Modeling the dynamics of coupled magnetic tunnel junctions

Arthur Courberand: contribution to Spintheory project

Ajay Jha (SPINTEC), Ricardo Sousa (SPINTEC), Joo-Von Kim (C2N), Ursula Ebels (SPINTEC), Liliana D. Buda-Prejbeanu (SPINTEC)

Career

Bachelor Physics-Chemistry-Mathematics-Mechanics
Université Grenoble Alpes 2019-2022

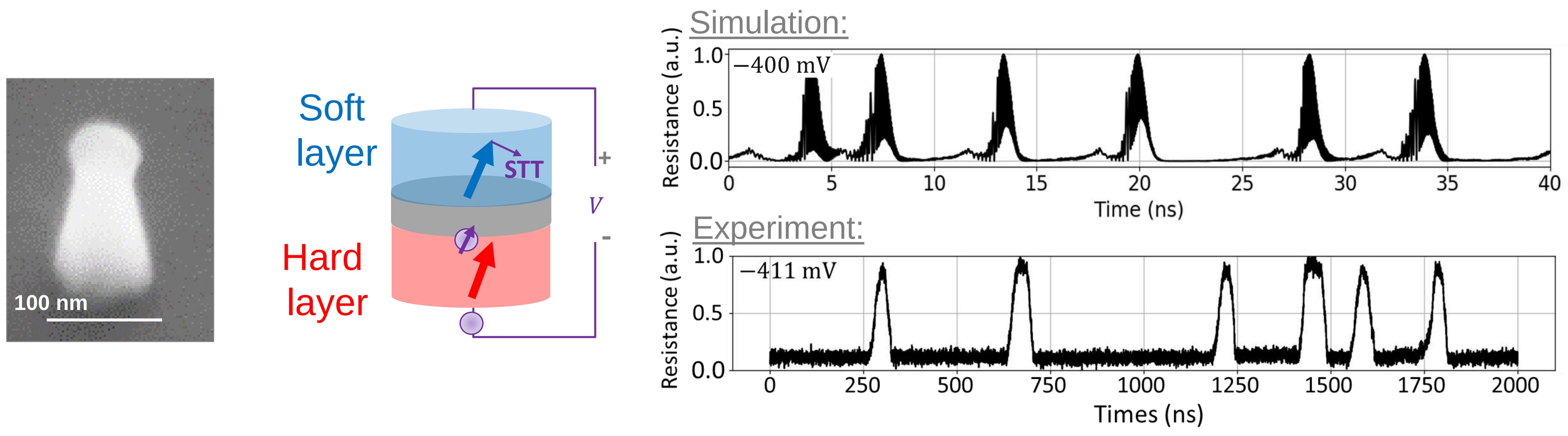
Master Nanophysics and Quantum Physics
Université Grenoble Alpes 2022-2024

UGA Université Grenoble Alpes

International Master specialized on semiconductors, spintronics, magnetism, and quantum physics
Practical training in nanofabrication and simulation.

Coupled spiking neurons

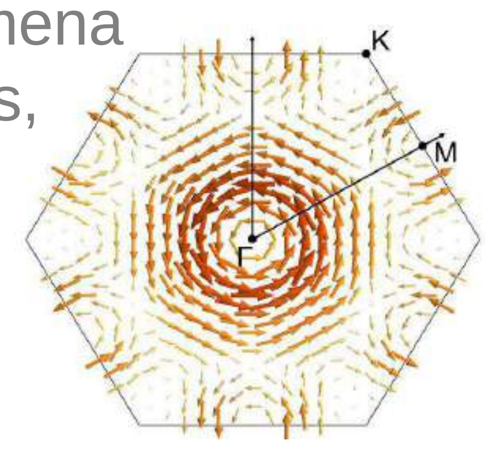
Dual free layer magnetic tunnel junction under DC current bias exhibit a spiking behavior similar to that of a biological neurons.



