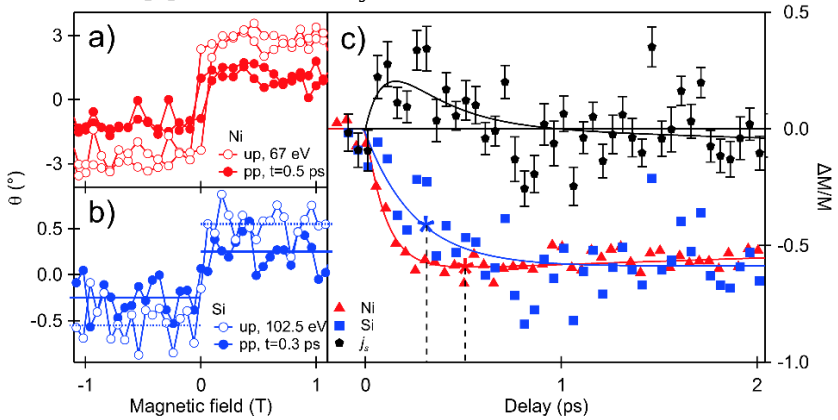

Figure 1: Unpumped and pumped RMOKE magnetic hysteresis at the Ni $M_{2;3}$ edge (panel a) and at the Si $L_{2;3}$ edge (panel b). Panel c) relative change of the site resolved magnetization M (Ni - red dots and Si - blue dots) as a function of the time delay measured in a saturation magnetic field. The solid lines represent the fitting results, from which we extract the two characteristic times for demagnetization (τ_m) and recovery (τ_r). The difference of the two magnetization dynamics, defined as $(\Delta M/M)_{js}$, is also shown (gray pentagons).

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Supermagnonic propagation in 2D antiferromagnets

Magnons, the collective excitations of magnetic materials can oscillate up to 100 THz over a distance of less than one nanometer. With intrinsically small energy loss, such magnons have great potential for smaller, faster and more energy-efficient data processing. However, understanding the magnon spectrum at such short wavelengths has been challenging even for the simplest model: the antiferromagnetic Heisenberg model in 2D. Furthermore, studying the space-time dynamics of this model defines an intricate quantum many-body problem out of equilibrium, for which until recently no accurate methods were available.
Here we adopt a machine learning inspired ansatz to simulate the dynamics of the 2D Heisenberg model [1]. We show that ultrashort perturbations of the exchange interaction excite dynamics of spin correlations, which propagate highly anisotropic in space. Interestingly, at the shortest length and time scale, we find that the propagation speed is up to 40% above the highest magnon velocity [1]. By employing Schwinger-boson mean field-theory, we show that this effect is the result of a subtle interplay between propagating magnon modes, and a quasi-bound state that results from magnon-magnon interactions [2]. Our results therefore suggest new possibilities for manipulating information transfer at ultrashort length and time scales.

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In-vitro Real-Time Magnetic Recording of Neuronal Activity on Spinal Cord Slices

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Recording neural activity, originated from action potential dynamics, has long been a major pursuit in neuroscience that calls for the development of seamless neural interfaces for probing, understanding, and repairing signal transmission at the nervous system. Conventional electrodes (direct voltage measurements) and emergent optical imaging (using genetically encoded fluorescence indicators) are complementary technologies to measure neuronal activity *in vivo*, but intrinsically present general physical constrains. Both are blind to the direction of the ionic flow and require sophisticated equipment, which make them non-portable.

Magnetic probes for neuronal activity recording could be complementary to electrophysiology. Contrary to electric fields, which strongly depend on the dielectric properties of the tissue, magnetic properties of tissue are similar to those of free space and , in contrast to voltage measurements where the recordings yield scalar values, magnetic field is a vector, and thus, magnetic recording provides a more precise and complete scenario of the neuronal activity. Additionally, magnetic detection is reference-free and therefore allow for an unbiased measure of connectivity. Magnetoencephalography (MEG) [1] and Optically Pumped Magnetometers [2] are extremely sensitive magnetic technologies for monitoring neural signals. However, MEG require cryogenics and both use complex architecture difficult to miniaturize, not allowing chronical implantation. Magnetoresistive sensors, free of these limitations, have demonstrated the capability to read magnetic signals from different neural tissues using sensors based on gigant magnetoresistance [3].

We are going to present our results on the *in-vitro* measurement of neuronal activity from spinal cord slices (SCSs) using spintronic-based magnetic sensors, recorded at physiological conditions with no magnetic shielding. In particular, we introduce differential measurements, using an improved differential sensing approach in a gradiometer configuration to record real-time neural activity at different conditions driven by pharmacology, i.e., at collective excitation (mediated by Bic/Stryc) and blocked (mediated by TTX) states, to address the biological origin of the signals. Ca^{2+} imaging and electrophysiology acquired simultaneously with magnetophysiology measurements confirm the real-time insight and the biological origin of the recorded neural activity. Our results pave the way towards the development of portable devices capable of detecting magnetic fields created by neuronal activity.

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Simulation of *in vivo* tests of magnetic hyperthermia

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In magnetic hyperthermia, the temperature increase in diseased tissues is achieved after the administration and activation of magnetic nanoparticles (MNPs), which release heat when exposed to AC magnetic fields with frequency of 50-500 kHz. The evaluation of MNP efficacy involves preclinical studies, generally conducted on murine models [1]. During *in vivo* tests, several factors have to be considered to optimize heat deposition and reduce side-effects, like hot spots caused by eddy currents. These factors comprise the fulfilment of biophysical limits when selecting field parameters [2], the dependence of MNP specific heating power on experimental conditions, the field applicator geometry and positioning, and the spatial distribution of MNPs within the tumour, strongly influenced by administration route. This scenario requires the development of methodologies able to guide the experiments on animals and support the result interpretation, for a possible translation to humans.

In this framework, we developed *in silico* models to support *in vivo* tests of magnetic hyperthermia [3]. We focused on the evaluation of the possible eddy currents induced in the body during hyperthermia sessions and the calculation of thermal effects, consequent to MNP excitation. The simulations were performed on digital phantoms of murine models (mice and rats), with a high-resolution reproduction of tissues and organs. Different applicators were compared, studying the role of geometry and position on the magnetic field distribution within the target tissue. To avoid adverse eddy current effects, we considered the Herg-Dutz limit for selecting field frequency and amplitude. *In silico* experiments were then performed to evaluate the heating effects produced by MNPs, versus MNP type, dose and spatial distribution.

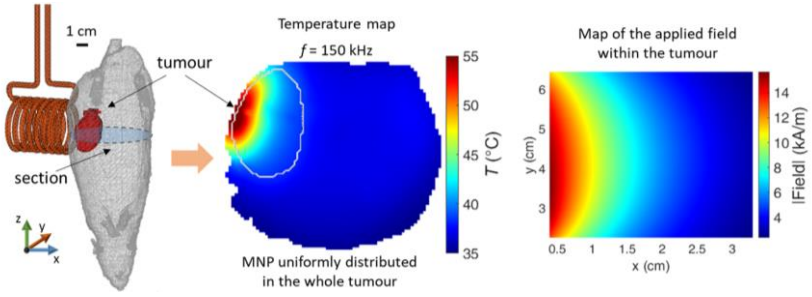

Figure 1: The figure shows the results obtained for a 500 g rat, when treating tumour with iron oxide NPs activated by a 150 kHz magnetic field, generated by a solenoid placed close to the target region.

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Engineered magnetic plucking for frequency up-conversion in energy harvesters

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Today, almost all portable electronic devices rely on batteries. In this context, harvesting energy from the surroundings is a valuable option to extend the durability of the battery charge and enable new powering solutions. Collect energy from mechanical vibrations is one of the most desirable types of harvesting due to the large availability of acoustic waves in every context. The challenge of this type of harvesting is to convert low frequency vibrations (typical of human activities) to high frequency ones (optimal for energy transducers). This process is called frequency up-conversion and it can be obtained by a non-linear interaction (magnetic or mechanical) between a seismic mass and the harvester [1]. The principle of magnetic plucking is depicted in Fig 1a. A first magnet connected to the seismic mass interacts with a second magnet on the transducer, the two magnets can be in attractive or repulsive configuration. The second magnet is first displaced by the magnetic force and then released. During the release phase, the transducer undergoes a ring-down at its resonance frequency (high-frequency) and the mechanical oscillations are converted to energy by a piezo element. Ideally the release phase needs to be as sharp as possible to excite high frequency vibrations. Magnetic plucking usually suffers from slow release due to the relatively long range of magnetic interaction [2]. It is therefore necessary to engineer the magnetic interaction between the two magnets.

In this work, we investigate an approach to optimize the magnetic interaction. Considering Fig 1b, we propose to split the driving magnet into subdomains with opposite magnetization. The effect of this configuration has evident advantages if we consider the magnetic plucking simulations reported in Fig 1c, where the proposed configuration (red curve) allows larger vibrations of the plucked magnet, hence producing larger displacement of the transducer.

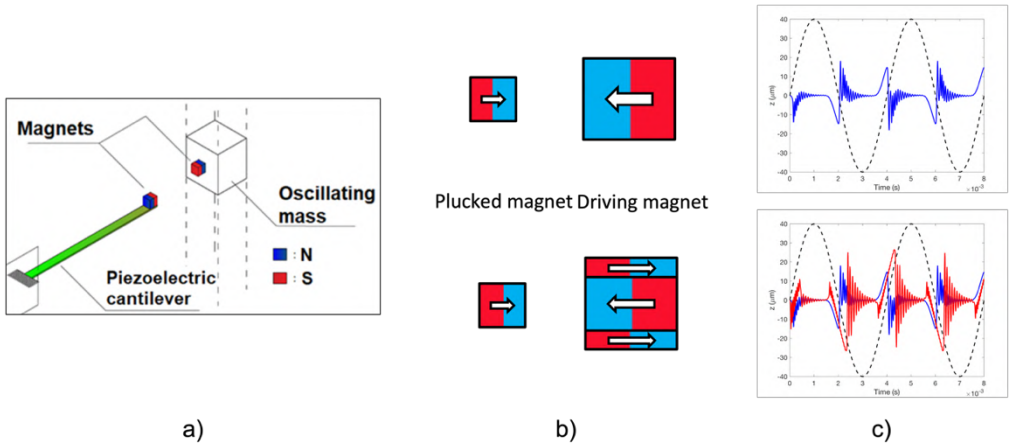

Figure 1: a) schematic view of the magnetic plucking principle; b) comparison between the typical configuration (top) and the one proposed by the authors (bottom); c) comparison between magnetic plucking simulations in the two configurations.

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Magnetization in cylindrical nanowires: the role of chirality

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The magnetization dynamics in low-dimensional structures is one of the most studied topics in the last years in both fundamental and applied magnetism. In particular, the control of the movement of magnetic domain walls (DW) along nanostructures by means of magnetic fields or electric currents is a key aspect in the design of novel devices. Although most of the studies up to now have been focused on nanostripes[1,2]—elongated structures with rectangular cross section, cylindrical electrodeposited nanowires are starting to play a key role in this field of nanomagnetism and spintronics[3].

The passage from flat structures to cylindrical electrodeposited nanowires (NWs) brings the emergence of novel DW structures directly linked to the cylindrical geometries,such as Bloch points[5], which interact with a spin-polarized current in a very different way than in 2D geometries[4], and also other structures with chiralily. In addition, the possibility of tailoring the nanowires or the templates used for their fabrication introduces additional degrees of freedom, producing magnetic tridimensional structures and enabling the appearance of new physics to exploit. These advances in the growth of 3D structures should be also accompanied by strategies and methodologies to map the tridimensional spin textures associated.

Here, We will present an overview of our recent results in the control of the magnetic configuration of cylindrical nanowires as well as the approach followed to unravel the spin texture in these structures using x-ray microscopy[6,7]. On one hand, I will show the role of chirality in the stabilization of topologically non-trivial domain wall in permalloy nanowires when local changes in composition along the wire are introduced. On the other hand, I will introduce novel strategies to introduce additional 3D magnetic textures in the nanowires (compositional axial gradients and radial modulations of composition) and their impact in the magnetization processes.

