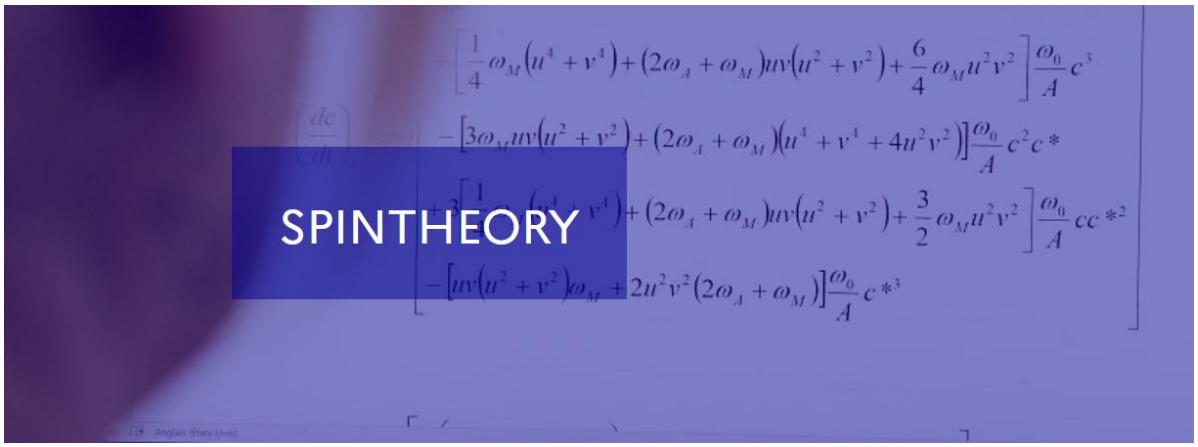


WORKSHOP
SPINTHEORY 2026

02-03 April 2026

Saclay, Orme des Merisiers

PROGRAM

Thursday April 02, 2026

schedule	title	name
09:00-09:20	*SpinSwift: A software for deterministic modelling of thermal effects in spintronics*	Pascal Thibaudeau
09:20-09:40	*Simulating a realistic spintronic Ising machine*	Chloé Chopin
09:40-10:00	*Stability diagram for dual free layers magnetic tunnel junction*	Arthur Courberand
10:00-10:20	*Finite element modelling for spintronics*	Daria Gusakova
10:20-10:50	SPINCHARAC	Stanislas Rohart
10:50-12:00	Café + Poster Session	
12:00-14:00	Lunch Break + Poster	
14:00-14:20	*Ultrafast electron-magnon interactions in ferromagnetic materials*	Benjamin Bakri
14:20-14:40	*Automating the symmetry-adapted discovery of magnetic Multipolar Orders and related response functions*	Maxime Braun
14:40-15:00	*Modelling Spin-Orbitronics Effects at Interfaces and Chiral Molecules*	Poonam Kumari
15:00-15:20	*Local spin magnetization in noncollinear magnets: role of interband spin coherences*	Fréderic Piechon
15:20-15:40	Break	
15:40-16:10	SPINMAT	Pierre Seneor
16:10-16:40	ADAGE	Myriam Pannetier-Lecoeur
16:40:17:10	*Hommage à Daniel Spanjaard*	C. Barreteau

Friday April 03, 2026

schedule	title	name
09:00-09:20	*Injection of Spin-Hall current into a load circuit at zero external magnetic field*	Jean-Eric Wegrowe
09:20-09:40	*LCAOtools: A Python package for computing spin-orbitronics and orbitronics properties*	Dongzhe Li
09:40-10:00	*Orbital dynamics through chiral phonons in low-Z materials*	Armando Pezo
10:00-10:20	*Topological fragility and bilinear magneto-resistance in spin-momentum locked edge states*	Cosimo Gorini
10:20-10:50	*TOAST*	Henri Jaffrès
10:50-12:00	Café + Poster Session	
12:00-14:00	Lunch break+Poster	
14:30-14:20	*Rotating Spin-Wave Modes in Nanoscale Mobius Strips*	Riccardo Hertel
14:20-14:40	*Atomistic spin dynamics modelling of antiferromagnetic skyrmions and bimerons in spintronic devices*	Coline Thevenard
14:40-15:00	*Current-Induced Nucleation and Transport of Magnetic Hopfions in Chiral Nanotubes*	Louis Gallard
15:00-15:20	*Optimaly stable room temperature sub-10 nm Neel skyrmion at zero applied magnetic field in an antisymmetric bilayer*	Anne Bernand-Mantel
15:20	Closing	

ABSTRACTS

ORALS

SpinSwift: A software for deterministic modeling of thermal effects in spintronics

Pascal Thibaudeau*†[1], Mouad Fattouhi[2], and L. D. Buda-Prejbeanu[2]

[1]CEA, DAM, Le Ripault (CEA Le Ripault) – CEA DAM Le Ripault – BP 16 37260 Monts, France
[2]SPINtronique et TEchnologie des Composants (SPINTEC) – Centre National de la Recherche Scientifique, Institut de Recherche Interdisciplinaire de Grenoble, Université Grenoble Alpes – Institut de Recherche Interdisciplinaire de GrenobleCEA-Grenoble17, avenue des Martyrs 38054 GRENOBLE CEDEX 9, France

Résumé

Controlling magnetization dynamics through thermal stimuli has emerged as a central theme in modern spintronics, driven by the quest for fast, energy-efficient, and scalable mechanisms for magnetic switching and manipulation. Temperature gradients and ultrafast heating; whether induced by electrical currents, phonon transport, or optical excitation; can strongly modify spin transport, magnetic damping, and effective torques, giving rise to phenomena such as thermally assisted switching, spin Seebeck effects, and heat-driven spin currents. From a theoretical standpoint, thermal–magnetic coupling is most commonly described using the stochastic Landau–Lifshitz–Gilbert (sLLG) equation in conjunction with multi-temperature frameworks, such as the two- and three-temperature models (2TM/3TM) (1). These approaches capture energy exchange between electrons, phonons, and spins by solving coupled stochastic and thermal evolution equations over many realizations and performing ensemble averaging. Although physically accurate, this methodology is computationally demanding, limiting its efficiency for large-scale or three-dimensional micromagnetic simulations.

Here, a fully deterministic framework is adopted to investigate thermally driven magnetic phenomena, including ultrafast demagnetization and spin-transfer-torque–induced magnetization switching. This approach is based on solving the dynamical Landau–Lifshitz–Bloch (dLLB) equation for each spin within a multi-spin system (2,3), enabling a direct description of longitudinal relaxation and temperature-dependent magnetization dynamics beyond the validity of the conventional LLG formalism. This solver is implemented in the in-house code SpinSwift, which incorporates deterministic spin-transfer torque formulations together with coupled two- and three-temperature models, allowing for a self-consistent treatment of heat flow and spin dynamics across multiple timescales. Initially, the Curie temperature Tc of these ferromagnets is determined using dLLB equation with a classical fluctuation dissipation relation (CFDR) (1), which overestimates Tc due to the mean-field approximation (MFA) of the exchange interaction. To correct this, a linear adjustment to the MFA exchange constant is applied, mimicking second-order fluctuations. It is found that dLLB with CFDR does not accurately capture the magnetization behavior at lower temperatures (4,5). This issue was addressed by using information from the magnon band structure, which can be

*Intervenant
†Auteur correspondant: pascal.thibaudeau@cea.fr

measured experimentally or computed, to better model energy transfers (6). This approach employs a quantum fluctuation dissipation relation (QFDR) based on Bose-Einstein statistics instead of the Maxwell-Boltzmann statistics used in CFDR. By simulating the ultrafast demagnetization of Ni, Fe, and Co with femtosecond laser heating using dLLB and QFDR, the energy exchange between different reservoirs is accurately modeled, and we find that the results match the experimental data (7). This demonstrates that dLLB equation can efficiently model all-optical switching mechanisms, avoiding the need for multiple statistical realizations required in methods based on the stochastic Landau-Lifshitz-Gilbert equation (5).
The Landau-Lifshitz-Bloch-Slonczewski equations are used to model switching of a free magnetic layer with and without magneto-crystalline anisotropy under high-current spin-transfer-torque operation. These dynamic equations are compared to their stochastic equivalents, showing similar modifications to the energy landscape and switching dynamics in high-anisotropy systems, yielding accurate and accelerated predictions of critical currents and switching times (8).

In conclusion, deterministic atomistic spin simulations based on the dynamic Landau-Lifshitz-Bloch equation have proven to be highly efficient tools for modeling thermal effects in spintronics.

Acknowledgements: This work is supported partly by France 2030 government investment plan managed by the French National Research Agency under grant reference PEPR SPIN – (SPINTHEORY) ANR- 22-EXSP-0009, and CEA Exploratory Program, Bottom-Up 2023 ref.59 (THERMOSPIN).

References:

(1) Atxitia and O. Chubykalo-Fesenko, Phys. Rev. B 84 (2011)
(2) P. Thibaudeau, J. Tranchida, and S. Nicolis, IEEE Trans. Magn. 52, 1300404 (2016)
(3) J. Tranchida, P. Thibaudeau, and S. Nicolis, Phys. Rev. E 98, 042101 (2018).
(4) M. D. Kuz'min, Phys. Rev. Lett. 94, 107204 (2005).
(5) O. Eriksson, A. Bergman, L. Bergqvist, and J. Hellsvik, Atomistic Spin Dynamics: Foundations and Applications (Oxford university press, Oxford, 2017).
(6) E. D. Thompson and J. J. Myers, Phys. Rev. 153, 574 (1967)
(7) M. Fattouhi, P. Thibaudeau, and L. D. Buda-Prejbeanu, Phys. Rev. B 112, 014435 (2025)
(8) P. Thibaudeau, M. Fattouhi, and L. D. Buda-Prejbeanu, "Dynamic Landau-Lifshitz-Bloch-Slonczewski equations for spintronics," (2025), arXiv:2510.04562.

Mots-Clés: spintronics, atomistic modelling

Simulating a realistic spintronic Ising machine

Chloé Chopin[1*], Hakam Abderrazak[1], Mateo Ibarra Gomez[1], Erwan Aubouin[1], Leandro Martins[1], Simon de Wergifosse[2], Franck Badets[3], Louis Hutin[3], Luana Benetti[4], Alex Jenkins[4], Ricardo Ferreira[4], Flavio Abreu Araujo[2], Liliana Buda-Prejbeanu[1], Philippe Talatchian[1], Ursula Ebels[1]

[1]Univ. Grenoble Alpes, CEA, CNRS, Grenoble-INP, SPINTEC, 38000 Grenoble, France
[2]Institute of Condensed Matter and Nanosciences, Université catholique de Louvain, Place Croix du Sud 1, 1348 Louvain-la-Neuve, Belgium
[3]Univ. Grenoble Alpes, CEA, LETI, 38000 Grenoble, France.
*chloe.chopin@cea.fr

Abstract:

Ising machines (IMs) are gaining interest as specialized systems designed to efficiently solve widespread combinatorial optimization problems (COPs) like the travelling salesman problem or graph coloring. Indeed, when using conventional computer architecture to solve COP, the time needed to solve them can scale exponentially with the size of the problem. IMs leveraging the Ising model (see Fig. a) are a promising hardware implementation to solve COP efficiently. They are a network of binary-valued spins with specific spin coupling interactions. The configuration of collective spin states seeks its lowest energy state or ground state, representing the COP solution. While several hardware implementations [1] are under study, our proposal takes advantage of the stochastic IM's cost-free thermal noise, exploring the complex energy landscape while escaping local minima.