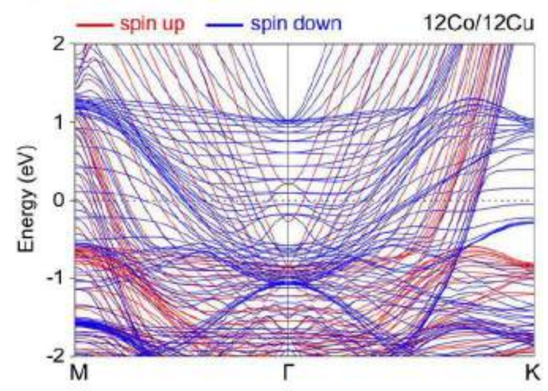
This spiking behavior can be harnessed for neuromorphic computing. Achieving this objective requires characterization of individual devices and of the coupling mechanisms between junctions.

SPINTHEORY

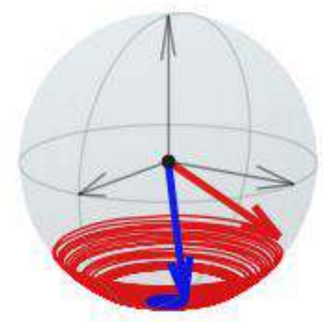
Spintheory: Project dedicated to spintronics theory, combining analytical approaches and numerical simulations to study spin-dependent phenomena in magnetic materials and spintronic systems, focusing on the link between electronic structure, transport, and magnetism.



The research covers different scales, from first-principles DFT calculations and atomistic simulations of magnetic materials to spin transport, spin dynamics, spin-orbit phenomena, and magnetic textures.

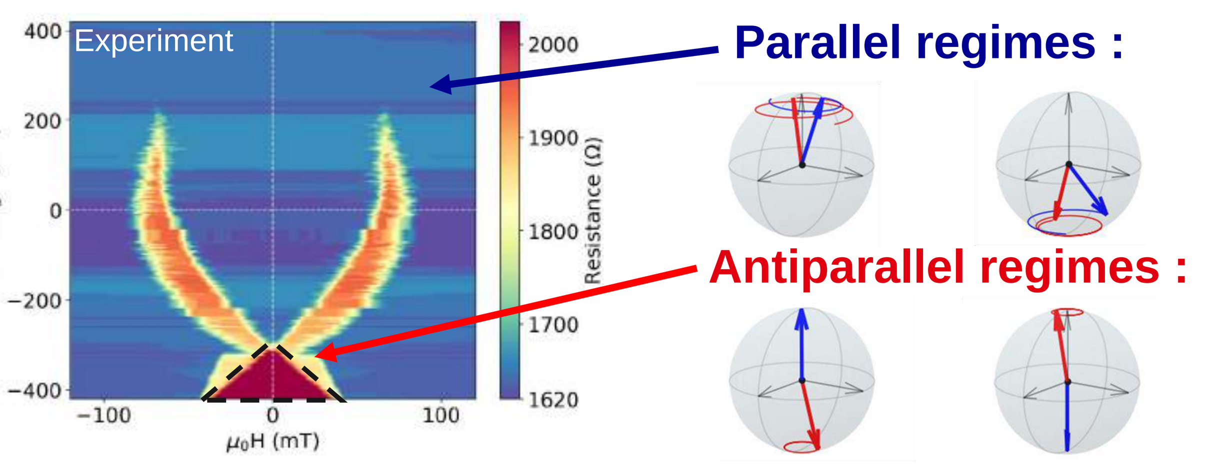


My PhD project is part of WP5 and focuses on spin dynamics, as it involves the use and development of solvers for macrospin modeling of MTJs. “Flexspin” program is designed with versatility, enabling the simulation of different junction configurations and various types of layers.