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Magnetic domains in W(d_W)/Co(d_{Co})/Pt ultrathin epitaxial layers

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The ferromagnetic films sandwiching between asymmetric heavy metal layers (like Ta, W, Pt, Ir, etc.) with strong spin-orbit coupling have been intensively studied recently for Dzyaloshinskii-Moriya interaction (DMI). Such complex systems exhibit different interesting stable magnetic structures including skyrmions [1, 2, 3]. High quality epitaxial structures Pt(bottom)/W(d_W)/Co(d_{Co})/Pt(top) with different thicknesses of tungsten d_W and cobalt d_{Co} layers were deposited on sapphire (0001) substrate by molecular beam epitaxy. The influence of electric current on domain wall motion were performed for selected W and different Co thicknesses for patterned films. Polar magneto-optical Kerr effect (PMOKE) microscopy and magnetometry were used for domain structure (DS) visualization and magnetization reversal studies. Brillouin Light Scattering spectroscopy (BLS) was applied for DMI strength evaluation. Changing the duration of light pulses in wide range it is possible to provide dynamic studies of DS motion without or under magnetic field or electric current pulses using PMOKE microscopy. Fast Fourier transformation of acquired PMOKE images allows us to determine the DS's geometrical parameters.

In this work we focused on magnetic properties for selected d_W, d_{Co} and Pt overlayer thicknesses. PMOKE magnetometry defined d_W and d_{Co} thicknesses where perpendicular magnetic anisotropy (PMA) is occurred. The strength of DMI interaction D_{eff} also depends on d_{Co}, d_W and its maximal value was as high as 1.5 mJ/m^2. For fixed d_W while decreasing the d_{Co} the transition from PMA to superparamagnetic state (SP) was observed. During this transition we observed: (1) strong decrease of the coercivity field H_C down to fraction of Oe; (2) DS is changed from an irregular, typical for ultrathin films [3], into a stripe-like, (3) approaching SP state the domain period strongly decreases, and the fluctuation of DS in real time is observed. The skyrmion bubbles structure near SP state can be stabilized with small (few Oe) out-of-plane magnetic field. The intensity of DS fluctuations is increased while decreasing d_{Co} and approaching the SP transition - similar as it was observed in [2] for ultrathin Pt/Co/Os/Pt-type structures. Studies with different light duration pulses allow to follow the dynamic studies of DS motion under without or under magnetic field or electric current pulses. The stability and the motion of DS near SP transition d_{Co} thickness were studied as the functions of applied out-of-plane magnetic field and electric current pulse density.

This work was supported by the Polish-German Beethoven project (Polish National Science Center and German Research Foundation under the projects: 2016/23/G/ST3/04196 and DFG MC 9/19-1) and also Polish National Science Center 2020/37/B/ST5/02299 and German Research Foundation DFG MC 9/21-1.

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Scale-up the electrodeposition of magnetic nanowires for the application in composite bonded magnets

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Nanowires are expected to play a key role in the development of new nanodevices in many fields of applications: magnetic recording, nanomedicine, neuroscience, energy applications... The amount of material produced in laboratory procedures is enough to develop proof of concept and lab-scale applications. However, the use of nanowires in industrial applications, i. e. nanomedicine [1] or the production of new composite materials [2], is still not exploited because of the lack of an appropriate synthesis process that allows the fabrication of larger quantities of nanowires.

In this work, we present a new synthesis route to scale up the production of magnetic nanowires [3]. There were two main objectives to bring nanowires to industrial applications: increasing the amount of nanowires and reducing the cost associated to the synthesis process. Template electrodeposition was chosen to grow the nanowires because it is a versatile and non-expensive technique that allows the synthesis of a wide range of metallic and oxide materials [4]. There are two main processes involved in the production of magnetic nanowires using electrodeposition, the preparation of the alumina templates and the growth of nanowires inside the pores, being the first one the limiting process in terms of both, costs and time. We have settled down a protocol to produce the alumina that have allow us to to reduce the price and the synthesis time, increasing the production of nanowires.

We will also show an application where FeCo nanowires, grown using this scaled-up procedure, combined with strontium ferrite powder were used to synthesize a composite based permanent magnet [5] with improved values of energy product. This composite can be a promising candidate to replace rare-earth-based magnets in select applications that require only moderate energy products.

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Origins of magnetic anisotropy in $Mn_5Ge_3C_x$ films studied by NMR

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Mn_5Ge_3 thin films, epitaxially grown on the Ge (111) substrate are a potential source of polarized carriers directly into Ge. They also display strong perpendicular magnetocrystalline anisotropy due to the unquenched orbital moment of manganese, which was observed in form of anisotropic orbital contribution to the ^{55}Mn hyperfine field [1]. Their Curie temperature can reach up to 430 K upon doping with carbon, but the addition of carbon causes a drop of magnetocrystalline anisotropy, evidenced by the FMR data. To investigate the anisotropic properties on a microscopic scale, we have undertaken the ^{55}Mn NMR study in the entire concentration range of carbon. The unit cell of Mn_5Ge_3, (hexagonal $D8_8$ structure, space group P63/mcm) contains two formula units, with manganese atoms in two crystallographic positions: 4*(d)* (here denoted as Mn_I sites) and 6*(g)* (Mn_{II} sites).

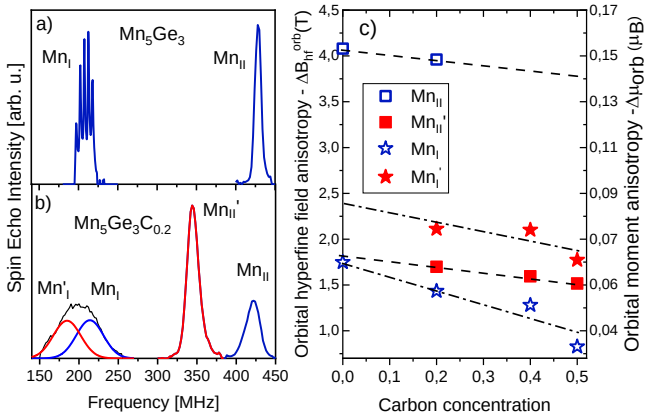

Fig.1 a,b) ^{55}Mn NMR spectra from Mn_5Ge_3 and $Mn_5Ge_3C_{0.2}$ epitaxial films. c) anisotropy of the orbital hyperfine field (ΔB_{hf}^{orb}) and orbital moment ($\Delta\mu_{orb}$) versus carbon content. Blue symbols: original Mn_I (open squares) and Mn_{II} (open stars), full red symbols: new NMR lines due to carbon neighbour.

Fig. 1a shows the NMR spectrum recorded while magnetisation was pointing along the film normal. i.e. hexagonal c-direction. Mn_I atoms give rise to the NMR line at 207.5 MHz (hyperfine field B_{hf} = 19.67 T). On the other hand, hyperfine field measured in-plane is 21.19 T, thus the anisotropy of the orbital contribution to the hyperfine field (ΔB_{hf}^{orb}) is 1.52 T. In the Mn_{II} sites (NMR line along the c-axis at 428 MHz) the anisotropy between the c-axis and c-plane is even larger and amounts to 4.08 T. The effect of carbon is evidenced by the onset of new NMR lines: Mn_I' and Mn_{II}' (red segments in the Fig 1b), originating from those Mn atoms that have carbon in vicinity. These new sites display a significant drop of anisotropy, particularly dramatic in the Mn_{II} sites (see Fig 1c). These experiments show that the main mechanism responsible for the dramatic drop of the bulk magnetocrystaline anisotropy upon carbon doping consists in a rapid growth of carbon-affected manganese sites, prompted by the highly ordered carbon penetration [2].

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Magnetic interactions in Mn_2GaC films studied by NMR.

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Mn_2GaC films belong to a rich family of compounds composed of the nanolaminated carbides and nitrides, known as the MAX phases. Complex magnetic interactions between the elements forming this quasi two dimensional structure are not yet well understood. The model of Mn_2GaC magnetic structure, proposed on the basis of DTF calculations and neutron reflectometry implies a two sublattice antiferromagnet with some canting between sublattices. With the aim to shed more light on the microscopic magnetic properties of this structure, we have undertaken a comprehensive nuclear magnetic resonance (NMR) study on the 100 nm thick epitaxial film of MgO(111)/Mn_2GaC(001).

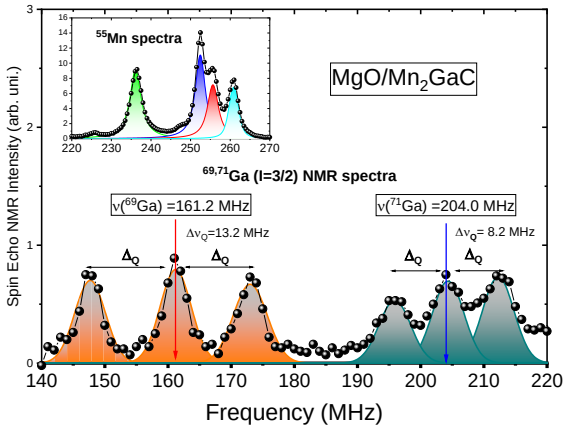

Figure 1: ^{69}Ga (orange), ^{71}Ga (green) and ^{55}Mn (inset) NMR spectra recorded from the MgO(111)/Mn_2GaC epitaxial film. All data taken at 4.2K, in zero external magnetic field.

Figure 1 shows the NMR spectra recorded from ^{69}Ga and ^{71}Ga, each revealing a clearly resolved quadrupolar structure (I=3/2). The respective central frequencies (ν [^{69}Ga] = 161.2MHz, ν [^{71}Ga] = 204.0 MHz) correspond to the gyromagnetic factors (10.22 MHz/T and 12.98 MHz/T) of the two isotopes and indicate a single value of the local field on all gallium nuclei. The frequency separation Δ_Q between the quadrupole satellites (13.2 MHz and 8,2 MHz) reflects the quadrupole moments of the respective isotopes and shows that the distribution of electric charges is identical around all gallium sites. Considering that the local field at Ga nuclei, measured in the NMR experiment, is the transferred field from the surrounding Mn magnetic moments, its non-zero value cannot be reconciled with the postulated antiferromagnetic arrangement of manganese layers across the gallium layer. On the other hand, the ^{55}Mn NMR spectrum shown in the inset of Figure 1 consists of the four well resolved resonance lines evidencing several magnetically nonequivalent manganese positions despite only one crystallographic Mn position in the hexagonal structure of Mn_2GaC. This observation, in conjunction with the nonzero magnetic field at gallium nuclei points to a complex interaction between the Mn layers via carbon.

This work has been supported in part by a grant from the National Science Center, Poland (UMO-2019/35/B/ST3/03676)

Effect of buffer and cap layer on the thermally stable perpendicular magnetic anisotropy in buffer/CoFeB/MgO/cap structure

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The effect of buffer and cap layer on thermally stable perpendicular magnetic anisotropy (PMA) in buffer/CoFeB/MgO/cap structure was designed to detailed study. In order to increase the memory capacity, a wide thickness range for CoFeB to maintain PMA is important for the fast-speed, tunable, and thermally stable magnetic random access memory (MRAM) cell [1,2]. Not only the buffer layer is crucial, but the type of cap layer also affects the thermal stability of PMA. Via the detailed anomalous Hall effect (AHE) measurements, the effect of buffer and cap layer was investigated to achieve the high thermal stability of PMA. As shown in Fig. 1(a), for the Ta samples, the PMA only exists in a narrow CoFeB thickness range from 1.3 to 1.6 nm. The narrow PMA thickness range reduces magnetic tunability. Relative to the Ta samples, the CoFeB thickness range becomes much wider (from 1 to 1.8 nm) for the samples of W buffer layer, as shown in Fig. 1(b). Similarly, for the samples of W cap layer, the PMA also exists in a wider CoFeB thickness range from 1.1 to 1.6 nm compared with that of Ta samples, as shown in Fig. 1(c). Hence, the wide PMA thickness can be achieved through selecting the appropriate buffer or cap layer material, it is beneficial to increase magnetic tunability and achieve a high thermally stable PMA for MRAM devices. This work provides a promising way to obtain high thermally stable PMA in CoFeB-MgO-based spintronic device applications, and it is significant for designing the next-generation information storage devices.