Spin-torque nano-oscillators (STNOs) are good candidates for such stochastic IMs [2, 3]: (i) when injection-locked to a microwave signal at twice its frequency, the difference between the STNO phase Φosc and source phase becomes binarized (see Fig. b) ; (ii) thermal noise stochastically triggers transitions between those two phase states; (iii) several controllable coupling mechanisms exist to control Ising spin interactions.

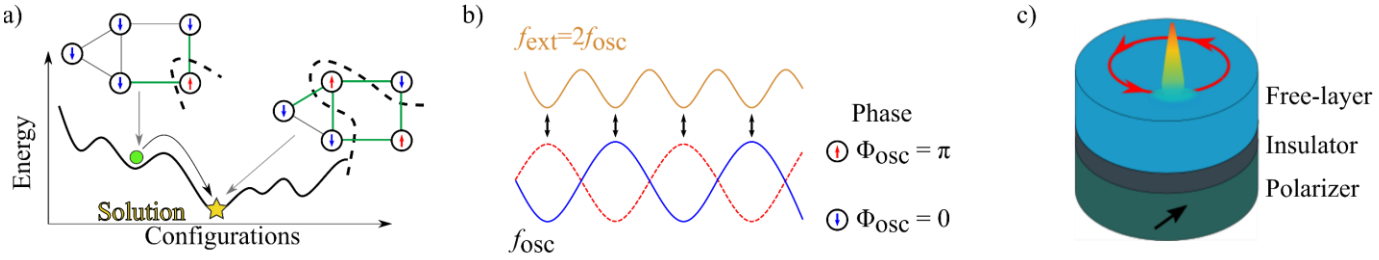


Figure: a) Illustration of the Ising machine based on the Ising Hamiltonian $\mathcal{H} = \sum_{i<j} J_{ij}\sigma_i\sigma_j - \sum_j h_j\sigma_j$ and the corresponding energy landscape. Here σ_i, σ_j are binarized spins of values ± 1, J_{ij} are the coupling constants and h_j is a bias. Relaxation towards the global energy minimum corresponds to the COP solution. b) Illustration of the phase binarization of an oscillator due to second harmonic injection locking. c) Illustration of a vortex-based STNO composed of a polarizer, an insulating non-magnetic spacer layer, and a free layer that has a magnetic vortex as ground state.

While the first two requirements have been verified experimentally [2], setting coupling weights that encode a COP in IMs remains challenging. Ongoing experiments make use of vortex-based STNOs (see Fig. c), which can be well modeled using the stochastic Thiele equation approach [4, 5]. Simulation is a precious tool to understand how the couplings will effectively impact the IMs dynamics. We first successfully reproduced experimental results where the phase α of an additional RF magnetic field emulating an STNO array controls the probability of being preferentially in one of the two phase states. Thus we can use our binarized STNO as a probabilistic bit. Then, we implemented the couplings between STNOs similarly to the experiments. We first demonstrate that the IMs implementation is successful

in solving a combinatorial optimization problem. Then, we show that we have several ways to control the effective temperature of our system, which impacts the output of our IMs and thus the interpretation of the solution of the encoded COP. Those results will allow us to optimize the procedure for solving COPs before implementing it experimentally.

[1] Y. Zhang, Y. Deng, *et al. Oscillator-Network-Based Ising Machine*. Micromachines **13**, 1016 (2022).
[2] N.-T. Phan, N. Prasad, *et al. Unbiased random bitstream generation using injectionlocked spin-torque nano-oscillators*. Physical Review Applied **21** (2024).
[3] D. I. Albertsson, M. Zahedinejad, *et al. Ultrafast Ising Machines using spin torque nano-oscillators*. Applied Physics Letters **118** (2021).
[4] A. A. Thiele. *Steady-State Motion of Magnetic Domains*. Physical Review Letters **30**, 230–233 (1973).
[5] F. A. Araujo, C. Chopin, and Simon de Wergifosse. *Ampere–Oersted field splitting of the nonlinear spin-torque vortex oscillator dynamics*. Scientific Reports **12** (2022).

Stability diagram for dual free layers magnetic tunnel junction

Arthur Courberand[1*], Ajay Jha[1], Ricardo C. Sousa[1], Joo-Von Kim[2], Ursula Ebels[1], and Liliana D. Buda-Prejbanu[1]

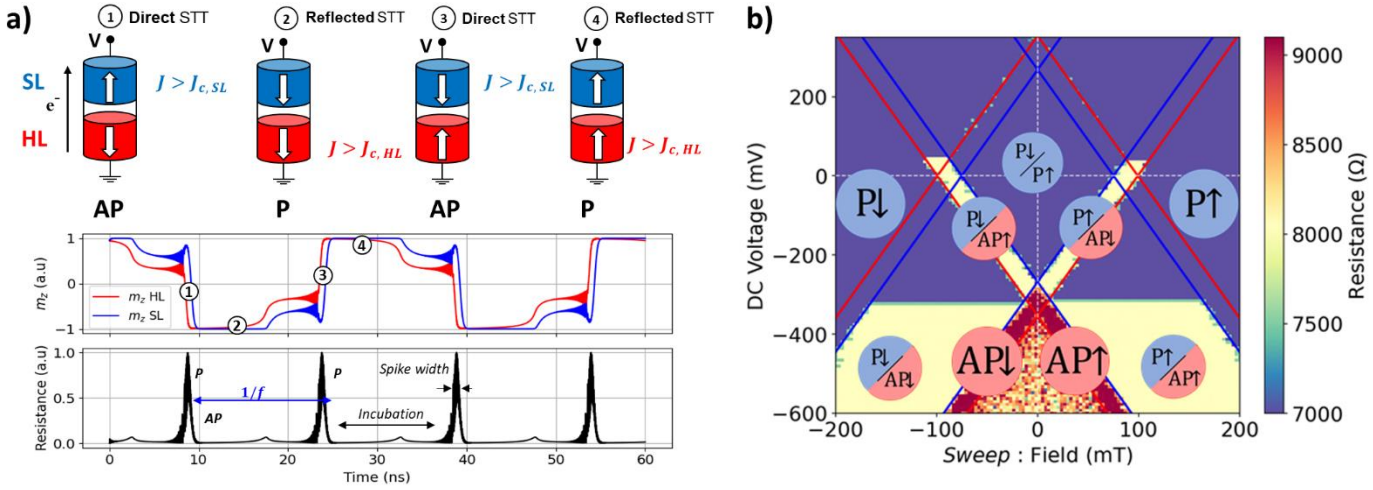
[1]Univ. Grenoble Alpes, CEA, CNRS, Grenoble INP, SPINTEC, Grenoble, France

[2]Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, Palaiseau, France

*arthur.courberand@cea.fr

Abstract:

Devices capable of generating spikes like biological neurons are promising elements for alternative computing. In particular, bio-inspired neural networks such as spiking neural networks (SNNs) require energy-efficient, CMOS-compatible, and scalable devices that can reproduce the behavior of biological neurons [1]. One candidate for such application is the dual-free-layer perpendicular magnetic tunnel junction, which generates spikes through the continuous reversal of its coupled layers [2]. This dynamic feature, illustrated in Figure 1 appears when enough voltage is injected through the junction, generating a spin-transfer torque that overcomes intrinsic relaxation. The condition under which dynamic operation starts is essential for applications, and a precise description of its dependence on various parameters (materials, geometry, etc.) will enable an appropriate solution to be found for low-power consumption.



(a) Schematics of the windmill dynamics triggered in a dual free-layer magnetic tunnel junction (MTJ). The four switching processes occur sequentially, beginning with reflection-electron STT (1→2), followed by direct STT (2→3), and then reflection STT (3→4). The cycle repeats, consequently giving rise to characteristic spiking resistive signal.

(b) Simulated phase diagram of a dual free-layer MTJ. Each point represents the average resistive state after system stabilization, computed from both increasing and decreasing field sweeps. The blue and red circles indicate the magnetic state of the system. The blue and red lines correspond to the critical lines extracted from the analytical model (eq. 1 and eq. 2)

The system dynamics can be accurately captured using a coupled macrospin model, as each free layer is considered uniformly magnetized. By applying magnetic field and voltage stimuli and allowing the system to relax to a steady state, the stable magnetic configurations of the junction can be identified. The results are summarized as stability diagram (Fig 1) mapping these configurations and revealing the boundaries between distinct regimes, particularly that of the windmill regime.

The regions corresponding to parallel, antiparallel, and dynamical state can be clearly distinguished. At high magnetic fields, the system stabilizes in a low-resistance state, indicating parallel alignment of both layers along the external

field. At lower fields and higher voltage, a dynamical regime appears, corresponding to the windmill regime, characterized by increased resistance variability due to its non-stationary behavior. Other more complex and bistable regimes appear between them.

To describe these limits, an analytical model was developed based on a stability analysis [3] whose predictions agree well with the numerical results.

$$H_{sw}^{SL} = -m_{HL}\left(\frac{a_{DL}}{\alpha}V\right) - m_{SL}\left(\frac{2\,K_u^{SL}}{M_s} - \Delta N_{SL}M_s\right)$$
$$H_{sw}^{HL} = \quad m_{SL}\left(\frac{a_{DL}}{\alpha}V\right) - m_{HL}\left(\frac{2\,K_u^{HL}}{M_s} - \Delta N_{HL}M_s\right)$$

where m_{HL} and m_{SL} denote the z-axis macrospin projections; a_{DL} is the STT coefficient; α the Gilbert damping; K_u the anisotropy constant; M_s the saturation magnetization; and $\Delta N = N_{zz} - N_{xx}$ the demagnetizing factor.

These equations reveal the role of several material parameters in determining the boundaries of each regime. Enabling better control over the system behavior, especially the operating point at which spiking occurs. The precise control of spiking regime can reduce the voltage required for a network of neurons to spike, or enable tuning of individual neurons to achieve different type of spiking under the same bias voltage. Our analytical model is an effective tool for exploring the compatibilities of the double-layer free MTJ and optimizing its operation.

[1] J. K. Han, S. Y. Yun, *A review of artificial spiking neuron devices for neural processing and sensing*, Advanced Functional Materials, **32, 2204102** (2022).

[2] L. Farcis and B. M. S. Teixeira, *Spiking dynamics in dual free layer perpendicular magnetic tunnel junctions*, Nano Letters, **23, 7869–7875** (2023).

[3] N. Strelkov, A. Chavent, *Impact of Joule heating on the stability phase diagrams of perpendicular magnetic tunnel junctions*, Physical Review B, **98, 214410** (2018).

Finite element modeling for spintronics

Daria Gusakova*†[1], Natalia Boscolo Meneguolo[1], Mouad Fattouhi[1], Anaïs Fondet[1], Lucia Gomez-Cruz[1,2], Laura Álvaro Gómez[2], Aurélien Masseboeuf[1], Lucas Pérez[2], Christophe Thirion[3], Edgar Bonet[3], Olivier Fruchart[1], and Jean-Christophe Toussaint[3]

[1]Spintec – CEA-CNRS-Université Grenoble-Alpes – France
[2]Universidad Complutense de Madrid – Espagne
[3]Institut Néel – CNRS : UPR2940, Université Grenoble Alpes, CNRS – France

Résumé

Three-dimensional spintronics exploits the interaction of magnetic moments with electron spins in non-planar objects, such as cylindres. These 3D building blocks of nanoscale devices are fascinating objects for fundamental research as well as for data storage advanced technologies.
To simulate non-trivial 3D micromagnetic textures and the impact of current on its dynamics we have developed the multi-physics finite element C++ software *feeLLGood* which is suitable for irregular or curved geometries (1). The code includes self-consistent calculation of the magnetization and spin dynamics which may result in non-trivial STT (2) and SOT-induced effects. Our recent developments concerning complex 3D spin textures include post-processing tools for topological analysis (3) of such a system as well as the conversion of micromagnetic output into experimental contrast.