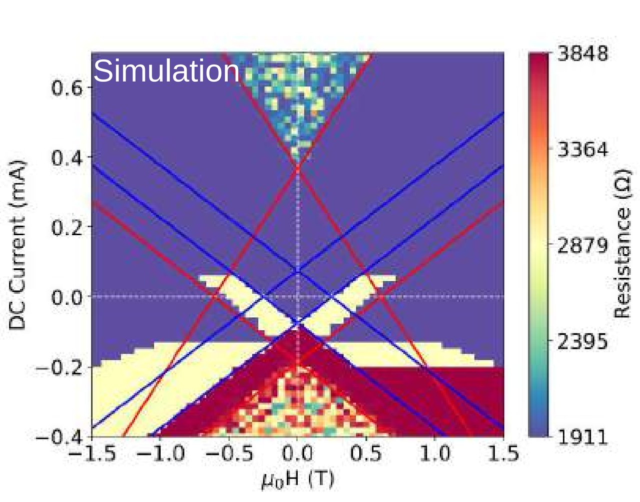


Stability diagram / Coupled magnetic tunnel junction

Single MTJ with dual free-layer is characterized by field-voltage state diagrams.

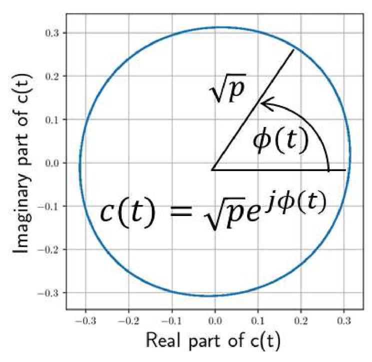


Though macrospin simulation the same regimes can be observed and identified.



c-model

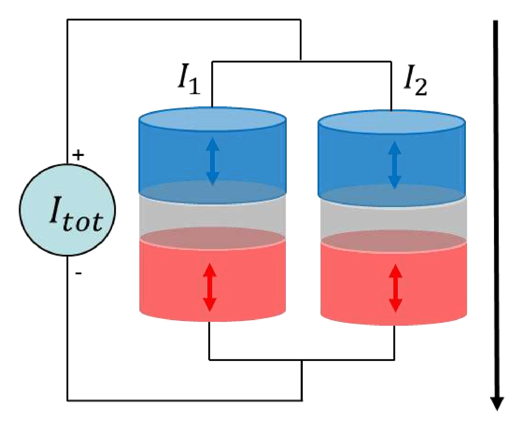
$$c = \frac{m_x - i m_y}{\sqrt{2(1+m_z)}}$$