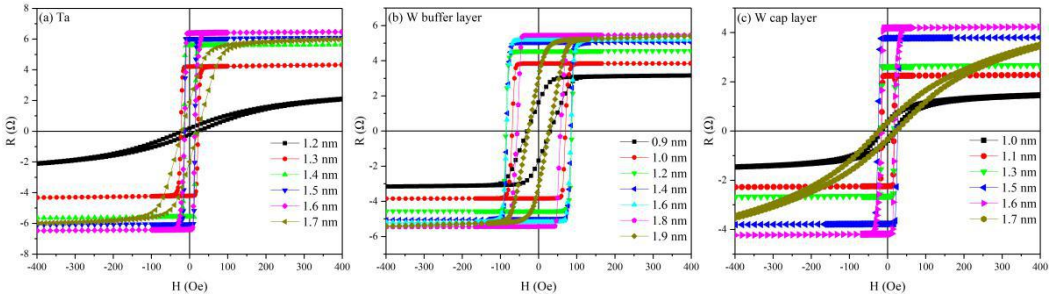

Figure 1: The AHE loops for (a) Ta(5)/CoFeB(t_{CFB})/MgO(1)/Ta(2), (b) W(5)/CoFeB(t_{CFB})/MgO(1)/Ta(2), and (c) Ta(5)/CoFeB(t_{CFB})/MgO(1)/W(2). All the samples were annealed at 270°C.

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Tuning the coexistence regime of incomplete and tubular skyrmions in thin film heterostructures

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Magnetic skyrmions can be considered as ideal information carriers due to their small size and possibilities of easily transporting them at room temperature. Even though there has been great progress towards the development of skyrmion-based memory applications, where the information can be stored by the presence/absence of a skyrmion, there are still some challenges that prevent their implementation in such devices. One of the fundamental limitations is not having stable inter-skyrmion distances, which leads to uncontrolled gaps between bits and, consequently, to large errors. To circumvent the distance problem, it was anticipated [1] that information could be stored by two different soliton states instead of just one with the experimental observation of skyrmion tubes coexisting with chiral bobbers at low temperatures within the same single crystalline material. However, for the realization of a real-world device, the two states should be stabilized at room temperature and in thin film multilayer systems for easy integration in current device technology. Using [Ir/Fe/Co/Pt] multilayers with Néel skyrmions stabilized by interfacial Dzyaloshinskii-Moriya interaction as building blocks, we developed [2] a ferro/ferri/ferromagnetic trilayer system that can host two distinct skyrmion types at room temperature: a tubular skyrmion (running through the entire trilayer) and an incomplete skyrmion (existing in the ferromagnetic layers only).

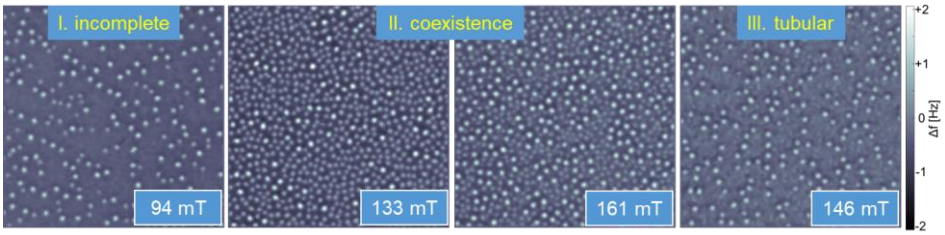

Figure 1: MFM data showing the three different regimes of skyrmion stabilization.

Applications of such a platform containing two types of skyrmions however, requires having a thorough understanding of the energies responsible for skyrmion stabilization and also a good control over the skyrmion type and density. By using a combination of magnetic force microscopy (MFM), vibrating sample magnetometry and Brillouin light scattering experiments, we show how changing the magnetic properties of individual layers modifies the energy landscape of the system, allowing it to support either two coexisting skyrmion types with varying densities or only one of the two types (Figure 1). We also perform micromagnetic simulations to further explore the stability range and uncover the spin profiles of the two distinct skyrmion types.

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Tuning magnetic coupling via defects formation at graphene/ferromagnet interface

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Antiferromagnets (AF) could represent a new class of materials for spintronic applications. AF exhibit interesting features: they are robust against magnetic fields perturbation, they can produce no stray fields due to zero net magnetization, display ultrafast dynamics, and magnetic order in AF can be controlled in many ways [1,2,3]. Two sample configurations have been under study: (i) antiferromagnetic (AFM) alloys, (ii) synthetic AFM stacks. The latter is made of two ferromagnetic layers coupled antiferromagnetically through a spacer layer. In this respect, the observation of strong AFM-coupled Fe/gr/Co/Ir(111) multilayer stacks has shown the possibility to use graphene as a spacer layer [4]. Here we present a synthetic AFM stack composed of Fe/gr/Co/Re(0001) that exhibit strong perpendicular AFM coupling. We have studied how the magnetic coupling between ferromagnets can be tuned from antiparallel to parallel by means of defects creation at the graphene/Co interface. This reveals how complex can be the role of the spacer (magnetic or not) in the coupling mechanism [5]. The experiments were carried out at the Nanospectroscopy beamline of Elettra Sincrotrone Trieste. The samples were grown in situ and characterized by XMCD-PEEM, which allow us to gain information about magnetic domains morphology and orientation [6].

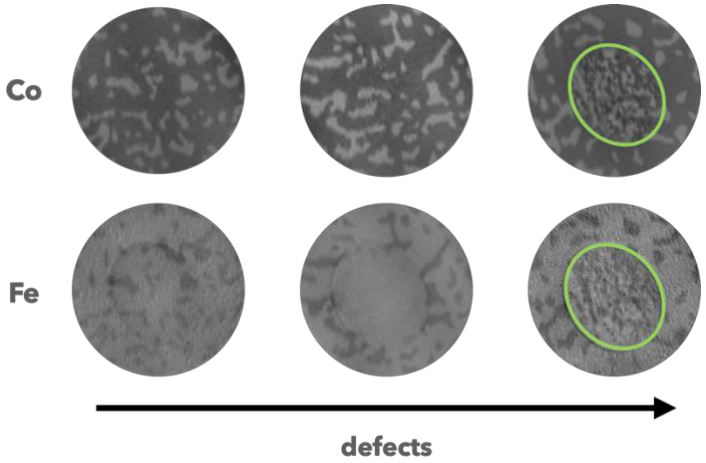

Figure 1: XMCD-PEEM images acquired at room temperature of the modified heterostack Fe/graphene/Co. Top images acquired at Co L_3 edge at 780 eV, bottom images acquired at Fe L_3 edge at 708 eV. From left to right, sample regions exhibit increased defects at the graphene/FM interface. The images reveal out-of-plane magnetic domains strongly AFM coupled between Fe and Co. Instead, the magnetic coupling is FM in the patterned region highlighted in green.

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Flexible thin film heterostuctures based on Co/Ni synthetic antiferromagnets: towards shapeable and sustainable spintronics

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Synthetic antiferromagnets with perpendicular magnetic anisotropy (PMA-SAFs) have gained a growing attention for both conventional and advanced spin-based applications. While the progress of PMA-SAF spintronic devices on rigid substrates has been remarkable, only few examples on flexible thin film heterostructures, all containing platinum group metals (PGMs), are reported in the literature [1-3]. In this contest, Co/Ni system may offer additional advantages (e.g., low damping, high spin polarization) for the development of advanced spin-based devices. Moreover, decreasing the content of critical PGM elements, may relieve the demand for strategic raw materials and reduce the environmental impact of related technologies, thus contributing to the transition towards a more sustainable future [4].

In this work, Co/Ni-based PMA-SAFs and GMR spin-valves (SVs) containing a SAF reference electrode (RL) and a Co/Ni free layer (FL) were deposited on flexible polyethylene naphthalate tapes (Fig. 1a) with different combinations of buffer (BL) and capping (CL) layers (i.e., Pt, Pd and Cu/Ta). High quality SAFs with a fully compensated AF region (Fig. 1b) and SVs with a sizeable GMR ratio (Fig. 1c), in line with the values reported in the literature for similar systems on rigid substrates, have been obtained in all cases. However, due to the different interdiffusion mechanisms occurring at the interface between the metallic layers, we demonstrated that while PGMs allow obtaining the best results when used as BL, Cu is the best choice as CL to optimize the properties of the stacks. The results thus indicate that complex Co/Ni-based heterostructures with reduced content of PGMs can be deposited on flexible tapes, allowing the development of novel shapeable and sustainable spintronic devices.

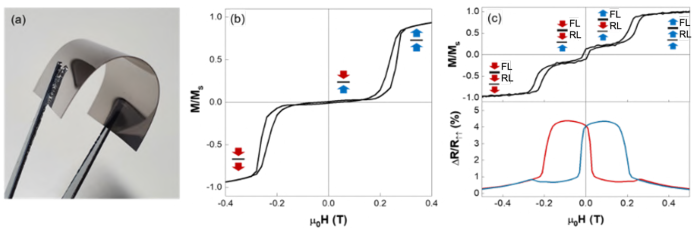

Figure 1. (a) Representative picture of a SAF-based SV. (b) Out-of-plane hysteresis loop of a flexible SAF (BL: Pt, CL: Cu). (c) Out-of-plane hysteresis loop and corresponding magneto-resistance response of a flexible SAF-based SV (BL: Pt, CL: Cu).

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Magnetocaloric response of quasicrystal-forming Al-Cu-Fe-B alloy improved by self-ordering of orthorhombic Fe_2AlB_2 phase

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The idea of refrigeration based on magnetocaloric effect (MCE) gained emerging popularity in the recent years. To achieve the goal of magnetic refrigeration for everyday applications like the food storage, materials with second-order near room-temperature magnetic phase transition are sought. One of such materials with ambient temperature magnetic transition is Fe_2AlB_2 [1]. Conventional approach reported in the recent literature was focused on the efforts on obtaining single-phase Fe_2AlB_2 in order to study its intrinsic properties [2], shorten the heat-treatment procedures in hope to reduce the manufacturing cost and to improve the magnetocaloric response of the material [3]. Our study explores the different option: the ferromagnetic Fe_2AlB_2 phase dispersed in its non-magnetic environment. This allows to investigate how coupling of magnetic moments will be affected by changes of physical shape and composition of secondary phases as well as the intrinsic properties of the magnetic phase grains separated with matrix.

My recent work [4] revealed that the primary phase that crystallizes from $Al_{55}Cu_{20}Fe_{15}B_{10}$ alloy melt is Fe_2AlB_2. The alloy contains four times less at.% expensive boron than currently described single-phase alloys. Thinking about this alloy as in-situ composite, one of the major matrix components is Al-Cu-Fe phase with quasicrystalline symmetry. The current study shown that thermal treatment allows to convert the matrix almost completely to the quasicrystal, yielding as much as 76 % of the alloy volume. But get back to Fe_2AlB_2 nanolaminate boride. The phase is ferromagnetic below its Curie point at near 300 K, grain growth habit prefers one direction and forms solid, well-developed grains which float in liquid matrix when annealed at 943° C. The critical exponents obtained from Kouvel-Fisher analysis revealed consistency with the mean-field model. The magnitude of magnetic entropy change was comparable with several iron-based metallic glasses reported in the literature. Influence of strain relaxation and secondary magnetic phase impurity were excluded as factors explaining the observed magnetic entropy change improvement. It was proposed that the major contribution was spontaneous parallel arrangement of bco-Fe_2AlB_2 grains, while the lower melting phases were in the liquid state.