(1) http://feellgood.neel.cnrs.fr/

(2) N. B. Meneguolo et al. "Simulation of current-driven magnetization switching in nanopillars with perpendicular shape anisotropy ", Phys. Rev. B 112, 014448 (2025)
(3) L. Álvaro-Gómez et al. "Topological analysis and experimental control of transformations of domain walls in magnetic cylindrical nanowires", Phys. Rev. Research 7, 023092 (2025)

Mots-Clés: finite elements, micromagnetics, spin dependent transport, complex spin textures

*Intervenant
†Auteur correspondant: daria.gusakova@cea.fr

Ultrafast electron-magnon interactions in ferromagnetic materials

Benjamin Bakri*[1], Giovanni Manfredi[2], and Paul-Antoine Hervieux*[3]

[1]Institut de Physique et Chimie des Matériaux de Strasbourg – CNRS – France
[2]Institut de Physique et Chimie des Matériaux de Strasbourg (IPCMS) – université de Strasbourg, CNRS : UMR7504 – 23 rue du Loess - BP 43 - 67034 Strasbourg Cedex 2 - France, France
[3]Institut de Physique et Chimie des Matériaux de Strasbourg – université de Strasbourg, Centre National de la Recherche Scientifique, Matériaux et Nanosciences Grand-Est, Réseau nanophotonique et optique, Réseau nanophotonique et optique – France

Résumé

Three decades after the discovery of ultrafast demagnetization, its underlying microscopic mechanisms are still being debated. Among the many scenarios that have been proposed as possible explanations, the interplay between electrons and spin waves (magnons) is of particular interest. In the present work, we investigate the ultrafast magnetization dynamics from the viewpoint of plasma physics, using a microscopic phase-space model that goes well beyond the simple quasi-equilibrium approach adopted in the three-temperature model.
We distinguish two types of magnetism: (i) itinerant magnetism, carried by the conduction electrons that are spatially delocalized (s orbitals) and (ii) fixed magnetism, carried by localized d-orbital electrons (hereafter denoted simply as "the ions"). The itinerant electrons are described by a set of Vlasov equations generalized to the case of spin-1/2 fermions, whereas the fixed ions are modeled by a Landau-Lifshitz equation. The two components (mobile electrons and fixed ions) interact not only through the electrostatic Coulomb force, but also via magnetic-exchange interaction terms.

The linear response analysis reveals the existence of a wave-particle resonance occurring at the magnon frequency. Depending on the initial electron spin polarization, the resonance can lead to either damping or instability of the wave. In the unstable case, this resonance gives rise to significant energy exchanges between the magnons and the electrons, resulting in a rapid loss of the localized magnetism, which is evocative of the ultrafast demagnetization observed in experiments on thin ferromagnetic films. In the damped case, the observed damping can be related to the phenomenological Gilbert damping term, which is currently used in micromagnetic simulations to reproduce the decay of spin waves.
These results show that wave-particle effects, similar to those frequently encountered in plasma physics, may play a key role in the intertwined charge and spin dynamics in ferromagnetic materials.

Mots-Clés: Ultrafast magnetism, spin polarized plasma, electron magnon interaction, Vlasov equation

*Intervenant

Automating the symmetry-adapted discovery of magnetic Multipolar Orders and related response functions

Maxime Braun*[1,2] and Quintin Meier[2]

[1]Condensed Matter Theory (TMC) – Institut Néel, CNRS, Univ. Grenoble Alpes – 25 Av. des Martyrs, 38042 Grenoble, France

[2]Matériaux, Rayonnements, Structure (NEEL - MRS) – INSTITUT NEEL – Institut NEEL, 25 rue des Martyrs, BP 166,38042 Grenoble cedex 9, France

Résumé

Standard magnetic classification schemes based on dipolar order often fail to capture the rich magnetostructural landscape of complex materials. We introduce **MultipoleCalculator**, a web-based tool designed to systematize the search for high-rank multipolar phases and their associated physical responses. The tool automates the symbolic derivation of electric and magnetic multipoles up to rank 5, providing an immediate dictionary between magnetic symmetry and macroscopic tensor properties such as electrostriction, flexomagnetism, and the magnetoelectric effect.

Furthermore, the tool implements an automated orbit analysis to classify magnetic structures as ferroic, antiferroic, or non-collinear based on the alignment of high-rank moments allowing the discovery of hidden (anti-)orders. This capability is critical for identifying materials where conventional magnetization vanishes but symmetry-protected multipoles drive phenomena like altermagnetism. We showcase the tool's utility by mapping the hierarchy of multipolar order parameters in rutile fluorides.

Mots-Clés: Multipoles, Magnetoelectricity, Altermagnetism, Physical Properties

*Intervenant

Modeling Spin-Orbitronics Effects at Interfaces and Chiral Molecules

Poonam Kumari∗1,2, Cyrille Barretaeu2, and Alexander Smogunov†3

1CEA Paris-Saclay – CEA Paris-Saclay – France
2SPEC, CEA Paris Saclay – Service de Physique de l'Etat Condensé, CEA Paris Saclay – France
3SPEC, CEA Paris Saclay – Service de Physique de l'Etat Condensé, CEA Paris Saclay – France

Spin-orbitronics, which is based on the use of orbital angular momentum as an information carrier, has gained significant attention in the recent past. In the structures which lack inversion symmetry, a formation of orbital angular momentum (OAM) in Bloch wave functions, independent of spin orbit coupling (SOC), has been predicted and is often considered to be a more generic effect implying that the orbital moment of an electron is the main driving force behind the Rashba effect rather than its spin. Here, using the electronic wave packets approach, we explore the possibility of generation and propagation of orbital currents in two representative systems: an oxidized copper surface (where large OAMs are formed at the Cu/O interface) and a model carbon chain/chiral molecule junction. In the Cu/O system, the orbital polarization of incident wave packets is strongly enhanced at the Cu/O interface but rapidly decays in bulk copper. Interestingly, if a finite transmission across the oxygen layer is allowed (a tunnel junction), a significant spin-polarization of transmitted current is predicted; it persists at long distance and can be tuned by applied in-plane voltage. For molecular junctions, the mixing of carbon px, py channels by a chiral molecular orbital gives rise to efficient generation of orbital current and to its long-range propagation along the carbon chain.

Local spin magnetization in noncollinear magnets: role of interband spin coherences

Doru Sticlet[1] , Frédéric Piéchon[2*]

[1]National Institute for R&D of Isotopic and Molecular Technologies, 67-103 Donat, 400293 Cluj-Napoca, Romania

[2]Laboratoire de Physique des Solides, Université Paris-Saclay, CNRS, 91405 Orsay, France

*frederic.piechon@universite-paris-saclay.fr

Abstract:

A key feature of itinerant non-collinear magnets is that Bloch band eigenstates are not eigenstates of the spin operator. As a result, the spin operator possesses finite inter-band matrix elements. In this work, we show that, in addition to the conventional intra-band local spin moment typical of collinear magnetic textures, the inter-band spin coherences play a crucial role in determining the local spin magnetization. More specifically, we show that, to linear order in an external magnetic field, the intra-band local moment contribution traduces an effective Zeeman shift of the energy bands, whereas the inter-band spin coherences capture the field-induced deformation of the eigenstates. The form of this latter contribution is reminiscent of the Berry-curvature term in orbital magnetization.

Power efficiency of the Spin-Hall current injected on a load circuit

S. Al Saati and J.-.E Wegrowe

LSI, CNRS, CEA/IRAMIS, Ecole Polytechnique
Jean-eric.wegrowe@polytechnique.edu

Abstract:

A recent study (theory and experiments) of the lateral injection of *anomalous Hall current* from a Hall bar into a load circuit [1-3] has shown that the behavior of the Joule power dissipated in the load resistance is universal, in the sense that the normalized power is the same whatever the materials that generates anomalous Hall effect (i.e. whatever the microscopic mechanisms). It has indeed been shown that the Joule power has the same profile - as a function of the load resistance and as a function of the Hall angle - whatever the materials tested (in the ferrimagnetic metals GdCo, HoCo, and in the altermagnets Si3Mn5 and MnTe).

In the present work, we are extending this investigation (theoretically and experimentally) to the case of the ***spin-Hall effect*** [4]. The system is typically a Hall bar of Pt or Ta, in contact to a lateral load resistance. The Hall voltage between the two edges is zero. However, some first experiments show Joule dissipation occurring inside the load circuit. What are the properties of the power produced by the Spin-Hall current into the load? The problem is known in the case of a submicron load circuit that preserves the spin current [4]. However, the question is open for the load resistance placed at a large distance with respect to the spin-diffusion length.

We propose a phenomenological model based on the variational approach developed in references [3] and [5] with adding the lateral load circuit. This approach allows the stationary state to be characterized in terms of the distribution of the density of carriers and electric currents through the whole circuit.

Indeed, in a usual *spin-Hall device*, a pure spin current is generated transverse to the Hall bar, without the need of an external magnetic field nor magnetic order parameter. The effective spin-orbit magnetic field is spin-dependent, so that the conductivity matrix is a 6 by 6 matrix (in the framework of the two spin-channel model). There is no electric voltage at the lateral edges (if the symmetry is strictly respected). However, the same Joule dissipation as for the anomalous Hall bar is produced inside the Hall bar, and the power density is injected - in some forms - into the load resistance. The model is developed assuming the two limiting cases: infinite [5] and negligible spin-diffusion lengths.

[1] D. Lacour et al. "*Injection of anomalous Hall current: the role of impedance matching*", J. Appl. Phys. **135**, 193903 (2024)
[2] V. Desbuis et al. "*Dissipation properties of anomalous Hall effect: intrinsic vs. extrinsic" J. Apple. Phys. 138, 233906 (2025)*
[3] J.-E. Wegrowe et al. "*Power efficiency of Hall-like devices: Comparison between reciprocal and antireciprocal Onsager relations"*, Phys. Rev. B **110**, 024412 (2024).
[4] Y. Omori, F. Auvray, T. Wakamura, Y. Niimi, A. Fert, and Y. Otani, *Inverse spin Hall effect in a closed loop circuit,* Appl. Phys. Lett. **104**, 242415 (2014)
[5] M. Creff et al. "*Screening effect in spin Hall devices*" Phys. Rev. B **105** 174419 (2023)

LCAOtools: A Python package for computing spin-orbitronics and orbitronics properties

Salomé Trillot[1] and Dongzhe Li*[1]

[1]CEMES, University of Toulouse, CNRS, F-31055 Toulouse, France – CEMES CNRS, 29 RUE JEANNE MARVIG, 31055 TOULOUSE, FRANCE – France

Résumé

Spin-orbitronics and orbitronics are emerging fields in condensed matter physics, but efficient and unified computational tools for predicting spin and orbital responses in real materials and devices are still lacking. We present LCAOtools, a Python package for computing spintronics observables based on Hamiltonians in linear combination of atomic orbitals (LCAO). It enables calculations of quantities such as spin and orbital textures, spin and orbital Edelstein effects, topological orbital moments, and spin-orbit torque (SOT) using LCAO and the nonequilibrium Green's function (NEGF) method. LCAOtools is written in a general way, allowing for easy interfacing with different tight-binding or Wannier-based Hamiltonians. Our package aims to lower the barrier for quantitative studies of spin and orbital transport phenomena in realistic materials and nanodevices at the *ab initio* level.
Acknowledgments: This work is supported by France 2030 government investment plan managed by the French National Research Agency under grant reference PEPR SPIN – (SPINTHEORY) ANR-22-EXSP-0009.