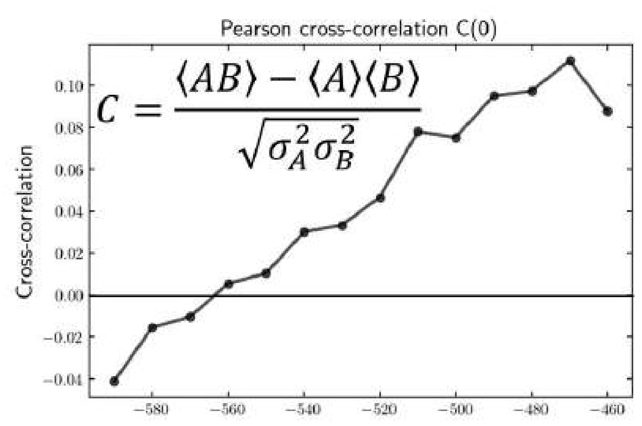
Stability condition

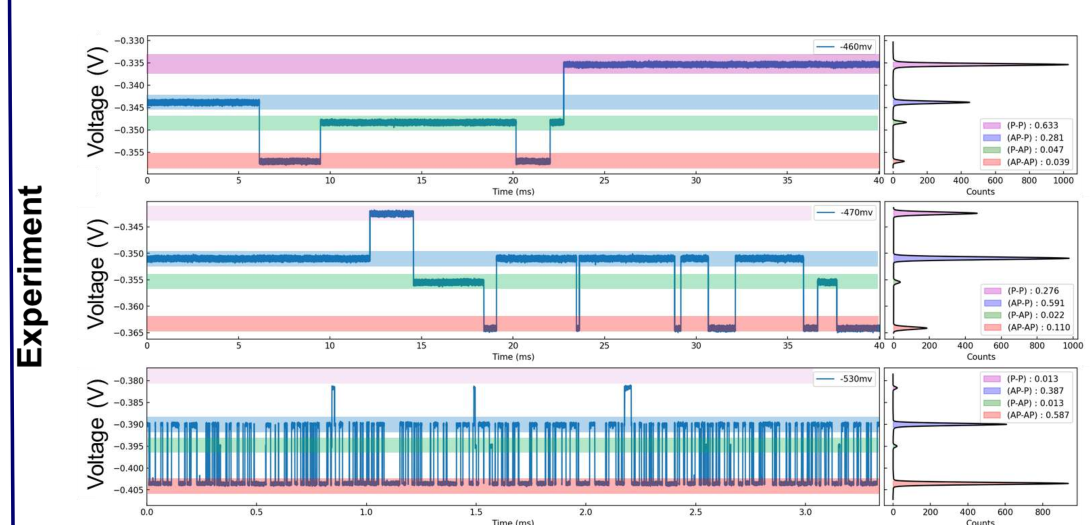
$$H \leq m_P \left(\frac{a_{DL} I R}{\alpha}\right) + m_L (H_k + H_{Dz})$$

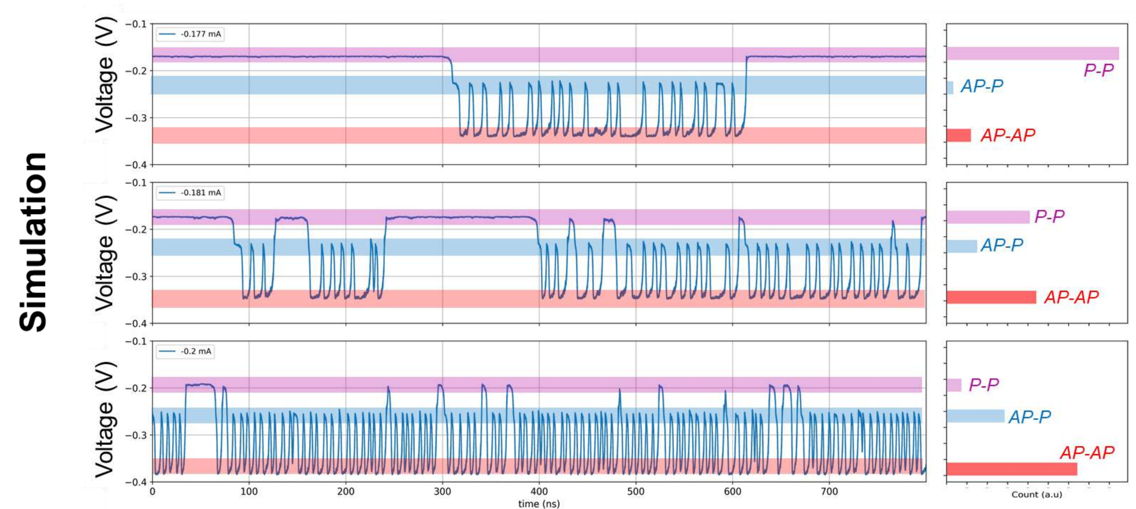
Two MTJs electrically connected in parallel share the total current, causing the current through each junction to depend on the resistive state of the other.



When the two MTJs are non-identical, four distinct resistive levels emerge, whose occupation can be controlled by adjusting the applied current. This behavior is successfully reproduced in simulations, while cross-correlation analysis highlights the mutual influence between the two junctions.







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Scan to discover the website

Acknowledgments:

Spintheory : ANR-22-EXSP-0009 https://anr.fr/ProjetIA-22-EXSP-0009

Orbital Current Effects on Magnetization and Magnetic Textures

Project coordinator: Stanislas ROHART, CNRS/LPS (stanislas.rohart@universite-paris-saclay.fr)