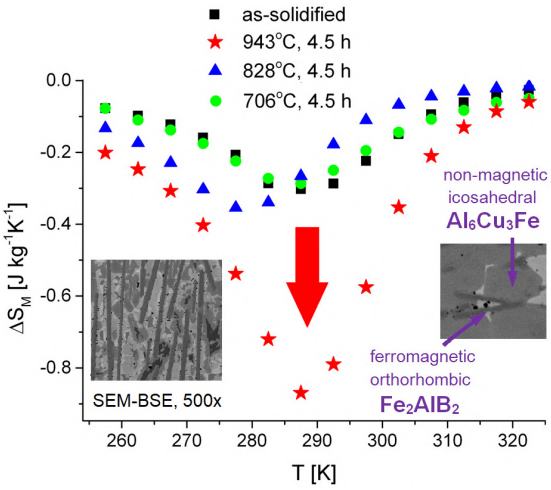

Figure 1: Temperature distribution of the magnetic entropy change ΔS_M obtained for the field $\mu_0 H$ = 0-2 T of $Al_{55}Cu_{20}Fe_{15}B_{10}$ alloy in as-solidified and annealed states

The research described was funded by the National Science Centre, Poland (NCN) research grant No. 2018/02/X/ST5/02997 (synthesis, microstructure, thermal and structural measurements) as well as National Science Centre, Poland (NCN) research grant No. 2020/36/C/ST5/00007 (magnetic properties).

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Memory and Communication Logic (MCL) in Magnetic Tunnel Junctions

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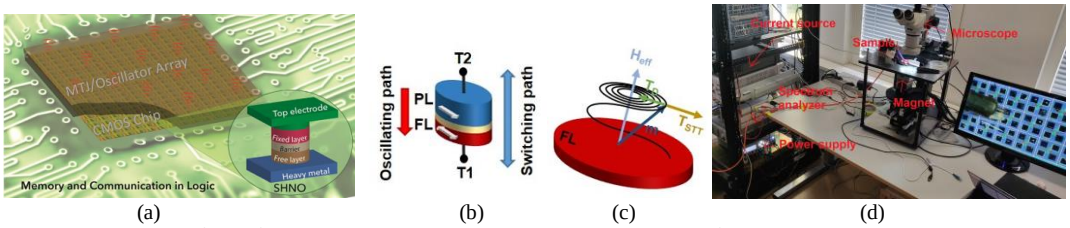
The ubiquitous use and deployment of sensors for wearable and implantable devices (WIDs) require game-changing technologies and concepts to sustain this growth beyond 2020. Any system on chip for such applications includes an analog front-end for sensing the data, a processing unit, a memory for storage, and a communication block for data transmission. Power, area, and speed are the main challenges of further development of WIDs, where depending on the applications each of them can be compromised. Moreover, the high energy consumption and large footprint of the communication block, and the speed limit due to the distance between logic and communication block remain challenging. Noted, the power consumption of wireless transceivers in WIDs is significantly larger than the logic unit for many applications[1]. Therefore, implementing communication and memory with a small footprint as close as to the processing unit with small power consumption while improving the speed is highly demanded next-generation WIDs.

The envisioned MCL system enables two functionalities: 1) storing the data and 2) transmitting the data using a high-frequency signal, shown in Fig. 1a. It improves the speed by at least 1-2 orders of magnitude by bringing the communication inside the logic (same speed for memory and logic; ~3-4GHz). Furthermore, it will make an on-chip small-area (~40-300nm circular[2] compared with ~15-240μm^2 CMOS on-chip oscillators[3]) and low power (10s of fJ/bit compared to 100s of pJ/bit for the state-of-the-art communication approaches[4]) communication possible that can be applied to many applications ranging from on-chip testing to sensing and data communication. As we know, magnetic tunnel junction (MTJ) consists of a thin oxide layer, sandwiched between two ferromagnetic layers, a free layer (FL) with changeable magnetization, and a pinned layer (PL) with fixed magnetization; see Fig. 1b. Further, Fig. 1c shows the magnetization direction of the FL (m) and different torques acting on it. T_P, T_D, and T_{STT} describe the precession torque, the damping torque, and the spin-transfer torque, respectively. The interaction of T_{STT} and T_D determines the oscillatory orbit of m[5]. Hence, in this work, we propose to use MTJ for both storing the data (memory) and communication, the measurement set-up is shown in Fig. 1d. In memory mode, a current greater than the switching critical current ($I_{MTJ}>I_{cr\_sw}$) will be used to perform the write operation, and a current less than switching and oscillation critical currents ($I_{MTJ}<I_{cr\_os}<I_{cr\_sw}$) will be used for the read operation. In communication mode, however, a current $< I_{cr\_sw}$ and $> I_{cr\_os}$ will be applied. As a result, the MTJ starts to oscillate and its magnetic oscillation will be sensed by a CMOS receiver wirelessly. Considering the different frequencies of oscillation in P- and AP-states, CMOS receiver will be able to detect the state of stored data in the MTJ.



(a) (b) (c) (d)

Figure 1: (a) Concept of MTJ for memory and communication logic, (b) schematic of STT-MTJ with switching and oscillating paths, (c) magnetization of free layer of MTJ with different torques, and (d) Set up for sample measurement

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Stable antivortex nucleation and spin-orbit torque driven dynamics

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In ferromagnetic thin-films, stable antivortex micromagnetic structure nucleation is facilitated by shape anisotropy to form a core by forcing the magnetization out of plane at the center. The dynamic and static behavior of antivortex is of great importance for potential applications in spintronic-based nano RF oscillators and new generation data storage devices.

In this study, a special geometry called Asteroid is designed and realized with a subtractive method using electron beam lithography and ion mill etching (see fig 1-a). Two different samples, NiFe(20)/Ti(3) and NiFe(20)/Pt(2)/Ti(1), were fabricated to be used in the static and dynamic investigation of the antivortex. (All thicknesses in nm)

Antivortex nucleation, annihilation, and manipulation with magnetic field in nano-patterned Asteroid geometry have been investigated by magnetic imaging technique (MFM) and compared with micromagnetic simulations. Also, we developed an electrical detection mechanism for the antivortex by measuring the anisotropic magnetoresistance with a dc electrical current (dc-AMR) [1]. In addition, we demonstrate through micromagnetic simulations that oscillations induced by the interaction of antivortex structure with the pure spin current perpendicular to the plane that arises from a heavy metal (Pt) deposited on NiFe, which can be obtained essentially in zero magnetic field, exhibits peaks between 700 MHz and 1.5 GHz (see fig. 1-b).

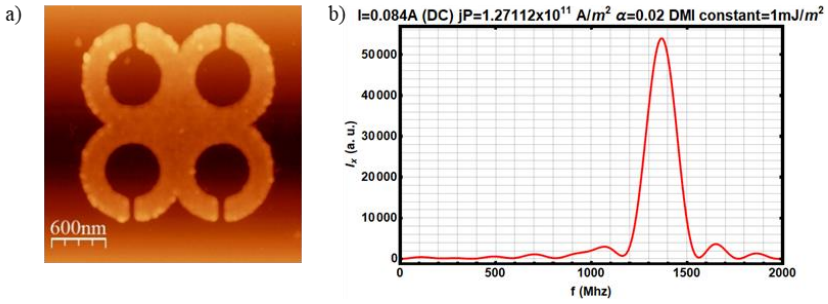

Figure 1: Atomic Force Microscope image of fabricated Asteroid (a) & Frequency Spectrum of Antivortex Magnetization (b).

We will discuss the spin-orbit torque driven excitations of the antivortex dynamic modes as a function of current and external magnetic field for nano-oscillator device applications.

Acknowledgment: This project was supported by TUBITAK and Bogazici University Research Fund with the project codes 113F378 and 16B03P5.

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Evidence of magnetism-induced topological protection in the antiferromagnetic topological insulator $EuSn_2P_2$

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The interplay between topology and magnetism in quantum materials has been receiving a great deal of attention, as it is predicted to give rise to the recently proposed axion insulator phase: an exotic case where the paradigm of "particles" and interactions applies in solid state physics, something up until now restricted to high-energy physics. The engineering of new quantum magnetic materials, initially relying on the exploitation of proximity effects and magnetic doping, has been progressing to the point of designing stoichiometric compounds exhibiting 3D A-type antiferromagnetism, suitable for hosting the axion insulator phase [1].

Here we shed light on magnetic and topological properties in a candidate axion insulator, the antiferromagnetic topological insulator $EuSn_2P_2$. We used X-ray magnetic circular dichroism and spin- and angle-resolved photoemission spectroscopy (spin-ARPES) to probe Eu local magnetic moments and surface states spin texture. By means of layer-dependent calculations corroborating experimental results, we specifically found that:

I. Topology and magnetism coexist in a layer-dependent fashion in the material;
II. Spin-momentum locking in P-derived topological surface states is found both below and above $T_{Néel}$ (Figure 1);
III. In-plane long-range magnetic order, coupled with layered antiferromagnetic coupling, are prerequisites for extra protection of topological states.

Our work reveals a rich and complex physics behind the axion insulator character of $EuSn_2P_2$, and establishes this material as a prime candidate for next-generation electronic devices [2].

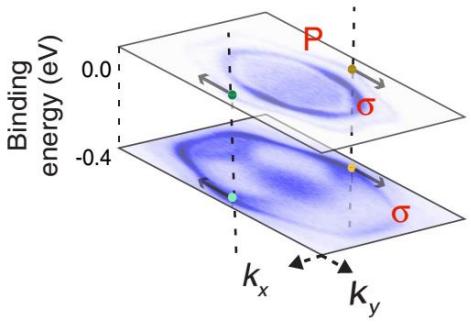

Figure 1: Isonergenetic ARPES maps showing experimental geometry of the spin-resolved measurement and the identification of the surface states (P and σ). The spin polarization of those surface states, measured with spin-ARPES below $T_{Néel}$ in the two opposite momentum points, is illustrated by dashed lines (indicating the acquired EDCs) and solid arrows (indicating the spin direction).

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Topological hybrids of magnons and magnon bound pairs

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In quantum condensed matter systems without particle-number conservation, states belonging to different particle-number sectors can hybridize. Typically, if single-particle states enter the continua of many-particle scattering states, the resulting hybridization leads to quasiparticle decay (spectral lifetime broadening) that is detrimental to single-particle topology [1]. If they do not, an effective quasiparticle interaction may arise perturbatively via the continua, which can establish topological band gaps in the single-particle spectrum [2].

Herein [3], we develop a theory of *coherent* coupling between single-particle states and two-particle states and reveal that it causes topological anticrossings in the spectrum. The resulting spectral gaps support chiral edge excitations whose wavefunction is a superposition of states in the two hybridized sectors.

The above outlined situation is realized in fully saturated spin-anisotropic quantum magnets without spin conservation, for example, in chiral spin-1/2 magnets with the Dzyaloshinskii-Moriya interaction (see Figure 1). Single magnons hybridize with magnon bound pairs, i.e., two-magnon bound states. The resulting chiral edge excitations, shown in Figure 1 (e,f), are exotic composites that behave simultaneously as a single particle and a particle pair. As such, they carry mixed spin-multipolar character, inheriting spin-dipolar and spin-quadrupolar character from their single-particleness and two-particleness, respectively.

In contrast to established topological magnons, the topological effects discussed here are of genuine quantum mechanical origin and vanish in the classical limit. We discuss implications for both intrinsic anomalous Hall-type transport and topological spintronics computation paradigms.