Mots-Clés: Orbitronics, Spin and orbital Edelstein effects, Topological orbital moments, Spin orbit torque

*Intervenant

Orbital dynamics through chiral phonons in low-Z materials

Armando Pezo*[1]

[1]Laboratoire Albert Fert – Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau, France – France

Résumé

Dans le cadre de la spintronique, l'intérêt porté à la dynamique du degré de liberté orbital a ouvert de nouvelles perspectives pour le contrôle des propriétés de transport quantique des matériaux, notamment en tenant compte de la présence d'un fort couplage spin-orbite. Contrairement à l'interaction observée entre les spins itinérants et la magnétisation aux interfaces des métaux lourd/ferromagnétique, l'équivalent orbital de ces effets présente un enchevêtrement distinct entre les caractéristiques orbitales du matériau et le transport électronique. Plus précisément, c'est le réseau cristallin qui interagit fortement avec ce degré de liberté, comme l'ont démontré des études récentes. Dans ce travail, nous effectuons des simulations numériques pour évaluer les avantages de l'exploitation de ces capacités. Nous nous concentrons sur les éléments légers pour nos calculs de transport et démontrons que cette interaction peut être efficacement utilisée dans les futurs dispositifs spintroniques, en tenant compte notamment des effets de la température.

Mots-Clés: Interaction électron, phonon, transport électronique, DFT

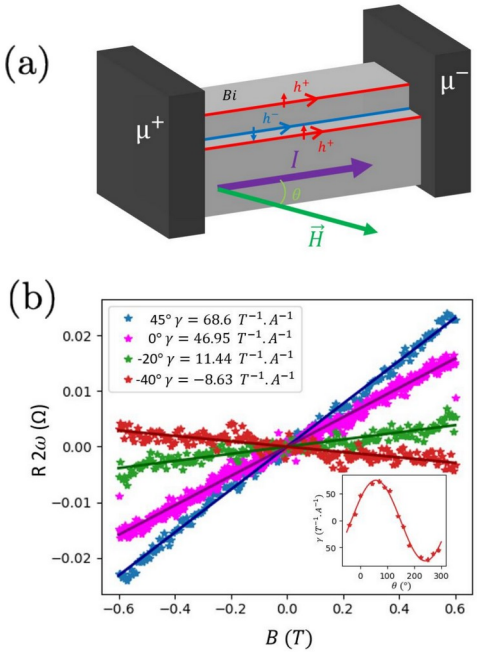
*Intervenant

Topological fragility and bilinear magneto-resistance in spin-momentum locked edge states

Cosimo Gorini[1*], Matthieu Bard[2] , Giovanni Vignale[3]
[1]SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, Gif sur Yvette, France
[2]Université Paris-Saclay, CNRS, Laboratoire de Physique des Solides, 91405 Orsay, France
[3]Institute for Functional Intelligent Materials, National University of Singapore
*cosimo.gorini@cea.fr

Time-reversal symmetric and topologically non-trivial electronic systems generally host one-dimensional (1D) spin-momentum locked states at their edges/hinges. Such 1D states are in principle fully protected against backscattering, and thus referred to as perfectly conducting: disorder cannot induce backscattering – not even via spin-orbit coupling – unless time-reversal is broken. We show however that such protection hides a remarkable fragility, yielding a bilinear magneto-resistance much stronger than in standard 2D systems [1]. The mechanism we propose is fundamental and general: it is based on spin-orbit interaction with the ever-present disordered background and does not require any higher-order correction such as trigonal warping. It should thus be relevant in any system hosting 1D Dirac-like states with linear dispersion. Our theory compares favourably with transport measurements in high-order topological hinge states in Bi performed at Université Paris-Saclay, LPS [2].

Figure - (a): Sketch of the experimental setup. The shape of the Bi nanowire defines multiple hinges of either helicities. An external field is applied in the wire plane at an angle θ. (b) Bilinear magneto-resistance (R 2ω) traces for varying θ. The data was antisymmetrized to isolate the bilinear component.



[1] He et al., *Bilinear magnetoelectric resistance as a probe of three-dimensional spin texture in topological surface states*, Nature Phys. **14**, 495 (2018)
[2] Gorini, Bard and Vignale, *in preparation*

Rotating Spin-Wave Modes in Nanoscale Möbius Strips

Riccardo Hertel*†[1]

[1]Institut de Physique et Chimie des Matériaux de Strasbourg (IPCMS) – université de Strasbourg, Centre National de la Recherche Scientifique, Matériaux et Nanosciences Grand-Est – 23 rue du Loess - BP 43 - 67034 Strasbourg Cedex 2 - France, France

Résumé

Curved and topologically nontrivial magnetic nanostructures offer new opportunities to control spin-wave dynamics beyond planar systems. In this presentation, I will discuss spin-wave modes in nanoscale Möbius-shaped soft-magnetic strips and show how their geometry gives rise to intrinsically nonreciprocal, rotating spin-wave modes that have no analogue in topologically trivial rings.
Using micromagnetic simulations, we compare Möbius strips with different numbers of twists to a twist-compensated bent ring (1). While the trivial ring supports well-defined standing-wave modes, Möbius nanomagnets exhibit frequency-split mode pairs corresponding to clockwise and counterclockwise rotating spin waves. This splitting originates from a twist-induced geometric (Berry) phase, which lifts the degeneracy between counterpropagating modes and leads to asymmetric dispersion relations, in quantitative agreement with a recently developed analytical theory (2). The non-orientable topology further imposes antisymmetric boundary conditions, resulting in half-integer wavelength quantization. We also show that localized RF excitation enables selective generation of rotating spin waves with a chosen propagation direction.

(1) A. Thonikkadavan, M. d'Aquino, and R. Hertel, npj Spintronics 4, 4 (2026).
(2) M. d'Aquino and R. Hertel, Phys. Rev. Lett. 135, 216705 (2025).

Mots-Clés: Micromagnetic Simulations, Spin Waves, Curvilinear Magnetism, Nonreciprocity

*Intervenant
†Auteur correspondant: riccardo.hertel@ipcms.unistra.fr

Atomistic spin dynamics modelling of antiferromagnetic skyrmions and bimerons in spintronic devices

Coline Thevenard*†[1], Miina Leiviska[1], Richard F. L. Evans‡[2], Daria Gusakova[1], and Vincent Baltz§[1]

[1]SPINtronique et TEchnologie des Composants (SPINTEC) – Centre National de la Recherche Scientifique, Institut de Recherche Interdisciplinaire de Grenoble, Université Grenoble Alpes – Institut de Recherche Interdisciplinaire de GrenobleCEA-Grenoble17, avenue des Martyrs 38054 GRENOBLE CEDEX 9, France

[2]School of Physics, Engineering and Technology, University of York – York YO10 5DD, Royaume-Uni

Résumé

Protected real-space topological states in compensated magnets, such as antiferromagnetic skyrmions and bimerons, offer a promising platform for efficient information transport. Their manipulation, however, is hindered by the absence of net magnetization. Using atomistic simulations, we demonstrate that interfacial exchange coupling with an adjacent ferromagnet, activated via a combined thermal and magnetic protocol, enables deterministic nucleation and detection of these topological states. We further show their stabilization and isolation, paving the way for robust, controllable, and energy-efficient spintronic information transport.

(1) C. Thevenard, M. Leiviskä, D. Gusakova, R. F. L. Evans, and V. Baltz, Imprinting of skyrmions and bimerons in an antiferromagnet, Phys. Rev. B 111, 224429 (2025).

(2) M. Leiviskä, S. Jenkins, R. F. L. Evans, D. Gusakova, and V. Baltz, Local setting of spin textures in a granular antiferromagnet, Phys. Rev. B 108, 184424 (2023).

(3) K. G. Rana, R. Lopes Seeger, S. Ruiz-Gómez, R. Juge, Q. Zhang, K. Bairagi, V. T. Pham, M. Belmeguenai, S. Auffret, M. Foerster, L. Aballe, G. Gaudin, V. Baltz, and O. Boulle, Imprint from ferromagnetic skyrmions in an antiferromagnet via exchange bias, Appl. Phys. Lett. 119, 192407 (2021).

(4) M. Leiviskä, C. Thevenard, C. Cronshaw, J. Rial, S. Jenkins, D. Gusakova, R. F. L. Evans, and V. Baltz, Antiferromagnetic skyrmions in spintronics, edited by A. Hirohata et al. (Elsevier, New York, 2026), hal-04390931.

Mots-Clés: antiferromagnetism, atomistic, bimerons, skyrmions, spintronics

*Intervenant

†Auteur correspondant: coline.thevenard@cea.fr

‡Auteur correspondant: richard.evans@york.ac.uk

§Auteur correspondant: vincent.baltz@cea.fr

Current-Induced Nucleation and Transport of Magnetic Hopfions in Chiral Nanotubes

Louis Gallard*†[1] and Riccardo Hertel[1]

[1]Institut de Physique et Chimie des Matériaux de Strasbourg (IPCMS) – université de Strasbourg, Centre National de la Recherche Scientifique, Matériaux et Nanosciences Grand-Est – 23 rue du Loess - BP 43 - 67034 Strasbourg Cedex 2 - France, France

Résumé

Magnetic Hopfions are three-dimensional topological spin textures with particle-like properties and attractive features for spintronic applications, including current-driven motion without transverse deflection. Using finite-element micromagnetic simulations, we investigate the stabilization, transport, and injection of Hopfions in chiral magnetic nanotubes. We show that the shape anisotropy of the tubular FeGe geometry stabilizes Hopfions under an external magnetic field applied along the tube axis. The required field can be significantly reduced by introducing a uniaxial bulk anisotropy. Once stabilized, Hopfions are transported rigidly along the tube axis by spin-transfer torque, and multiple Hopfions can coexist and move collectively, forming a Hopfion "train". Furthermore, we demonstrate a geometry-assisted nucleation and injection mechanism based on a constriction at the wire's end, where short current pulses generate and inject Hopfions into the nanotube. These results establish key ingredients for controlled Hopfion-based transport in three-dimensional spintronic architectures.