Greis Cipi[1] and Stanislas Rohart

[1] : Laboratoire de Physique des Solides (LPS), CNRS / Université Paris-Saclay

Academic path

Bachelor degree in Physics at Alma Mater Studiorum - Università di Bologna

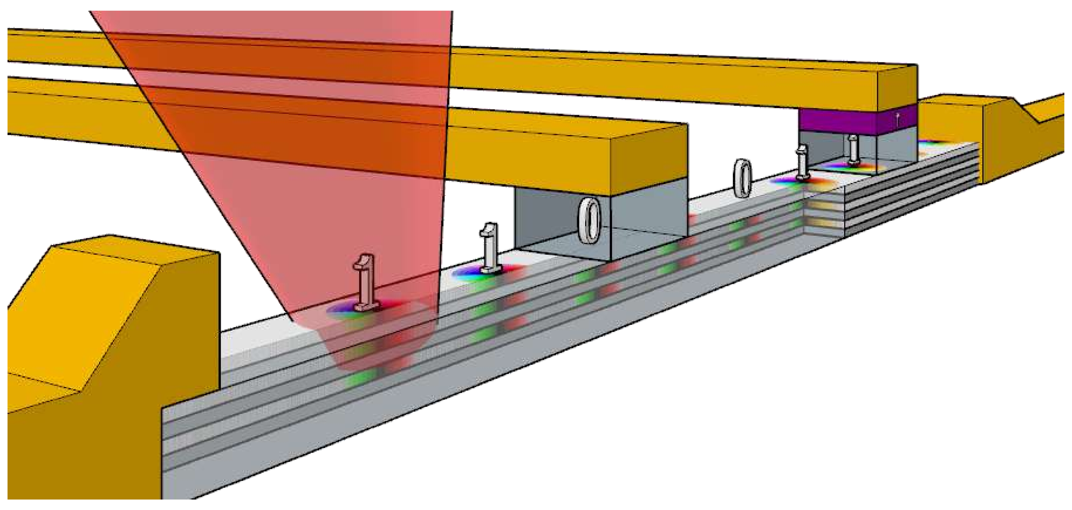
Double Master degree:

1. Material Physics and Nanoscience at Alma Mater Studiorum - Università di Bologna
2. Sciences des matériaux et nano-objets at Sorbonne Université

Currently: PhD @ LPS within PEPR-SPIN CHIREX

CHIREX: Beyond CMOS with Chiral textures

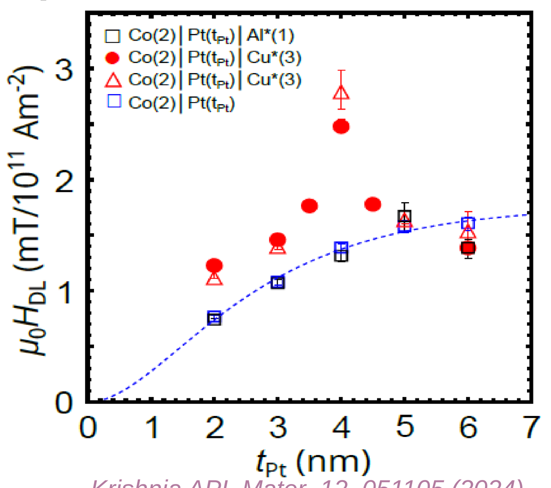
The objective of Chirex is to integrate the progresses on chiral texture current induced manipulation in advanced spintronic component. This includes domain walls, skyrmions and 3D texture interconversion, manipulation using current, electric field and light, and integrated electrical read-out.



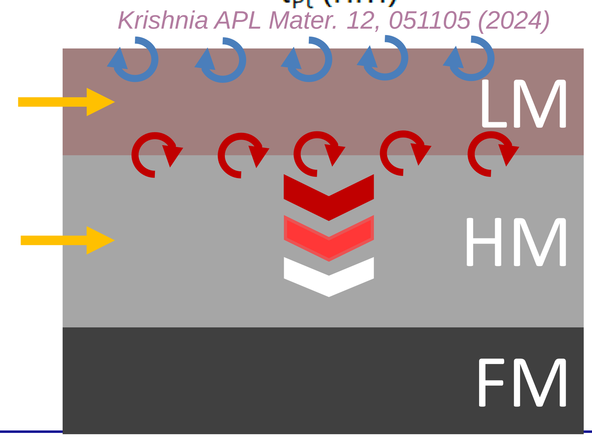
Orbital physics in spintronics

The Spin-orbit coupling (SOC) modified the way we understand and describe magnetism:

1. It induces the DMI ⇒ chiral magnetic textures
2. It created a new mechanism to generate spin current ⇒ the SOT



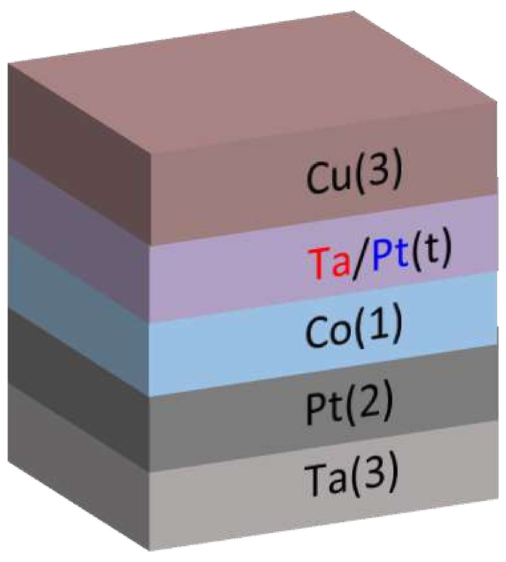
Krishnia APL Mater. 12, 051105 (2024)

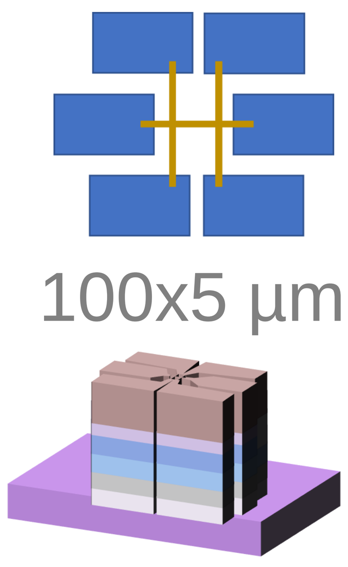


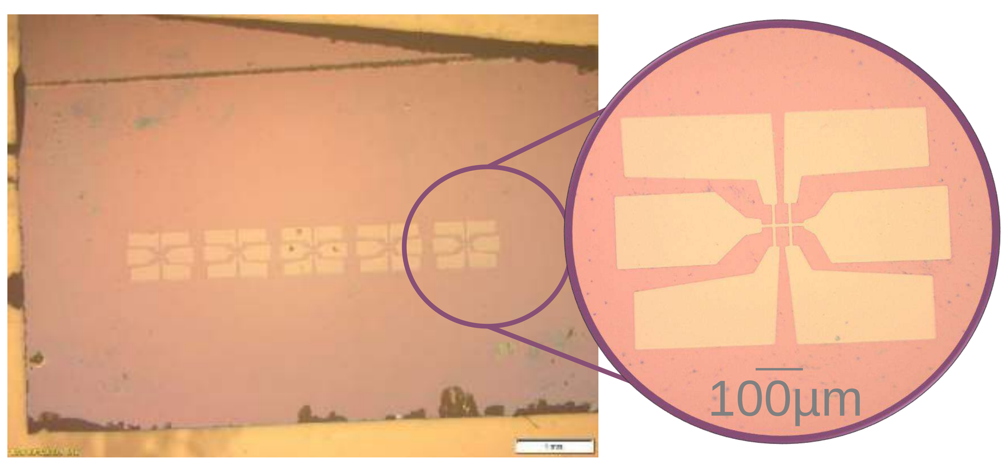
Investigation of the heavy-metal layer in the orbital-to-spin current conversion