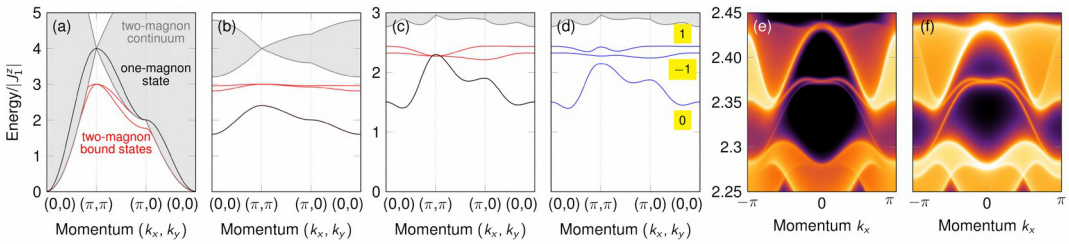

Figure 1: One and two-magnon spectrum of a chiral spin-1/2 ferromagnet on the square lattice. (a) Isotropic nearest-neighbor coupling. (b) Anisotropic nearest-neighbor coupling. (c) Anisotropic nearest- and third-nearest neighbor coupling. (d) Same as (c) but with Dzyaloshinskii-Moriya interaction. (e,f) Spectral functions for open boundary conditions, revealing chiral edge states.

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Topological Hall effect in ferromagnetic and antiferromagnetic chiral spin textures

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The topological Hall effect (THE) is known as a transport phenomenon in various magnetic systems due to the exchange interaction of free carriers with chiral magnetization textures such as magnetic skyrmions. Like the anomalous Hall effect, THE is observed in structures with broken symmetry with respect to time reversal and is considered as a promising tool for studying topologically nontrivial spin structures, as well as for applications, in particular, for racetrack memory devices.

THE is usually spin-dependent, i.e. it is a spin Hall effect leading to separation of incident electrons with different spin projections. This is realized in most common adiabatic regime described by geometrical Berry phase theory. In this case the topological Hall resistance appears to be proportional to the topological charge of a chiral spin texture [1]. We present analytical and numerical calculations of THE in topologically charged and topologically trivial textures visualizing electron trajectories and discussing the Hall response features in these cases.

We also discuss the case of antiferromagnetic skyrmions being of particular interest. The theory of THE in such systems is mainly represented by first-principles numerical calculations. Using the theoretical model proposed in [2] we analyse the magnitude of the THE response for skyrmions on a square antiferromagnetic crystal lattice. It is shown that, in contrast to the ferromagnetic case, the Hall response for an antiferromagnetic skyrmion in the adiabatic regime can be a non-integer value in units of the topological charge.

As the skyrmion size decreases deviations from the adiabatic theory are expected. In the non-adiabatic regime THE becomes spin-independent, i.e. for both spin-up and spin-down electrons scattering asymmetry is the same leading directly to the charge Hall effect rather than to the spin Hall effect. At the same time the role of the topological charge as an integral characteristic of a chiral spin texture becomes unimportant so that any chiral spin texture can produce Hall response. A manifestation of additional non-skyrmion contribution to the THE THE has been observed experimentally [3].

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Insight into chemical and magnetotransport properties of epitaxial α-Fe_2O_3/Pt bilayers

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Spintronic devices based on antiferromagnets (AFMs) offer a wide range of unique properties, such as robustness against perturbations of magnetic field, fast spin dynamics and lack of stray fields. [1] However, the absence of the net magnetic moment in the AFM materials is a challenge for electrical reading of their magnetic state, particularly when the AFM layer is insulating. Recently the spin Hall magnetoresistance (SMR) was presented for Pt/α-Fe_2O_3(hematite) bilayers, for which the presence of small net magnetization in α-Fe_2O_3 layers enables to reveal magnetotransport properties of α-Fe_2O_3 in a relatively small magnetic field. [2], [3]

In our studies we investigated chemical and magnetotransport properties in epitaxial α-Fe_2O_3/Pt structures, where hematite α-Fe_2O_3(0001) thin films with a thicknesses of 6 nm and 15 nm were grown on a 7-nm thick epitaxial Pt(111) layer on MgO(111). Mössbauer spectroscopy measurements showed that the bulk-like hematite phase contributed to 96% and 66% of the total spectral intensity for the thicker and thinner oxide layer, respectively. SMR study revealed that chemical structure determines magnetotransport properties of the α-Fe_2O_3/Pt bilayer. We noted a sign change of SMR from positive to negative when the thickness of oxide was increased (Fig. 1), which was discussed in terms of residual ferrimagnetic phase present in the thinner layer. Finally, for α-Fe_2O_3(15nm)/Pt we demonstrated electrical switching. For the as-grown sample we registered steplike, nondecaying switching between three states of the antiferromagnetic order, which evidences stability of the interface in our samples (Fig. 2).

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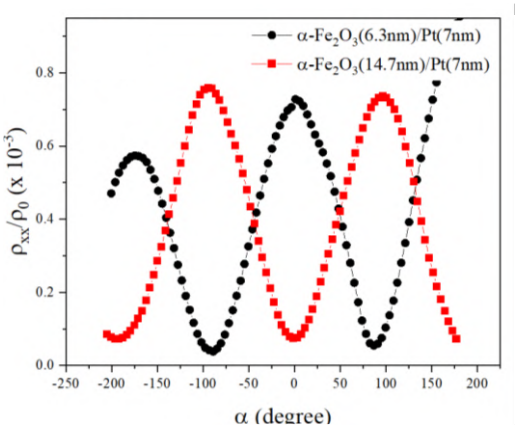

Figure 1 Longitudinal SMR for the α-Fe_2O_3(6nm)/Pt(7nm) (black circles) and α-Fe_2O_3(15nm)/Pt(7nm) (red squares) bilayers.

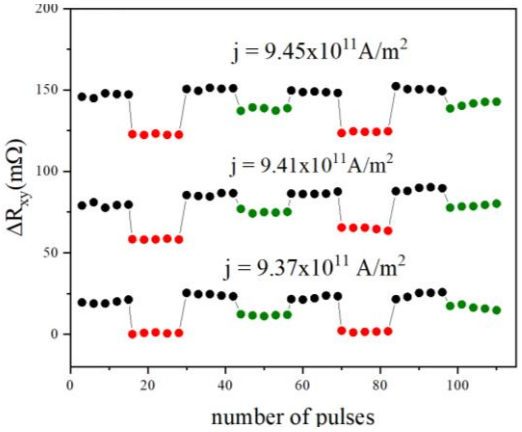

Figure 2 Change of a Hall resistance as a function of current pulses applied along the three easy axis of hematite in α-Fe_2O_3 (15nm)/Pt(7nm).

Surface magnetization and antiferromagnetic domain walls in Cr_2O_3

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Magneto-electric antiferromagnets hold promise for future spintronic devices, as they offer magnetic field hardness, high switching speeds and both electric and magnetic control of their order parameters, owing to the magneto-electric coupling [1]. As information and functionality is encoded in the antiferromagnetic order parameter, its manipulation, read-out and nanoscale textures are paramount for device operation, as well as interesting from a fundamental point of view. For applications the surface plays a key-role as the interface often dictates the read/write functionalities and gains importance as thin film devices are targeted.

Using scanning nitrogen vacancy magnetometry [2] we study a 'textbook', single crystal magneto-electric antiferromagnet Cr_2O_3 and perform nanoscale imaging of its surface magnetization, which is directly linked to its magnetic order parameter. We first confirm magneto-electric poling [3] of a homogeneous antiferromagnetic order and then utilize local electrodes to nucleate single domain walls. Manipulation of the domain wall path is demonstrated both by local laser heating, as well as the creation of an energy landscape for the domain wall position via topographic structuring [2]. A Snell like refraction of the domain wall path is found, that can be approximated as a 'refractive index' for a given island dimension and switching the domain wall between different stable positions via laser manipulation is shown.

Moreover, we study the stray field polarity at the surface depending on the field configuration used for the magneto-electric poling. Our results for the (0001)-surface indicate the existence of a magnetically disordered surface layer. Such a disordered layer has been theoretically predicted [4] and is consistent with our experimentally detected stray field polarities, when considering the bulk magneto-electric response and calculated energetically favourable non-polar atomic configuration on the surface. Based on DFT calculations this magnetic disorder may be attributed to the reduced exchange interactions at the surface layer and it can be expected to be important for devices that rely on spin-scattering properties or magnetic noise on the Cr_2O_3 interfaces.

Finally, we present preliminary results on our studies of other surface orientations, with oblique angles to the uniaxial anisotropy axis. For this, we probe the stray fields of various differently oriented topographic islands on the surface of an oblique crystal cut. These stray fields contain information on both the magnetization of the top surface plane as well as on the islands' sidewall planes. A comparison of our stray field data with magnetization models gives first indications on these surface magnetizations. Understanding the various properties and stability of the magnetic order at the direct surfaces may aid in exploring their suitability as interfaces in spintronic devices and its relation to the intrinsic bulk magnetic order and interactions.

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Preparation of Cr_2O_3 nanostructures for the application in organic antiferromagnetic spintronics

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Oxide nanostructures interfaced with metallic substrates are thoroughly investigated systems in modern nanoscience, featuring several intriguing electronic, magnetic and chemical properties [1,2]. Interfaces play a prominent role in spintronics, typically involving the coupling of ferromagnets (FM) with different type of materials, ranging from non-magnetic substances to antiferromagnets (AF), of which several are oxides. In this respect, a deep knowledge of the interface physical/chemical properties is needed in order to understand the magnetic phenomena and, eventually, succeed in tailoring them.

A fine control of an oxide/metal interface can be obtained by exploiting an appropriate buffer layer, which is expected to both protect the substrate's surface and to act as a template for a good quality epitaxial growth. We have been able to show that graphene (Gr) can act as an ideal buffer layer for the growth of Cr_2O_3 ultrathin films on a Ni(111) surface, resulting in a very high-quality two-dimensional oxide layer, avoiding oxidation/reduction reactions at the interface, despite the high compressive strain (~15 %) experienced by the ultrathin oxide on Gr [3]. Similarly, FeO was grown on Gr/Ni(111), resulting in this case in the development of three-dimensional nanostructures [4]. In view of the exploitation of AF oxides in the rapidly developing field of Antiferromagnetic Spintronics and supported by a recently granted EU project that aims to develop applications based on interfaces between molecular layers and AF materials [5], we have been extending our investigations to Cr_2O_3 on Gr/Pt(111) and on different Cu substrates (thus non-magnetic ones), of which successful preliminary results are available (Fig. 1).

Magnetic measurements and theoretical calculations on the different Cr_2O_3 nanostructures are currently ongoing. Concerning the molecular overlayer, we have been focusing on the effect that the adsorption of the molecules has on the magnetic properties of the AF oxide surface and on the effective role played by the interface states for the filtering of spins, which can be potentially exploited in organic spintronics applications. We will present, in particular, promising results concerning the magnetic ordering of Iron phthalocyanine (FePc) as self-assembled monolayers on Cr_2O_3.

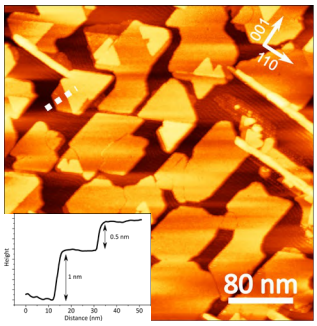

Figure 1: STM image of 0.5 nm Cr_2O_3 on Cu(110). Inset: line profile along the dashed line.

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THz-field-induced transient magnetization and ferroelectric polarization in quantum paraelectric $KTaO_3$

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[c]Stockholm University, Sweeden
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Recently, Juraschek *et al.*[1,2] theoretically predicted that circularly polarized phonons should carry orbital magnetic moment even in diamagnetic or paramagnetic materials. The macroscopic orbital magnetic moment should be induced by the excitation of two perpendicularly polarized degenerate polar phonons using circularly polarized THz radiation. Unfortunately, experimental evidence of this phenomenon has been lacking.