Mots-Clés: Hopfion, Current induced dynamics, Chiral Nanotube, Micromagnetic Finite Element Simulations

*Intervenant

†Auteur correspondant: louis.gallard@ipcms.unistra.fr

Optimaly stable room temperature sub-10 nm Néel skyrmion at zero applied magnetic field in an antisymmetric bilayer

Anne Bernand-Mantel*[1], Cyrill Muratov[2], and Valery Slastikov[3]

[1]Centre d'élaboration de matériaux et d'études structurales (CEMES) – CNRS – 29 Rue Jeanne Marvig - BP 94347 31055 TOULOUSE CEDEX 4, France

[2]Dipartimento di Matematica, Universita di Pisa, Largo B. Pontecorvo, 5, 56127 Pisa, Italy – Italie

[3]School of Mathematics, University of Bristol, Bristol BS8 1UG, United Kingdom – Royaume-Uni

Résumé

The quest for predicting optimally stable and compact isolated magnetic skyrmions suitable for information technology applications relies on solving the micromagnetic equation. In the past few years, we have successfully used the tools of calculus of variations to develop an analytical skyrmion theory that enables a systematical prediction of skyrmions characteristics including results on the role of long range dipolar interaction in the stabilization of compact skyrmions as a function of the film effective thickness and the derivation of an explicit Arrhenius law for skyrmion lifetime (1). Our work on the continuum micromagnetic model, as well as other works based on atomic spin models, have predicted the energy path for skyrmion annihlation. However, the energy path that prevents skyrmion to stripe-out or burst (2) into a larger object at zero applied magnetic field have been largely overlooked despite being an equaly important source of instability for skyrmions. We will present our latest results where we carried out optimization of the stability of skyrmions at zero applied magnetic field for both collpase and bursting mechanism. In addition to this, we propose to further enhance the skyrmion stability by exploiting an additionnal stabilization mechanism in a multilayer : the interlayer volume-surface dipolar interaction, which takes the form of an additional Dzyaloshinskii-Moriya like term for Néel skyrmions in an antismymetric bilayer (3,4). This optimization enables us to obtain record stabilities for compact zero-field skyrmions which are very promessing for applications.

(1) A. Bernand-Mantel, C. Muratov and T. Simon PRB 101, 045416 (2020), A. Bernand-Mantel, C. Muratov and V. Slastikov PNAS 119, e2122237119 (2022)

(2) A. Bernand-Mantel et al PRB 108, L161405 (2023)

(3) N. Dubicki, V. Slastikov, A. Bernand-Mantel, C. Muratov JourNonLinSci 36, 7 (2026)

(4) A. Bernand-Mantel, V. Slastikov and C. Muratov in preparation

Mots-Clés: skyrmion, bilayer, micromagnetic modeling

*Intervenant

ABSTRACTS

POSTER

Toward numerical twins: connecting experiments and theory through micromagnetic simulations and simulated magnetic imaging of skyrmions and nanowires

Anaïs Fondet*†[1], Christophe Gatel[2], Anne Bernand-Mantel[3], Aurélien Masseboeuf[1], and Daria Gusakova[4]

[1]SPINtronique et TEchnologie des Composants – Centre National de la Recherche Scientifique, Institut de Recherche Interdisciplinaire de Grenoble, Université Grenoble Alpes, Centre National de la Recherche Scientifique : UMR8191, Institut de Recherche Interdisciplinaire de Grenoble : DRF/IRIG/DEPHY – France

[2]Centre d'élaboration de matériaux et d'études structurales (CEMES) – CNRS, CNRS : UPR8011 – France

[3]Centre d'élaboration de matériaux et d'études structurales – CEMES CNRS, 29 RUE JEANNE MARVIG, 31055 TOULOUSE, FRANCE – 29 Rue Jeanne Marvig - BP 94347 31055 TOULOUSE CEDEX 4, France

[4]SPINtronique et TEchnologie des Composants (SPINTEC) – Centre National de la Recherche Scientifique, Institut de Recherche Interdisciplinaire de Grenoble, Université Grenoble Alpes – Institut de Recherche Interdisciplinaire de GrenobleCEA-Grenoble17, avenue des Martyrs 38054 GRENOBLE CEDEX 9, France

Résumé

In the quest for novel spin textures, their dynamics and new spin-based technologies, the combined use of micromagnetic simulations and spin-sensitive experimental techniques, such as magnetic force microscopy (MFM), x-ray magnetic circular dichroism scanning transmission x-ray microscopy (XMCD-STXM), or electron holography (EH) has proven essential for the understanding of complex magnetic materials. In this context, there is a strong need for reliable micromagnetic simulations and for simulated experimental contrast in order to accurately interpret experimental observations. In my work, I have investigated skyrmion-based ferromagnetic multilayers (Pt/Co/Ta) through a combined experimental and numerical approach, and more recently extended this methodology to permalloy nanowires, where microscopy and x-ray measurements are coupled to finite-element method (FEM) simulations. For the multilayer systems, we present a study of Néel stripe domains, which constitute the zero-field magnetic configuration of our skyrmion-hosting material under applied magnetic field. This study combines micromagnetic simulations performed with Mumax3(1) and Lorentz transmission electron microscopy (LTEM) in Fresnel mode.
In (Pt/Co/Ta)×n system, room-temperature skyrmions as small as 50 nm have been observed when the Co thickness was tuned close to the spin reorientation transition (2). In

*Intervenant

†Auteur correspondant: anais.fondet@cea.fr

our study, we fixed the Co thickness at 0.8 nm and tuned the thickness of the total system by varying the number of repetitions n of the Pt/Co/Ta tri-layer, allowing selective tuning of stray-field effects while keeping the intrinsic magnetic parameters (magnetocrystalline anisotropy, saturation magnetization and DMI) roughly constant. In the first place, we conducted an experimental study of the stripe domains as a function of the multilayer total thickness. The application of an *in situ* magnetic field and temperature variation enabled us to identify the stripe-to-skyrmion transition and the regimes of isolated skyrmions and skyrmion lattice. These observations were used to construct experimental phase diagrams, for several samples, which are interpreted and compared with theoretical predictions based on the skyrmionic bubble model (3), supported by magnetometry measurements. We will present our understanding of these diagrams. Moreover, we further investigated these samples using EH, enabling quantitative measurements of the magnetic phase of Néel-type skyrmions, correlated to simulation.

Finally, in the continuity of the previous work, and in the framework of of Diwina project (ANR), we will present a preliminary study on understanding the link between nanowires in core (3D) magnetization and both Fresnel and STXM images. Magnetic nanowires present interest for the presence of Bloch points in certain conditions (4,5) and the rapid motion of domain walls beyond the Walker limit, for future spintronic applications. In these magnetic samples, presenting in surface an azimuthal magnetization (6), the link between nanowire composition, anisotropy and transition from the uniform (parallel to the nanowire axis) in core, and azimuthal in surface is yet to be specified, and linked precisely between both experimental images and series of simulated ones. Simulated images are computed from FEM based LLG integration simulation code for micromagnetic simulations, in static or dynamic, named FeeLLGood (7).

References

(1) Arne Vansteenkiste, Jonathan Leliaert, Mykola Dvornik, et al. The Design and Verification of MuMax3. AIP Advances4, 107133 (2014).

(3) Anne Bernand-Mantel, Anaïs Fondet, Sarah Barnova, Theresa M. Simon, and Cyrill B. Muratov. Theory of MagneticField Stabilized Compact Skyrmions in Thin-Film Ferromagnets. Physical Review B 108, L161405 (13, 2023).

(2) Lei Wang, Chen Liu, Nasir Mehmood, et al. Construction of a Room-Temperature Pt/Co/Ta Multilayer Film withUltrahigh-Density Skyrmions for Memory Application. ACS Applied Materials & Interfaces 11, 12098–12104 (27, 2019).

(4) Claire Donnelly, Sebastian Gliga, Valerio Scagnoli, et al. Tomographic Reconstruction of a Three-Dimensional Magne-tization Vector Field. New Journal of Physics 20, 083009 (7, 2018).

(5) L. Álvaro-Gómez, J. Hurst, S. Hegde, et al. Topological Analysis and Experimental Control of Transformations of Do-main Walls in Magnetic Cylindrical Nanowires. Physical Review Research 7, 023092 (28, 2025).

(6) L. Álvaro-Gómez, S. Ruiz-Gómez, C. Fernández-González, et al. Micromagnetics of Magnetic Chemical Modulations inSoft-Magnetic Cylindrical Nanowires. Physical Review B 106, 054433 (26, 2022).
(7) FeeLLGood – an FEM Micromagnetic Simulator. URL: https://feellgood.neel.cnrs.fr/ (visited on 01/28/2026)

Mots-Clés: micromagnetic, simulation, TEM, skyrmion, nanowire, FEM

Ab initio study of orbital moments in transition-metal oxides

Timothé Loussalez*†[1], Rémi Arras[2], Aurelien Manchon[3], and Lionel Calmels‡[2]

[1]Centre d'élaboration de matériaux et d'études structurales (CEMES) – CNRS, CNRS : UPR8011 – France

[2]Centre d'élaboration de matériaux et d'études structurales – CNRS – France

[3]Centre Interdisciplinaire de Nanoscience de Marseille – CNRS – France

Résumé

Recent advances in spintronics have enabled the development of non-volatile memories with low-energy consumption, as well as magnetic oscillators and sensors. Current research often focuses on devices that rely on the generation of spin currents to manipulate spin magnetization. The production of their building-block components requires the use of scarce and heavy elements (e.g., Pt, Ta, W, Bi) with strong spin–orbit coupling. To overcome this limitation, recent studies have shown that using currents of orbital angular momentum1,2,3 could be an alternative to spin currents. This approach would both reduce energy consumption and enable the use of light and abundant elements (e.g., CuOx, Ti, Zr, Al). While various materials have already been explored to generate orbital currents, transition-metal oxides have been overlooked, while they appear to be promising candidates, as they are known to possess a large variety of highly-tunable atomic structures, which would provide an efficient way to modulate orbital currents through the modifications of their associated crystal field.
This work employs ab initio calculations to investigate the emergence and control of orbital moments within transition-metal oxides. Preliminary results show that nickel and cobalt monoxides seem to exhibit robust orbital physics4,5.

We will present the electronic and magnetic properties of interfaces between CoO and various transition-metal thin films. Using DFT-based methods, we aim to understand the interplay between crystal field symmetry and interfacial hybridization, the fundamental mechanisms governing the orbital response. By identifying these structural and chemical parameters, we seek to explore how these interfaces can be engineered to maximize orbital angular momentum transfer and transport for the next generation of energy-efficient orbitronic devices.

Références

*Intervenant

†Auteur correspondant: timothe.loussalez@cemes.fr

‡Auteur correspondant:

1 Jo, D. Go, H. Lee, Phys. Review B. 98.21 (2018)

2 D. Go, J. Hanke, P. M. Buhl, F. Freimuth, G. Bihlmayer, H. Lee, Y. Mokrousov, S. Blügel, Scien. Rep. 7.1 (2017)

3 S. Ding, A. Ross, D. Go, L. Baldrati, Z. Ren, F. Freimuth, S. Becker, F. Kammerbauer, J. Yang et al., Phys, Rev. Lett. 125, 177201 (2020)

4 S. Ding, et al. "Generation, transmission, and conversion of orbital torque by an antiferromagnetic insulator". Nature Communications 16, 9239 (2025)
5 S. I. Csiszar, et al. "Controlling orbital moment and spin orientation in CoO layers by strain". Physical Review Letters 95, 187205 (2005)

Mots-Clés: Spintronics, Orbitronics, Orbital Angular Momentum, Density Functionnal Theory (DFT), Transition, Metal Oxides.