We decided to pump the ferroelectric soft mode in quantum paraelectric $KTaO_3$ single crystal using extremely intense pulses with frequency 0.7 THz. The pulses with a duration of about 10 ps were generated by the free-electron laser at the TELBE beamline in the Helmholz Zentrum in Rossendorf. The transient magnetic moment on the picosecond time scale was measured via the transient birefringence at a probe wavelength of 800 nm, expected to induce the Faraday effect. A possible breaking of inversion symmetry was sensed by measuring the second harmonic generation at 400 nm. The experiments were performed between 10 and 300 K.

At low temperatures, the THz pump frequency was close to the soft-mode frequency, and a fairly strong transient birefringence was observed. However, THz pump-induced transient birefringence was detected not only using a circularly polarized THz beam, but also upon pumping with a linearly polarized beam. We explain this by the THz-field-induced Kerr effect which was recently observed also in the quantum paraelectric $SrTiO_3$.[3] In $KTaO_3$, a transient polarization and the related broken inversion symmetry were proved also by measuring the transient second harmonic generation.

The excited phonons were polarized in the sample plane, so the induced magnetization should be perpendicularly to the sample plane. In this case, theoretically, the magnitude of the Faraday signal should be the same after pumping using clockwise and anticlockwise circularly polarized THz radiation. Surprisingly, we detected a marked difference. We explain our observations by a combination of Faraday and Kerr effects, combined with the directional dichroism which is allowed in non-centrosymmetric diamagnetic systems in the presence of magnetic field.[4] In our case, the magnetic field was induced by the circularly polarized phonons.

In summary, we demonstrated that a transient polarization and magnetization can be induced simultaneously, by a strong excitation of polar phonons in a diamagnetic and quantum paraelectric crystal.

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Spin Hall magnetoresistance in 3D antiferromagnet insulator, $Ho_{0.5}Dy_{0.5}FeO_3$|Pt heterostructure

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Rare-earth orthoferrites (*RE*FeO_3), are 3D antiferromagnets (AFM) that exhibit a weak ferromagnetism originating from slight canting of the spin moments and display a variety of spin reorientation transitions in the magnetic field (*H*)-temperature *(T*) parameter space. We have studied spin Hall magnetoresistance (SMR) on a *b*-plate of single crystal $Ho_{0.5}Dy_{0.5}FeO_3$|Pt hybrid, carried out by rotating *H* in the ac-plane (*α*-scan) at various *T* down to 11 K. In $\Gamma_4(G_x, A_y, F_z)$ phase, application of *H* above a critical value (H_c) causes switching between the two degenerate domains; $\Gamma_4(\pm G_x, \pm F_z)$. At 300 K ($H \geq H_c$) in $\Gamma_4(G_x, A_y, F_z)$ phase, SMR vs. *α* yielded a highly skewed curve with a sharp change, accompanied by a rotational hysteresis around a-axis. Notably, α-scans ($H < H_c$) on the single domain ($\Gamma_4(\pm G_x, \pm F_z)$ domain) exhibited an anomalous sinusoidal signal of periodicity 360 deg. Low-*T* SMR ($H \approx 2.4$ kOe) resulted in a weakening of the anisotropy possibly due to the *T*-evolution of Fe-*RE* exchange coupling. Besides, below 25 K the SMR modulation showed an abrupt change around *c*-axis, marking the transition to $\Gamma_2(F_x, C_y, G_z)$ phase. A simple Hamiltonian was employed to compute SMR and to examine the observed SMR-modulations. Our SMR studies not only serve as an effective probe for magnetic anisotropy and spin reorientation but also, highlight the potential of $Ho_{0.5}Dy_{0.5}FeO_3$ for future AFM spintronic devices.

Characterization of Finite-Size Effects in Antiferromagnetic Films Using Spin Pumping Effect

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Recently, there has been an increasing need to come up with alternative methods for the magnetic characterization of antiferromagnets after the realization that antiferromagnetic materials can have spintronic device applications such as magnetic data storage as well as THz signal generation. The biggest challange in the characterization of an antiferromagnetic order is the absence of magnetic stray fields and the weak response to externally applied magnetic fields. However, there have been important recent discoveries that lead to having these materials play an active role in device applications. Also, it becomes extremely important to determine the thermal stabilities of antiferromagnetic materials at reduced dimensions and thickensses for the possible applications of spin-orbit torque oscillators and data storage units.

The temperature at which the AFM ordering begins to degrade is called Neel temperature. Neel temperature is unique to Antiferromagnetic materials and Neel temperature can be interpreted incorrectly in such a way that it can be confused with blocking temperature. The Blocking temperature is defined as the temperature at which the amount of shift in the hysteresis loop due to exchange anisotropy is zero and it can be easily measured [1]. In contrast, Neel temperature of a single antiferromagnetic thin film is extremely difficult to measure. Conventional techniques yield results only with sufficiently thick thin films or multilayer structures. Therefore, a more effective and alternative characterization method should be considered for materials of finite size, where conventional methods fail. Spin pumping method, which was discovered during the previous years, is one of the most effective alternative techniques.

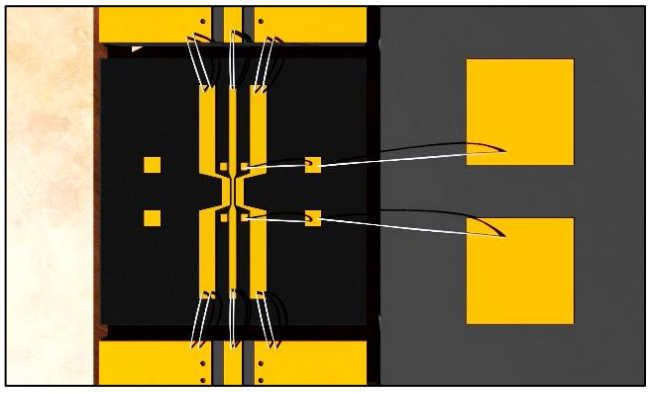

Figure 1: *Schematic of Spin Pumping Device*

Three-layer AFM/Cu/FM structures containing heavy metal components such as IrMn are used in the spin pumping method. By using a microwave source, the dynamic pattern of magnetization can be stimulated in a ferromagnetic layer sputtured on an AFM layer. It has been observed that the pure spin current pumped into the AFM layer during a magnetization dynamic evolving around a resonance frequency can be also measured as charge current which is called the Inverse Spin Hall Effect. [2] In addition, it is possible to observe the changes in the characteristic damping parameter of the dynamic motion at temperatures near phase change temperature of AFM layer. Thus, characteristics of AFM materials can be determined by observing changes in certain parameters. In this study, the finite size effects of heavy metal-containing antiferromagnetic IrMn, PdMn, PtMn and soft metal containing FeMn,NiMn will be investigated. Also, the blocking temperatures of continous film bilayer AFM(t:1.25nm)/NiFe(t:5nm) structures were investigated. Next, the pumping devices (see Figure 1) will be produced and Neel temperature experiments will be carried out. The obtained Neel temperatures will be compared with the blocking temperatures.

Acknowledgments:
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Antiferromagnetic-like optical transition in thin YIG films as seen by quadratic magneto-optics

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Yttrium Iron Garnet (YIG) is a widely used magnetic insulator owing to its macroscopic magnetization at room temperature, the lowest known Gilbert damping or high spin pumping efficiency [1]. From the microscopic point of view, it represents a model system of the transition between ferromagnetic and anti-ferromagnetic (AFM) spin ordering due to the presence of two anti-ferromagnetically coupled spin sublattices [2]. The magnetizations of the two sublattices are not fully compensated, thus YIG is a ferrimagnet. Magneto-optical (MO) response in general reflects the internal symmetry of the magnetic material: AFM ordering reveals as an increased ratio between the quadratic and the linear MO response. The linear part eventually diminishes, as demonstrated in collinear AFM materials [3]. In this work we show the presence of a giant quadratic MO response in 50-nm thin YIG film [4]. We detected MO hysteresis loops containing contributions both of the quadratic MO effect ("Cotton-Mouton effect, CME) and the linear MO effect in transmission geometry (LMET), as shown in Fig. 1(a). Clearly, the amplitude of CME can exceed that of LMET. Such situation occurs if the wavelength of light is fine-tuned around 405 nm [see Fig 1(b)], which corresponds energetically to the optical transitions between Fe-3d and O-3p states. We interpret the observations in terms of mutual cancelation of the partial LMET signals from the two sublattices of Fe spins. In contrast, partial CME responses add constructively and the effect is amplified, which proves strength of the quadratic MO method for sensitive detection of AFM interactions.

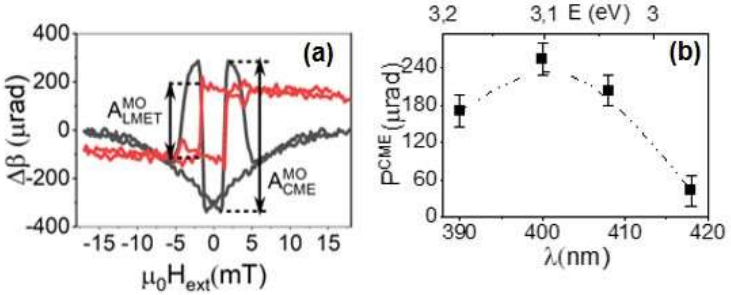

Figure 1: (a) Magneto-optical (MO) hysteresis loops, measured at 50 nm-thick YIG film with wavelength of 405 nm at room temperature. Loops were symmetrized and antisymmetrized, respectively, to separate the quadratic Cotton-Mouton effect (CME) and linear MO effect (LMET). (b) Spectral dependence of the CME coefficient P^{CME}, obtained from the hysteresis loops.

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Antiferromagnetic THz oscillations excited by sub-picosecond structured laser pulses

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Ultrafast laser sources provide unique tools to control the magnetic properties of materials, both spatially and temporally. Since the pioneering work on ultrafast laser induced demagnetization [1], femtosecond (fs) laser pulses have been widely used in theoretical and experimental studies of femtomagnetism. Recent technological advances have made possible to harness the polarization structure of ultrashort laser beams, allowing the generation of radially or azimuthally polarized laser pulses. In particular, it has been recently proposed that Tesla-scale fs magnetic fields (B), isolated from the electric field (E), can be obtained through the use of ultrafast azimuthally polarized laser beams [3]. Such configuration offers a unique opportunity to perform pure magnetic interactions with intense fs B fields.

In this work we numerically analyse the generation of THz oscillations in antiferromagnetic materials induced by isolated magnetic fields, such as those obtained from a structured azimuthally polarized laser beam. Our micromagnetic simulations demonstrate that intense ultrafast magnetic pulses (of few hundreds of Tesla) with central wavelengths of the order of 1μm and temporal durations at the sub-picosecond scale, excite self-oscillations in an antiferromagnetic sample (see Fig. 1 (a) and (b)). Interestingly, the amplitude of the oscillations can be controlled by the laser pulse duration. In addition, we demonstrate that the use of subsequent magnetic pulses allows us to enhance the THz signal (Fig. 1(c)), whose oscillation amplitude can be further controlled through the delay between the magnetic pulses. Our work opens a path to achieve THz oscillators through the use of structured laser beams at the optical – near-infrared frequency range.

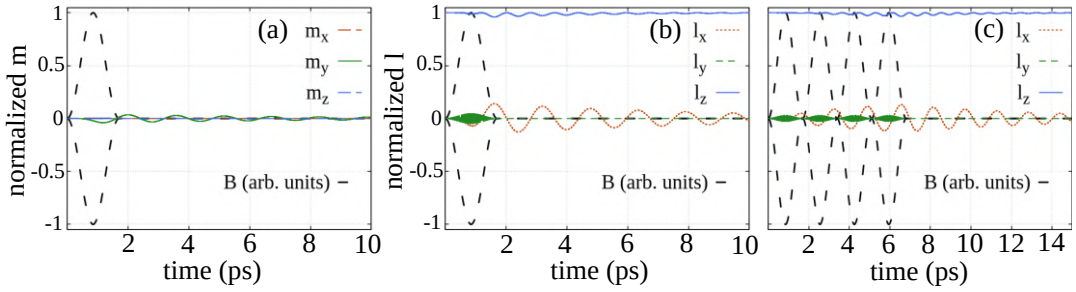

Figure 1: (a) Small magnetization dynamics excited by one laser pulse of $f = 125$ THz and $B = 200$ T (b) Néel vector dynamics excited by one laser pulse of $f = 125$ THz and $B = 200$ T (c) Oscillation amplitude enhancement by the application of various pulses. In this case, the frequency is kept constant but the magnetic field is reduced to B = 120 T, leading to the same oscillation amplitude.

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How THz circularly polarized ligth can be used to determine the mass of vortices in superconductors submitted to a magnetic field

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The determination of the mass of Abrikosov vortices in superconductors is a long standing issue. Whereas the theoretical approximations spand over 8 orders of magnitude, only two experimental evaluations had been previously performed, one using an electro-acoustic method [1], the second one magneto-optical imaging [2]. Here we propose an approach based on far-infrared magnetic circular dichroism [3].

Our method is inspired by the standard determination of cyclotron mass of charge carriers in semiconductors in magnetic field through measuring the cyclotron resonance. In the case of vortices, we probe their interaction with circularly polarized far-infrared light under external magnetic field of up to 11 T. It differs for the clockwise and anti-clockwise polarized light cases, resulting in the so-called circular dichroism, which manifests itself as a difference in the transmittance of the light through the superconducting sample. We propose a model to relate the ratio of transmittances of opposite helicity to the mass of the vortices μ.

We have chosen to concentrate our efforts on YBaCuO, the most common high-temperature superconductor. It has been prepared in the form of a 107 nm-thick film with CuO_2 planes parallel to the surface of a (100) lanthanum aluminate substrate using pulsed laser deposition. The sample parameters have been determined by usual techniques or taken from the literature. Additional film properties in the far-infrared range have been established in a separate experiment using standard time-domain THz spectroscopy. With such inputs, we show that the theory of the vortex mass developed by Kopnin and coworkers [4] matches our experimental data *without any additional fitting parameter*.

At THz frequencies, where the circular dichroism is observed, both diagonal and off-diagonal masses are complex at finite frequencies, which reflects a delay between a change of the vortex velocity and a change of the total momentum of quasiparticles in its core. Both components become real in the low-frequency limit. The off-diagonal mass describes a property common in anisotropic systems that the velocity of an excitation is not parallel with its momentum.

For YBaCuO at 45 K, in the zero-frequency limit, the diagonal mass of Abrikosov vortices amounts to 2.2 x 10^8 electron masses per centimeter, while the off-diagonal one reaches 4.9 x 10^8 electron masses per centimeter.

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Light and magnetic vortices: the experimental evidence of magnetic helicoidal dichroism

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The use of light beams possessing orbital angular momentum (OAM) is becoming more frequently a tool for manipulating physical systems and probing their properties. The wave-fronts of such beams develop a distinctive corkscrew shape determined by an azimuthal angular dependence of $\exp(i\ell\phi)$ for the electric field phase, which is associated with an OAM of $\ell\hbar$ per photon. In this framework, it has been theoretically predicted that OAM beams should allow for novel kinds of dichroism experiments, paving the way for new spectroscopic tools in the fields of orbital physics and magnetism [1]. In particular, after the scattering of an OAM beam from magnetic structures featuring a non-uniform magnetization, like magnetic vortices, the far field intensity profile will encode the vortex symmetries in a way that depends on the sign and value of ℓ, giving rise to magnetic helicoidal dichroism (MHD) [2].

During the talk, I will show the experimental verification of this effect carried out at the DiProI end-station of the FERMI free-electron laser, using p-polarized 52.8 eV photons (matching the Fe M-edge) and measuring the resonant scattering in reflection geometry. Well-defined OAM values were imposed on the beam by using spiral zone plates, and the sample consisted in a 15 µm wide Fe-Ni disk, whose shape was designed to form a clean remanent magnetic vortex with reconfigurable clockwise (CW) or counter-clockwise (CCW) circulation. The MHD for opposite OAM values ($\ell = \pm 1$ in Fig. 1) was obtained by taking the difference divided by the sum of two scattered intensity images collected for CW and CCW magnetic vortices [3]. The measured patterns well compare with the results of numerical simulations, and the effect has been proven to have the right symmetry for representing a proper MHD signal. Moreover, we also performed preliminary time-resolved measurements, to understand what kind of information can be gathered from MHD when applied to the detection of ultrafast magnetization dynamics, especially for non-uniform complex spin textures.

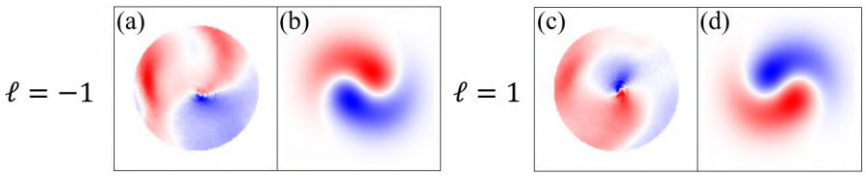

Figure 1: Experimental and simulated MHD signals for (a),(b) $\ell = -1$ and (c),(d) $\ell = 1$.

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Thermoplasmonic nanomagnetic logic gates

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Nanomagnetic logic, in which the outcome of a computation is embedded into the energy hierarchy of magnetostatically coupled nanomagnets, offers an attractive pathway to implement in-memory computation. This computational paradigm avoids energy costs associated with storing the outcome of a computational operation. Thermally-driven nanomagnetic logic gates, which are driven solely by the ambient thermal energy, hold great promise for energy-efficient operation, but have the disadvantage of slow operating speeds due to the lack of spatial selectivity of currently-employed global heating methods. As has been shown recently, this disadvantage can be removed by employing plasmon-assisted photo-heating, where selective local heating is achieved by the polarisation dependence of the optical absorption cross section of the nanomagnet[1]. Here, we show by means of micromagnetic and finite-elements simulations how such local heating can be exploited to design reconfigurable nanomagnetic Boolean logic gates[2]. The reconfigurability of operation is achieved either by modifying the initialising field protocol or optically, by changing the order in which two orthogonally polarised laser pulses are applied. Our results thus demonstrate that nanomagnetic logic offers itself as a fast (up to GHz), energy-efficient and reconfigurable platform for in-memory computation that can be controlled via optical means.

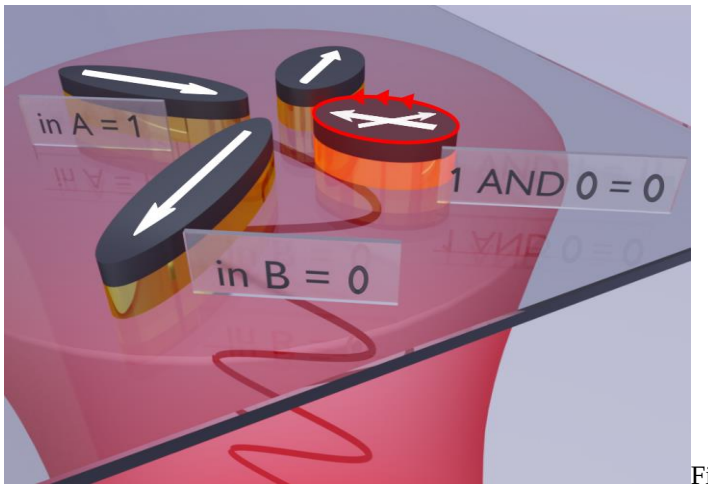

Figure 1: Reconfigurable thermoplasmonic nanomagnetic and-or gate, showing the operational principle of the and gate. The gate consists of four hybrid nano-islands combining magnetic (gray) and thermoplasmonic (yellow) properties. The linearly-polarised laser-beam (red, coming from below) only heats the output island (on the right) close to the magnetic Curie temperature via the shape- and polarisation-dependent absorption cross section of the plasmonic elements. This selective heating allows for thermally-assisted magnetic switching of the output moment towards the logically correct state, as determined by the magnetic configuration of the input moments (A and B).

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Mag2exp: simulating experimental techniques from micromagnetic simulations

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The number of experimental techniques and their capability to measure and image magnetic behaviour is constantly increasing, along with the ability to computationally study magnetic structures using micromagnetic simulations. These micromagnetic simulations allow magnetism to be studied on nm to microscopic length scales with material dependent parameters producing tailored magnetic systems [1]. However, given a magnetic structure, it is often not trivial to predict the results of experimental techniques directly from magnetisation structures.

We have produced the python software package *mag2exp* [2], as part of the micromagnetic simulation environment *Ubermag* [2, 3], which enables realistic virtual experiments to be easily and quickly performed on magnetic structures using a range of experimental techniques. These techniques include Lorentz transmission electron microscopy, magnetic force microscopy, x-ray holography, small angle neutron scattering, and torque magnetometry, along with other useful experimental procedures.

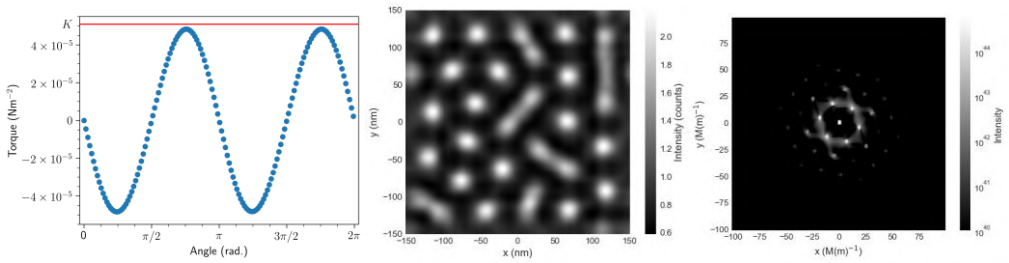

Figure 1: Examples of *mag2exp* results for (left to right): torque magnetometry, Lorentz transmission electron microscopy, and small angle neutron scattering.

This package is open source, allowing anyone to use, view, verify, and add to the code and is continuously evolving with the addition of new techniques. This software aims to help bridge some of the gap between computational micromagnetic simulations and experiments, leading to the potential for simulations to inform real world experiments and vice versa.

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The quantum thermodynamics of exchange stiffness

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The temperature dependence of effective micromagnetic parameters such as anisotropy (K), exchange stiffness (A) and the Dzyaloshinskii–Moriya interaction (DMI) are usually written as a power law of the magnetisation. For anisotropy this is well founded, based on Callen-Callen theory[1]. For exchange stiffness and DMI the power laws are based on classical numerical models, or assumed to be the same as anisotropy. Recently there has been a lot of interest in the temperature dependence of these properties because their value affects spin textures like skyrmions[2].

Inferring the DMI from experimental measurements requires first deducing the exchange stiffness by using *m* scaling laws from classical atomistic models[2]. Classical models cannot reproduce Bloch's $T^{3/2}$ law for ferromagnets or the T^2 dependence of sublattice magnetisation in antiferromagnets[3]. Classical models are a poor approximation for the thermodynamics of exchange in real materials where the quantum distribution of magnons plays a large role.

Here we discuss a quantum implementation of atomistic spin dynamics[3], compare with classical results and present the temperature scaling of the micromagnetic exchange stiffness for both ferromagnets and antiferromagnets calculated from domain wall widths and a new method directly calculating the energy difference between a uniform state and chiral texture. We show the scaling using quantum statistics don't follow the usual power law from classical simulations.

Figure 1a shows the disagreement of classical models and Bloch's law, and the quantitative power of quantum simulations. Figure 1b shows the thermal behaviour of the exchange stiffness and the associated *m* scaling laws. The exchange stiffness is much less sensitive than classical models predict. Preliminary results also indicate that the temperature dependence of bulk DMI is identical to exchange. The temperature dependence of exchange stiffness in the prototypical antiferromagnet NiO [4] will be discussed.