Excitation of vortex core gyration in nanopillars through driven Floquet magnons

Gauthier Philippe*†[1] and Joo-Von Kim[1]

[1]Centre de Nanosciences et de Nanotechnologies (C2N) – Université Paris-Saclay, Centre National de la Recherche Scientifique, Centre National de la Recherche Scientifique : UMR9001 – 10 Boulevard Thomas Gobert, 91120, Palaiseau, France

Résumé

Magnetic vortices in ferromagnetic nanodisks support rich dynamical excitations, including low-frequency vortex core gyration and geometrically quantized azimuthal spin wave modes. When these degrees of freedom interact nonlinearly, time-periodic dynamics can emerge in the form of magnon Floquet states, manifested as frequency combs in the spin-wave spectrum. In this work, we present a combined theoretical and micromagnetic study of self-induced vortex core gyration in vortex-state nanopillars driven by high-frequency in-plane radio-frequency magnetic fields.
Using micromagnetic simulations of a 300-nm-diameter, 20-nm-thick ferromagnetic disk, we show that driving azimuthal spin wave modes can indirectly excite steady-state vortex core gyration above a finite threshold field. This self-induced mechanism gives rise to Floquet magnon frequency combs with spacing determined by the gyration frequency. We demonstrate that the onset and structure of these combs are strongly correlated with the gyration radius of the vortex core. Remarkably, for certain driving frequencies and amplitudes, multiple metastable gyration radii coexist, leading to distinct and history-dependent frequency comb spectra and implying hysteretic behavior.

To interpret these results, we extend the Thiele collective-coordinate model to include nonlinear three-particle scattering processes between azimuthal magnons and the gyrotropic mode. By parametrizing the resulting nonlinear interaction term using simulated Floquet spectra, the model quantitatively predicts thresholds, bifurcations, and the existence of multiple stable and unstable gyration orbits, in good agreement with full micromagnetic simulations. These findings highlight the central role of nonlinear magnon–core interactions in sustaining vortex dynamics and establish vortex-state nanopillars as a platform for studying Floquet magnetism and nonlinear spin-wave phenomena.

Acknowledgments
This work was supported by the European Commission's Research and Innovation Programme Horizon Europe under NIMFEIA Grant No. 101070290.

Mots-Clés: Floquet magnons, vortex dynamics, Frequency combs

*Intervenant
†Auteur correspondant: gauthier.philippe@universite-paris-saclay.fr

SOT on in-plane MTJ : experiment and device toy model

R. Pachat[1], M. Fiat[1], R. Soucaille[1], A. Solignac[1], C. Fermon[1], and M. Pannetier-Lecoeur[1*]

[1] SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France
*myriam.pannetier-lecoeur@cea.fr

Spin-orbit torque (SOT) is an energy-efficient tool to manipulate magnetization dynamics in spintronic devices. SOT is facilitated by the transfer of angular momentum of electrons from the lattice to the spin system, i.e., when a charge current flows parallel to an interface with broken inversion symmetry, spin-orbit coupling generates a spin density at the interface and/or generates transverse pure spin current in the nonmagnetic metal layer, exerting torque on the adjacent magnetic layer. Depending on its origin, the exerted torque could be field-like or damping-like, enabling various manipulations of magnetization dynamics. The emergence of SOT has shown fast and low power magnetization switching in magnetic tunnel junctions, offering a potential alternative for cache memory applications [1, 2], current-induced magnetization dynamics such as skyrmion motion [3, 4], chiral domain wall motion [5, 6], and oscillation [7]. In addition, the three-dimensional detection of magnetic fields without the need for multiple sensors has been enabled by a single SOT-magnetic field sensor [8]. Therefore, SOT emerges as a promising energy-efficient methodology for advancing spintronic devices.
In this work, an SOT layer is integrated to a Magnetic Tunnel Junction (MTJ) sensing device (see Fig. 1). We study the effect of the SOT on the magnetization of the free layer and on the MTJ sensing response. We also present a macrospin approach to model the whole stack in terms of magnetic moment as well as magnetotransport, with and without SOT component.

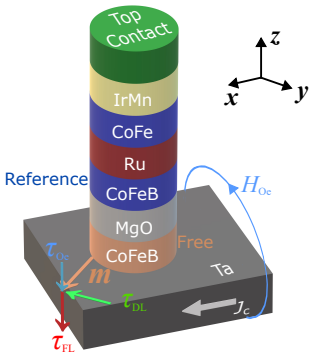


Figure 1. Figure 1: A schematic representation of the stack showing a charge current flowing through the Ta layer (current density J_c), generating an Oersted field H_{Oe} and the corresponding torque τ_{Oe}, as well as the distinct SOT components: fieldlike (τ_{FL}) and dampinglike (τ_{DL}) torques that act on the magnetization *m* of the CoFeB free layer.

References

[1] I. M. Miron *et al.* Nature, **2011**, 476, 189–193.
[2] M. Cubukcu, *et al*. Applied Physics Letters, **2014**, 104, 042406.
[3] W. Jiang *et al*. Science, **2015**, 349, 283–286.
[4] S. Woo *et al*. Nature Materials, **2016**, 15, 501–506.
[5] S.Emori *et al*. Nature Materials, **2013,**12, 611–616.
[6] K.S. Ryu *et al*. Nature Nanotechnology, **2013,** 8, 527–53.
[7] L. Liu *et al*. Science, **2012,** 336, 555–558.
[8] R. Li *et al*. Nature Electronics, 2021, 4, 179–184.

Interplay between Orbital Ordering, structural distortions and altermagnetism in ACrO3 Perovskites

Alejandro Gonzalez[1]
[1]Institut Neel
alejandro.gonzalez-pacheco@neel.cnrs.fr

Abstract:

Altermagnetism has recently been identified as a subgroup of standard antiferromagnets. Altermagnets shows zero net magnetization, however, unlike antiferromagnets, they exhibit a large, non-relativistic spin splitting of the electronic bands in momentum space (k-space). While typically altermagnetism has been associated with specific magnetocrystalline symmetries. In recent work, we show that in Ruddlesden-Popper chromates (Srn+1CrnO3n+1) [1,2] orbital ordering, rather than crystal symmetry, can serve as the primary driver for altermagnetic states.
Here, using first-principles calculations, we investigate the interplay between the d2 electronic configuration of Cr4+, Jahn-Teller distortions Orbital Ordering, and structural distortions. For SrCrO3, the alternating occupancy of dxz and dyz orbitals is sufficient to break the symmetry and induce spin splitting. However, due to the high-symmetry stacking of the perovskite layers, the spin splitting in adjacent layers is mutually compensated, resulting in an “anti-altermagnetic” state [2], where net spin-splitting vanishes. We then investigate how this picture evolves upon replacing Sr with Ca. In CaCrO3, the A-site cation stabilizes the Pnma, GdFeO3-type perovskite structure with pronounced CrO6 octahedral tilts, introducing an additional structural degree of freedom that couples to orbital and magnetic order. We show how the tilts hinder the interlayer compensation present in SrCrO3 and enable a finite net altermagnetic spin splitting to emerge.

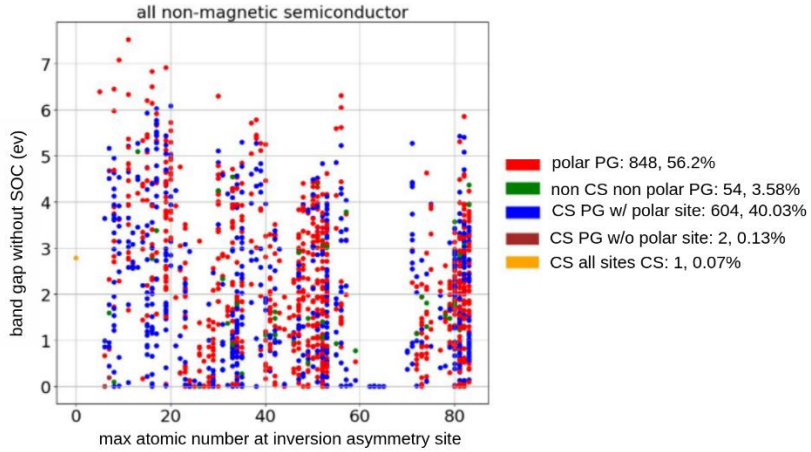
[1] S. Doyle, Q. N. Meier, et al. Orbital-driven altermagnetism in the ruddlesden-popper chromates. Phys. Rev. Mater.8,L071602, 2024.
[2] Q. N. Meier, A. Carta, C. Ederer, and A. Cano. Anti-altermagnetism and orbital ordering in transition metal oxides. arXiv preprint arXiv:2502.01515, 2025.

HIGH-THROUGHPUT SCREENING OF 2D RASHBA SEMICONDUCTORS

J. Yin[1*] , M. Chshiev[2] and T. Sohier[1]
1 Laboratoire Charles Coulomb (L2C), Université de Montpellier, CNRS, Montpellier, France
2 Univ. Grenoble Alpes, CEA, CNRS, Spintec, 38000 Grenoble, France
*junlin.yin@umontpellier.fr

Abstract:

Spintronic devices are seen as part of the next generation of microelectronic technology. Many of them rely on the spin-orbit effects. Thus, research on two-dimensional (2D) materials with large spin-orbit coupling (SOC) and specific spin textures is both necessary and fascinating. Among different types of spin-orbit coupling materials, the Rashba type attracts attention for the design of novel spintronic devices. Based on the Materials Cloud Two-Dimensional Structure Database (MC2D), we built a database of potentially large Rashba type SOC nonmagnetic semiconductor monolayer materials. To provide a deeper understanding and physical descriptor of the Rashba effect, we initially examine potential Rashba materials, focusing on their structures and point groups[1]. Among the most intriguing candidates, we carry out DFT+SOC calculations and analyze the orbital character of the band structures to uncover the microscopic origins of spin-splitting energy[2-4].



[1] Zhang Xiuwen, Liu Qihang, *Hidden spin polarization in inversion-symmetric bulk crystals*, Nature Physics, **10**, 387-393 (2014)
[2] K. V. Shanavas, Zoran S. Popović, *Theoretical model for Rashba spin-orbit interaction in d electrons*, Physical Review B, **90**, 165108 (2014)
[3] Lars Petersen, Per Hedegård, *A simple tight-binding model of spin–orbit splitting of sp-derived surface states*, Surface science, **459**, 49-56 (2000)
[4] Guilhem Manchon, Sumit Ghosh, *Semirealistic tight-binding model for spin-orbit torques*, Physical Review B, **101**, 174423 (2020)

High-throughput design of multiferroic tunnel junctions through geometric and compositional engineering of FM/FE interfaces

Augusto de Lelis Araújo[1*], Aurélien Manchon [1]
[1]Aix-Marseille Université, CNRS, CINaM, Marseille, France
*email of presenting author: augusto.de-lelis-araujo@cnrs.fr

Abstract:

The rational design of energy-efficient memory and logic devices is a central challenge for spintronic architectures and neuromorphic computing. Multiferroic tunnel junctions (**MFTJs**) based on two-dimensional van der Waals heterostructures constitute a promising platform to synergistically explore electrically controlled tunneling magnetoresistance (**TMR**) and tunneling electroresistance (**TER**) [1,2]. In this work, we are developing an automated high-throughput workflow based on the extension of the **SAMBA** [3] framework, originally created for the systematic construction of twisted bilayers. The extension of the code will allow us to generate and manipulate FM/FE interfaces and to explore multidimensional configurational spaces defined by composition and geometric degrees of freedom, including twist angles and lateral sliding. We expect these structural variations to act cooperatively in order to enable the modulation of interlayer coupling, symmetry breaking, polarization alignment, and magnetic proximity effects, leading to the reconstruction of the interfacial electronic structure and impacting spin-dependent transport [4]. By combining automated configurational scanning with first-principles calculations (DFT) and transport simulations, we aim to identify functional regimes favorable to tunneling control in heterostructures that are candidates for MFTJs. This strategy establishes computational foundations for the discovery and rational optimization of MFTJs based on vdW materials, positioning the geometric engineering of interfaces as a design parameter as relevant as composition [5]. The work connects automated materials exploration to device-oriented spintronic functionality, providing quantitative guidelines for future experimental implementations, in full alignment with the priorities of the **CNRS** and the initiatives of the **PEPR SPIN** (**France 2030**).