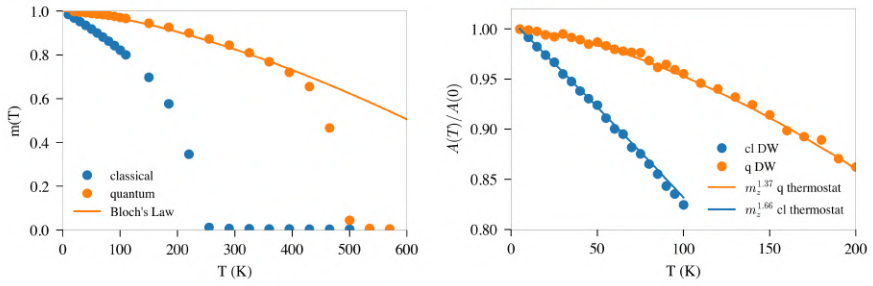

Figure 1: Classical and quantum *m(T)* curves for a ferromagnet. The analytic equation for Bloch's law is shown (no fitting). b) Comparison of classical and quantum calculation of finite temperature exchange stiffness in a simple cubic ferromagnet from domain wall widths - *m* scaling laws use the respective curves from a).

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Mean-field modelling of magnetocaloric effect of antiferromagnetic compounds

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Antiferromagnetic compounds are known in the literature to present the inverse magnetocaloric effect (MCE) [1]. This effect is characterized by the negative adiabatic temperature change, ΔT_S, of an antiferromagnetic material when submitted to an applied magnetic field. In an isothermal process, a positive entropy change, ΔS_T, is also expected. More recently, the anisotropic character of antiferromagnetic compounds, due to spin-flop and spin-flip transitions, has been pointed out highlighting the applicability of the antiferromagnetic compounds in a rotary magnetocaloric device [2].

In this work, we systematically investigate a mean-field model that describes the antiferromagnetic behaviour of materials in a multisublattice approach. Our model includes the intra- and inter-sublattices exchange interaction, the Zeeman effect, and a uniaxial anisotropy energy. We investigated the effect of anisotropy on the spin-flop and spin-flip transitions and on the usual and anisotropic MCE. We were also able to discuss a method to obtain the polycrystalline magnetization of antiferromagnetic compounds [3].

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Modelling design of magnetic nanomaterials for hyperthermia applications

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In the last decade, magnetic nanomaterials like superparamagnetic iron oxide nanoparticles have been intensively studied for potential application in cancer therapies based on hyperthermia [1,2]. Recently, the research attention has been shifted to both single- and multi-domain ferromagnetic nanostructures, because of the improvement of heating efficiency due to large hysteresis losses. Different strategies have been adopted to increase the hysteresis heating contribution, ranging from the use of materials with high saturation magnetization and/or high uniaxial magneto-crystalline anisotropy to the modification of nanostructure geometry. The latter has been explored by investigating nanodisks, nanorings and nanotubes, which lead to large hysteresis losses and to magnetic vortex configuration at remanence, thus reducing agglomeration effects and improving colloidal stability [3].

The present work focuses on magnetic nanodisks and nanorings, analysing the influence on specific heating capabilities and remanent state of material (NiFe, FeO), shape and size. The study, performed via in-house micromagnetic models exploiting GPU computing [4], is conducted on nanomaterials dispersed in liquid, considering effects related to mutual orientation and dipole-dipole magnetostatic interactions. The obtained results demonstrate that the heating efficiency is higher for well-dispersed nanomaterials, while a significant decrease in the heat release is found for dense and compact aggregates, where the remanence state is strongly affected by magnetostatic interactions [5].

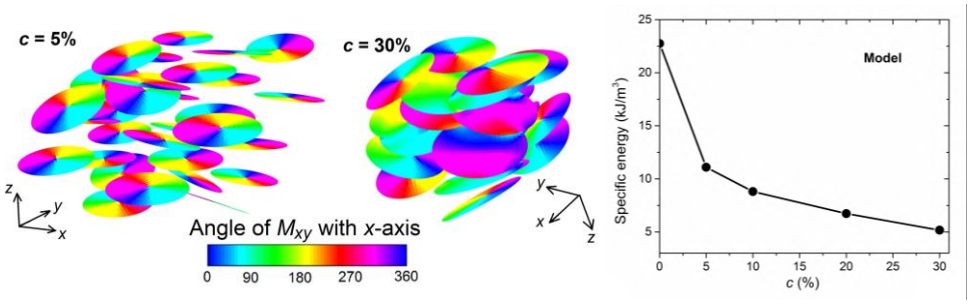

Figure 1: Left: Calculated magnetization configurations at remanence for NiFe nanodisks randomly distributed with different volume concentrations. Right: Specific energy losses calculated as a function of nanodisk volume concentration *c*.

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Highly isolated femtosecond magnetic fields driven by azimuthally polarized laser beams in apertured nanoantennas

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Ultrafast laser sources, in the femtosecond scale, have shown great potential to drive, observe and control ultrafast magnetism since the pioneering work on ultrafast laser-induced demagnetization by Beaurepaire et al. [1]. During the last years, the development of ultrafast structured light beams [2], such as radially or azimuthally polarized vector beams, has opened new perspectives to control laser-matter interactions in novel ways. As an example, it has been recently shown that isolated Tesla-scale femtosecond magnetic fields can be obtained from the interaction between azimuthally polarized beams and gold nanostructures [3]. The generation of magnetic fields isolated from the electric field in a spatial volume offers the possibility to achieve pure magnetic interactions, such as magnetic switching in ferromagnetic materials [4] or oscillations in the Néel vector in antiferromagnetic materials

In this work, we perform Particle-In-Cell simulations [5] to optimize the generation of isolated magnetic fields from gold nanoantennas. Simple antennas, based on a circular aperture (Fig. 1 a), allow the generation of needle-shaped isolated femtosecond magnetic fields. However, the magnetic-to-electric field contrast rapidly decreases at distances of tens of nanometers. Our simulations demonstrate a double apertured gold nanoantenna (Fig. 1 b), can enhance by a factor of three the magnetic-to-electric field contrast. This allows keeping electric fields to low values preventing the sample damage. Further optimization of the antenna geometry could allow achieving even better contrast ratios. Our work paves the route to the use of structured laser beams and antenna designs to allow pure magnetic interactions with matter at femtosecond scales.

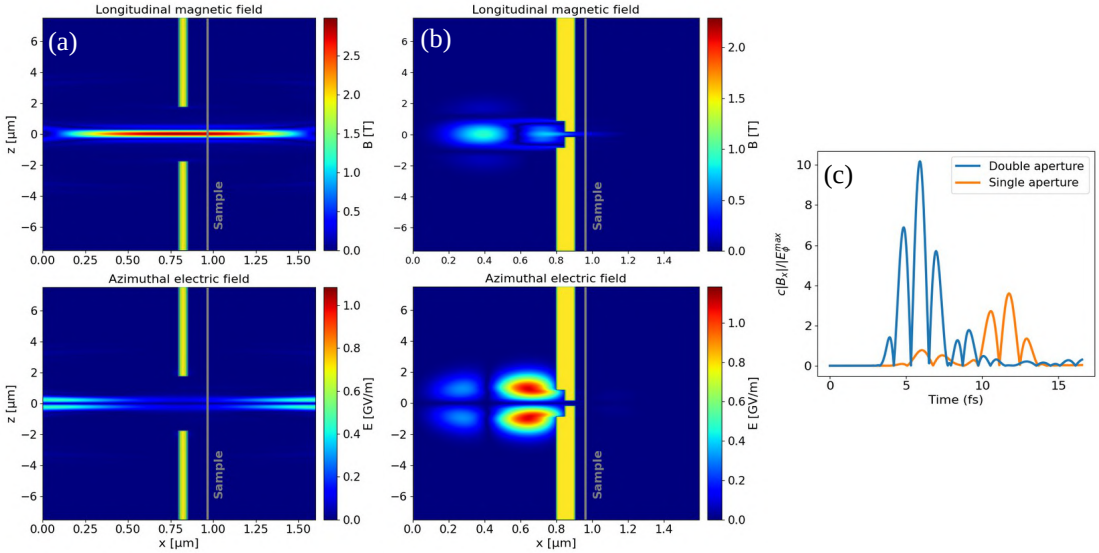

Figure 1: Spatial distribution, at *y=0*, of the longitudinal magnetic and azimuthal electric fields using (a) a single apertured antenna, as proposed in [2], and (b), a double apertured antenna. (c) Temporal evolution of the contrast at the sample for both antennas. The driving laser field is a two-period 800 nm pulse, with a peak amplitude of 0.86 GV/m.

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Robust phase retrieval method for broadband THz reflection spectroscopy

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Terahertz (THz, 10^{12} Hz) is a powerful tool to investigate collective excitations in spintronics, such as spin dynamics [1], spin current [2], spin precession and nutation [3]. Most of THz spectroscopy measurements are performed in transmission geometry, where precise reference measurements are routinely implemented to extract the complex dielectric function. However, many materials of interest are not transparent to THz radiation, in particular in the high THz range, thus restricting the applicability of THz transmission spectroscopy. THz spectroscopy in reflection geometry does not have these intrinsic limitations, but its phase retrieval depends critically on the total length of the optical path. This sets extremely stringent requirements on the experimental alignment, which often leads to an extraction of the dielectric function which heavily relies on sophisticated computations, and which is prone to error or not converging. Here, we have developed a novel and robust phase retrieval method based a non-iterative calculation from a single THz time-domain signal with arbitrary misplacement. The calculation is able to estimate a precise value for the misplacement which can also be used to adjust the setup and repeat the measurement. We simulate a reliable extraction of the complex dielectric function for a set of different materials, incident angles, and THz polarizations. We anticipate that our results will provide a substantial contribution to the fundamental understanding of antiferromagnetic dynamics.

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Terahertz spectroscopy of bulk InSb and $SrTiO_3$ in reflection geometry

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Terahertz time-domain spectroscopy (THz-TDS) is a reliable technique for studying the complex optical properties of materials. Its energy range makes it suitable for detecting low energy collective excitations such as phonons, magnons, and plasmons [1]. The technique for THz-TDS in transmission geometry has gained much attention over the years. However, despite the need for exploring reflective samples, the advancement of THz-TDS in reflection geometry has faced several obstacles, mainly due to its strict requirement for high precision in the placement of the sample and reference [2].

Here we show a technique for measuring samples in reflection geometry using THz-TDS which involves systematically resolving the misplacement issue by first isolating and correcting sources of error in the experimental setup. We then use a novel and robust phase retrieval method to detect and rectify the remaining misplacement with nanometre precision. This provides us with precise values for the phase of the THz pulse which allows us to accurately measure the complex properties of materials. This blend of experimental as well as code-based correction returns highly reliable optical properties of materials.

We use this technique to study non-transparent materials such as InSb and $SrTiO_3$, which were previously found to be challenging due to their strong spectral features and high reflectivity in the THz frequency range. The experimental results of incident angle and polarization dependent measurements are shown along with the retrieved complex refractive index and conductivity of these samples. Our method immensely simplifies the procedure for obtaining optical properties of samples in the THz range, thus allowing for more advances in this field by using strong electric fields, magnetic fields, new materials and more. We anticipate this technique can also contribute substantially to the fundamental understanding of magnetic materials.

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Transport properties in CrI_3-Bi_2Se_3-CrI_3 heterostructures

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When time-reversal-symmetry is broken with applying enough high magnetic fields or introducing exchange fields in 3D topological insulators, quantum Hall effect or quantum anomalous Hall effect emerges and display interesting transport properties for the spintronic applications. In this regard, we have considered a heterostructure consisting of Bi_2Se_3 which is sandwiched between CrI_3 monolayers to study its topological and transport properties. Combining DFT and tight-binding calculations along with non-equilibrium Green's function formalism, we show that a well-defined exchange gap (~3 meV) appears in the band structure in which spin polarised edge states are flowing. We also study the width and finite-size effect on the transmission and topological properties.

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