[1] M. Gajek, M. Bibes, S. Fusil, K. Bouzehouane, J. Fontcuberta, A. Barthélémy, and A. Fert, *Tunnel junctions with multiferroic barriers*, Nature Materials **6**, 296-302 (2007)

[2] H. Yang, S. O. Valenzuela, M. Chshiev, S. Couet, B. Dieny, B. Dlubak, A. Fert, K. Garello, M. Jamet, D.-E. Jeong, et al., *Two-dimensional materials prospects for non-volatile spintronic memories*, Nature **606**, 663-673 (2022)

[3] A. L. Araújo, P. H. Sophia, F. Crasto de Lima, and A. Fazzio, *A high-throughput framework and database for twisted 2D van der Waals bilayers***,** npj Computational Materials **12**, 40 (2025)

[4] Y. Su, X. Li, M. Zhu, J. Zhang, L. You, and E. Y. Tsymbal, *Van der Waals Multiferroic Tunnel Junctions*, Nano Letters **21**, 175-181 (2020)

[5] A. L. Araújo, F. Crasto de Lima, C. H. Lewenkopf, and A. Fazzio, *Design of spin-orbital texture in ferromagnetic/topological insulator interfaces***,** Physical Review B **109**, 085142 (2024)

Micromagnetic simulations of magnon-phonon coupling dynamics in CoFeB

Florian Millo[1*], Pauline Rovillain[1], Massimiliano Marangolo[1], Daniel Stoeffler[2]
[1]Sorbonne Université, CNRS, Institut des Nanosciences de Paris (INSP), F-75005 Paris, France
[2]Université de Strasbourg, CNRS, Institut de Physique et Chimie des Matériaux de Strasbourg, UMR 7504
*florian.millo@insp.jussieu.fr

The magnon-phonon coupling is possible by two phenomena called magnetoelasticity and magnetorotation, where the former links the elastic degrees of freedom with magnetization dynamics and the latter links the lattice rotations that phonons cause to the shape anisotropy of the magnetic film [1, 2]. The magnetization dynamics are driven by the surface acoustic wave (SAW) effective fields arising from the magnetoelastic (F_{mel}) and magnetorotation (F_{mrot}) energy terms. While SAW-driven magnetization dynamics have seen considerable experimental success, micromagnetic simulations that jointly accounts for both magnon-phonon coupling mechanisms remains unreported. In this work, for the first time, we demonstrate micromagnetic simulations using mumax3 [3] of magnon-phonon coupling dynamics in CoFeB. We find that the interplay among strain, rotation, and magnetic anisotropy gives rise to a particular parallel pumping configuration resulting in no excitation and no signal. In mumax3, we implement the additional energy density,

$$F_{\mathrm{mel+mrot}} = \left(B_{\mu\nu}\varepsilon_{\mu\nu} - \mu_0 M_s^2 \omega_{\mu\nu}\right) m_\mu m_\nu$$

where μ, ν representing x, y, z coordinates, $B_{\mu\nu}$ are the magnetoelastic constants ($B_{\mu\mu} = B_1, B_{\nu\nu} = B_2$), $\varepsilon_{\mu\nu}$ is the symmetric strain tensor and $\omega_{\mu\nu}$ is the skew-symmetric lattice rotation tensor. The quantity of interest that describes the magnon-phonon coupling at frequency f for an applied field B_0 making an angle ψ with the SAW propagation vector $\vec{k}_{\mathrm{SAW}}$ [Fig. 1a] is the power absorption $\Delta P(f, \psi, B_0) \sim \chi_{\mathrm{Polder}} \nabla_{m_\mu} F_{\mathrm{mel+mrot}}$.

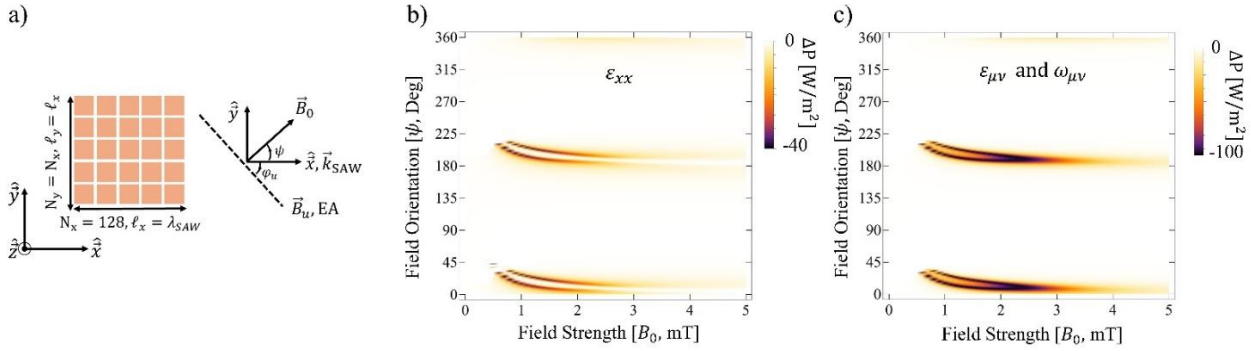


Figure 1: a) Geometry of the problem. At $B_u = 1.5$ mT and $\varphi_u = 105°$ // easy axis (EA), ΔP(f = 1.72 GHz) when: b) only longitudinal strain ε_{xx} and c) all terms of strain and rotation tensors are considered.

In Fig. 1b), we observe that the interplay between ε_{xx} and anisotropy B_u indicates a signature of a parallel pumping inefficient configuration i. e., $\Delta P = 0$ branch cuts at $\psi \approx 15°, 195°$ for $B_0 \geq 1$ mT. At these field orientations, the magnetoelastic field is collinear to the longitudinal magnetization hence unsuccessful to produce a torque. Moreover, the inclusion of all strain and rotation terms [Fig. 1c] closes this branch cuts and constrains the parallel pumping configuration at low B_0. Overall, we show that the magnon-phonon coupling dynamics reveal rich new dynamics which are realizable for future spintronic applications.

[1] C. Kittel., *Phys. Rev.*, 1958, *vol. 110*, 836–841.
[2] S. Maekawa et al., *AIP Conference Proceedings*, 1976, *vol. 29*, pp. 542–543.
[3] A. Vansteenkiste et al., *AIP Advances*, 2013, *vol. 4*, p.107133.

Harnessing Chromium Orbital Polarization for Ultra-Fast and Field-Free Magnetization Switching

Rodrigo Torrão Victor[1*], Guojun Lan[1,2], Pambiang A. Dainone[3], Armando Pezo[1], Yaohan Xu[1], Sophie Collin[1], Florian Godel[1], Yuan Lu[3], Nicolas Reyren[1], Henri Jaffrès[1], Jean-Marie George[1]

[1]Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau, France

[2]Laboratoire des Solides Irradiés, École Polytechnique, CEA/DRF/IRAMIS, CNRS, Institut Polytechnique de Paris, Palaiseau 91128, France

[3]Institut Jean Lamour, Université de Lorraine, CNRS, UMR 7198, 54011 Nancy, France

* rodrigo.torrao-victor@cnrs-thales.fr

Abstract:

Controlling magnetization via spin-orbit torques (SOT) is a promising pathways for advanced spintronic devices. Recent proposals integrate information processing, storage, and transmission through spin light-emitting diodes (spin-LEDs) where the light polarization is defined by the orientation of a magnetic layer controlled via SOTs [1]. However, device implementation requires SOT current below the LED's Schottky barrier requiring reduction of the critical current switching by SOT. It was recently proposed to use as a supplementary effect the orbital momentum of light element. However, the origin of this orbital polarization, which drives the enhancement in the SOT, is still an open discussion [2-5]. To address these challenges we experimentally probe the light metal Cr, capable of generating orbital momentum accumulation to increase SOT switching efficiency.

Using harmonic Hall measurements, we demonstrate that introducing a Cr layer into traditional heavy-metal-based systems (specifically CoFeB/W and Co/Pt) enhances damping-like torque efficiency by up to 5 times compared to heavy metals that rely solely on the spin Hall effect. This enhancement is attributed to an orbital polarization in Cr, which is efficiently converted into a spin current either in the heavy metal or the ferromagnetic layer, thereby exerting a stronger spin-orbit torque. The SOT magnetization switching threshold, evaluated via magneto-transport and Kerr microscopy, is considerably reduced due to the increase of the DL efficiency.

Our analysis reveals that the magnetization reversal initiates with domain nucleation followed by expansion, indicating that the switching mechanism is governed by domain-wall depinning rather than coherent macrospin rotation. Finally, we observe reproducible and deterministic magnetization reversal in the ultra-fast and field-free regimes, eliminating the need for external in-plane magnetic fields usually required in standard SOT geometries. Moreover, due to the lower resistivity of Cr compared to traditional heavy metals, a fourfold reduction in power consumption for magnetization switching was observed. This low-voltage operation is critical for preserving the integrity of sensitive interfaces establishing Cr as an effective orbital-torque material for low-power, ultra-fast, and field-free magnetization control.

[1] P. A. Dainone, N. Figueiredo, *Controlling the helicity of light by electrical magnetization switching*, Nature, **627,** 783-788 (2024).

[2] D. Lee, D. Go, *Orbital torque in magnetic bilayers*, Nature Communications, **12,** 6710 (2021).

[3] T. Valet, H. Jaffrès, V. Cros, and R. Raimondi, *Quantum kinetic anatomy of electron angular momenta edge accumulation*, Phys. Rev. Lett. **135**, 256301 (2025).

[4] D. Go, F. Freimuth, J.-P. Hanke, F. Xue, O. Gomonay, K.-J. Lee, S. Blügel, P. M. Haney, H.-W. Lee, and Y. Mokrousov, *Theory of current-induced angular momentum transfer dynamics in spin-orbit coupled systems*, Physical review research **2**, 033401 (2020).

[5] S. Lee, M.-G. Kang, D. Go, D. Kim, J.-H. Kang, T. Lee, G.-H. Lee, J. Kang, N. J. Lee, Y. Mokrousov, S. Kim, K.-J. Kim, K.-J. Lee, and B.-G. Park, *Efficient conversion of orbital hall current to spin current for spin-orbit torque switching*, Communications Physics **4**, 234 (2021).

Orbital relaxation and dipole-quadrupole coupling

A. Manchon[1], C. Sun[1]

[1] Aix-Marseille Univ, CNRS, CINaM, Marseille, France

aurelien.manchon@univ-amu.fr

Orbital angular momentum transport has recently emerged as a promising direction for beyond-spintronic technologies. Yet it raises a fundamental puzzle. Unlike spin—which is only perturbatively affected by spin–orbit coupling—the orbital moment couples strongly to the crystal field and is not a conserved quantity. This interaction is expected to quench the non-equilibrium orbital moment extremely rapidly, which appears incompatible with the long orbital diffusion lengths reported experimentally (up to 60 nm in Ti in Choi et al.). As a matter of fact, a recent theory [1] showed that orbital diffusivities in transition metals are one to two orders of magnitude smaller than spin diffusivities, consistent with experiments reporting values around 1–2 mm²/s. However, the mechanism of orbital relaxation remains unclear. In analogy with spin transport, strong disorder may compete with the crystal field and suppress relaxation via a D'yakonov–Perel' (DP)-like effect, yet this has lacked a transparent analytical demonstration and accurate examination. Because the orbital moment is not a good quantum number, perturbative approaches fail, leaving no controlled framework for understanding long-range orbital transport.

In this poster, I will present a recently-developed fully nonperturbative analytical formalism that resolves this difficulty and yields exact orbital relaxation dynamics for a model t_{2g} crystal-field environment [2]. Our method is valid across the entire disorder range, revealing a clear crossover between DP-like and Elliott–Yafet (EY)–like regimes. Furthermore, lowering the crystal field symmetry, we uncover a dipole–quadrupole coupling that produces oscillatory relaxation—a qualitative departure from spin dynamics that suggests unique multipolar orbital transport signatures [3].

[1] Ning *et al.*, *Orbital Diffusion, Polarization, and Swapping in Centrosymmetric Metals*, Physical Review Letters **134**, 026303 (2025).

[2] Manchon *et al.*, *Multipolar orbital relaxation of the t_{2g} states*, arXiv:2512.06355 (2025).

[3] Sun *et al.*, *Interfacial orbital transmission, conversion, and mechanical torque in metals,* arXiv:2602.17220 (2026).

Sp-d + Diffusive model for simulation of spintronic heterostructured devices

***P. Chailloleau*[*,1], *Q. Remy*[2], *H. Jaffrès*[3], *M. Hehn*[1], *S. Mangin*[1]**

1. *Université de Lorraine, CNRS, IJL, Nancy F-54000, France*
2. *Department of physics, Freie Universität Berlin, 14195 Berlin, Germany*
3. *Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau, France*

*pierre.chailloleau@univ-lorraine.fr

Abstract:

When exposed to a femtosecond laser pulse, ferromagnetic materials exhibit an ultrafast demagnetization process occurring within a few hundred femtoseconds — one of the fastest magnetic phenomena ever observed. Understanding this mechanism is crucial for the development of next-generation spintronic devices, where speed and energy efficiency are central challenges.

The aim of this project is to improve the theoretical understanding and numerical simulation of spintronic devices driven by ultrafast demagnetization, with a particular focus on spin valves & THz emission. To this end, we develop a phenomenological framework based on the sp–d exchange model [1,2], extended to include diffusive spin transport [3] and a detailed description of interfacial dynamics[4]. Our approach self-consistently couples magnetization dynamics, thermal processes, and spin currents, allowing us to capture the interplay between localized spins and itinerant electrons across multilayer structures.

First applications of the model to spin-valve configurations yield very encouraging results, showing good agreement with available experimental data and highlighting the key role of spin-dependent transport in the ultrafast regime. However, comparisons with THz emission experiments reveal limitations of a purely diffusive description, suggesting that ballistic electron contributions may play a significant role at sub-picosecond timescales.

These findings not only validate the robustness of the theoretical framework but also point toward necessary extensions of the model. Ongoing work aims at incorporating ballistic transport effects and extending the approach to ferrimagnetic compounds and other spintronic architectures, ultimately providing a predictive tool for ultrafast spintronic device design.

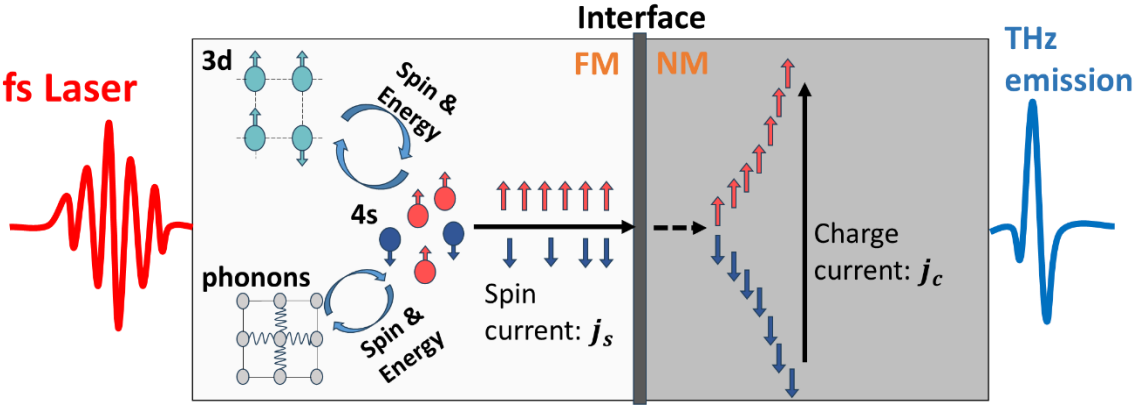


Figure: Scheme of the modeled phenomena in the case of THz emission

[1] Beens, M. ; Duine, R. A. ; Koopmans, B.: *s − d model for local and nonlocal spin dynamics in laser-excited magnetic heterostructures*. In: *Physical Review B* Bd. 102 (2020), Nr. 5, S. 054442

[2] Remy, Quentin: *Ultrafast spin dynamics and transport in magnetic metallic heterostructures*, Université de Lorraine, 2021

[3] Kimling, Johannes ; Cahill, David G.: *Spin diffusion induced by pulsed-laser heating and the role of spin heat accumulation*. In: *Physical Review B* Bd. 95 (2017), Nr. 1, S. 014402

[4] Dang, T. H. ; Hawecker, J. ; Rongione, E. ; Baez Flores, G. ; To, D. Q. ; Rojas-Sanchez, J. C. ; Nong, H. ; Mangeney, J. ; u. a.: *Ultrafast spin-currents and charge conversion at 3 d -5 d interfaces probed by time-domain terahertz spectroscopy*. In: *Applied Physics Reviews* Bd. 7 (2020), Nr. 4, S. 041409

Frustrated out-of-plane Dzyaloshinskii-Moriya interaction and the onset of atomic-scale 3*q* magnetic textures in 2D Fe_3GeXTe (X = Te, S, Se) monolayers

Rabia Caglayan[1†], Louise Desplat[2*†], Sergey A. Nikolaev[3], Fatima Ibrahim[2] , Jing Li[4], Yesim Mogulkoc[5], Aybey Mogulkoc[1], and Mairbek Chshiev[2]

[1] Department of Physics, Faculty of Science, Ankara University, 06100, Ankara, Turkey
[2] Universite Grenoble Alpes, CEA, CNRS, Grenoble INP, SPINTEC, 38000 Grenoble, France
[3] University of Osaka, Toyonaka, Osaka 560-8531, Japan
[4] Universite Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
[5] Department of Physics Engineering, Faculty of Engineering, Ankara University, 06100, Ankara, Turkey
*email of presenting author: louise.desplat@cea.fr
† equal authors contributions

Abstract:

The recent discovery of long-range magnetic order in 2D materials has stimulated new and exciting research on exotic 2D spin physics and the potential for applications in 2D spintronics. Among the rising number of reported 2D magnets, Fe_3GeTe_2 (FGT) stands out as a strong candidate, due to its unique magnetic properties, a relatively high Curie temperature, and perpendicular magnetic anisotropy, making it promising for spin-orbitronics.

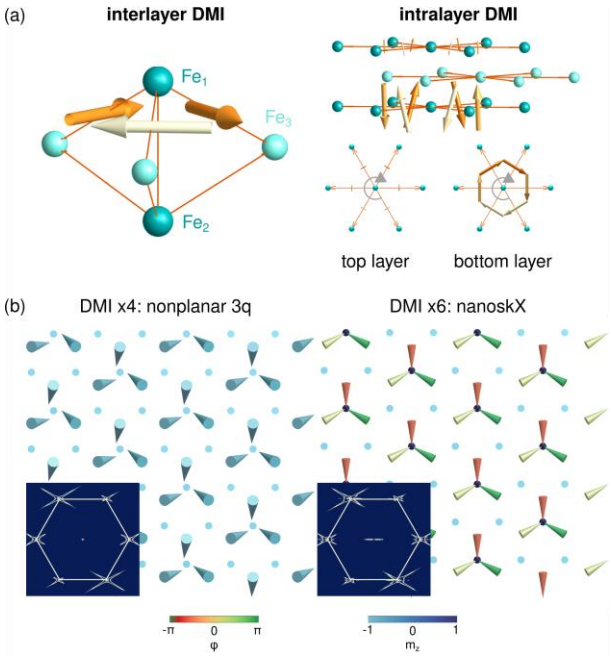


Figure 1: In FGTS, (a) anatomy of the DMI between first nearest neighbors, (b) example 3*q* ground state for different scaling factors of the DMI. The insets show the Fourier transform of the magnetization.

Magnetic skyrmions, topological spin textures at the nanoscale envisioned as potential information carriers in applications, were recently observed in FGT flakes [1], for which various stabilization mechanisms were reported. Skyrmions are typically stabilized by the interplay of the in-plane Dzyaloshinskii-Moriya interaction (DMI) with exchange and anisotropies. In pristine FGT, uncompensated in-plane DMI is forbidden by symmetry, and only out-of-plane components remain [2]. The latter were shown not to impact the stabilization of skyrmions, and have often been neglected in theoretical studies. The sough-after in-plane DMI in 2D materials can be induced by proximity effects in heterostructures, or through Janus structures, where the out-of-plane symmetry is broken by different elements in the top and bottom layers [3].

In this work [4], we study the effect of in- and out-of-plane DMI in Fe_3GeXTe (X=Te, Se, S) monolayers, where X=S, Se are Janus structures. We perform atomistic spin simulations with the extended Heisenberg Hamiltonian parametrized by first-principles calculations. While we find that the base DMI in these systems is not large enough to stabilize noncollinear states, we uncover how the frustrated out-of-plane DMI, as sketched in Fig. 1(a) for FGTS, favors atomic-scale, 3*q* magnetic states at the edge of the first Brillouin zone. We study the effect of tuning the DMI in the three systems, which can be achieved via applied strain or electric field, and report the onset of various 3*q* magnetic ground states under experimentally realistic scaling factors as low as 3, with some configurations reminiscent of a ‘‘nanoskyrmion’’ lattice (Fig. 1(b)). Our work adds another layer to the list of already reported exotic phenomena of spin physics in FGT.

[1] B. Ding *et al*., Observation of magnetic skyrmion bubbles in a van der Waals ferromagnet Fe_3GeTe_2, Nano Lett., **20**, 868 (2019) ; Y. Wu et al., Neel-type skyrmion in WTe_2/Fe_3GeTe_2 van der Waals heterostructure, Nature Commun. **11**, 3860 (2020) ; T. Park et al, *Neel-type skyrmions and their current-induced motion in van der Waals ferromagnet-based heterostructures*, Phys. Rev. B 103, 104410 (2021)
[2] S. Laref, K.-W. Kim, and A. Manchon, *Elusive Dzyaloshinskii-Moriya interaction in monolayer Fe_3GeTe_2*, Phys. Rev. B, **102**, 060402 (2020)
[3] J. Liang *et al*., *Very large Dzyaloshinskii-Moriya interaction in two-dimensional Janus manganese dichalcogenides and its application to realize skyrmion states*, Phys. Rev. B, **101**, 184401 (2020)
[4] R. Caglayan, L. Desplat *et al*., *Frustrated out-of-plane Dzyaloshinskii-Moriya interaction and the onset of atomic-scale 3q magnetic textures in 2D Fe_3GeXTe (X = Te, S, Se) monolayers*, in preparation (2026)