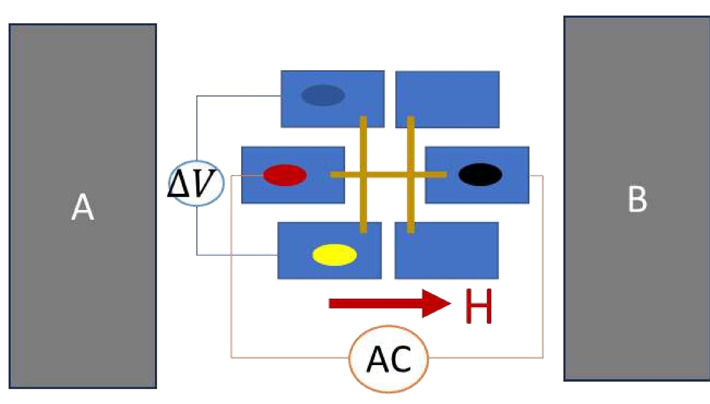
The goal now is to:

1. Go beyond the SOT and investigate the role of the orbital angular momentum
2. See the effect on the magnetic texture motion

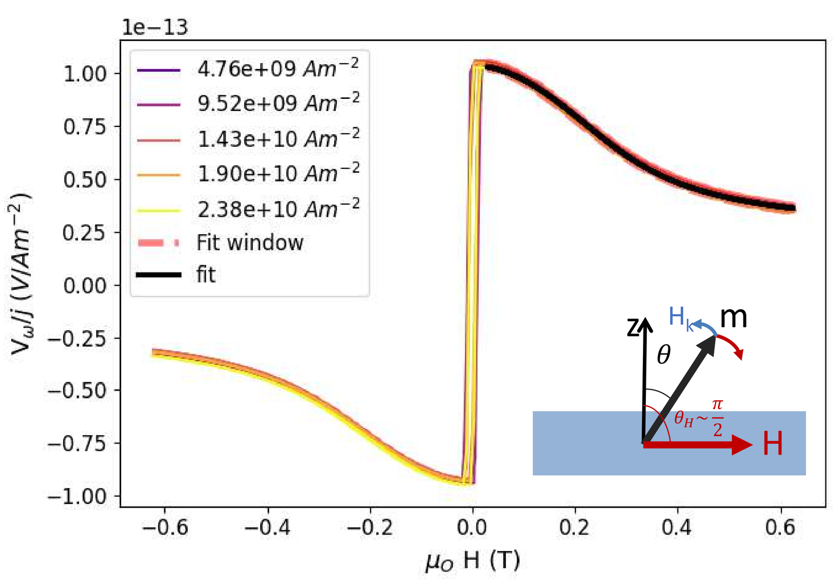


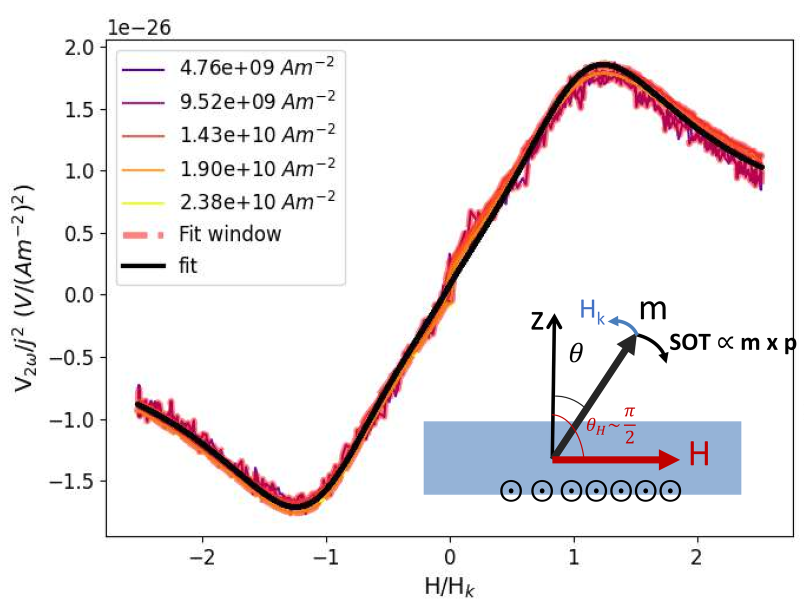




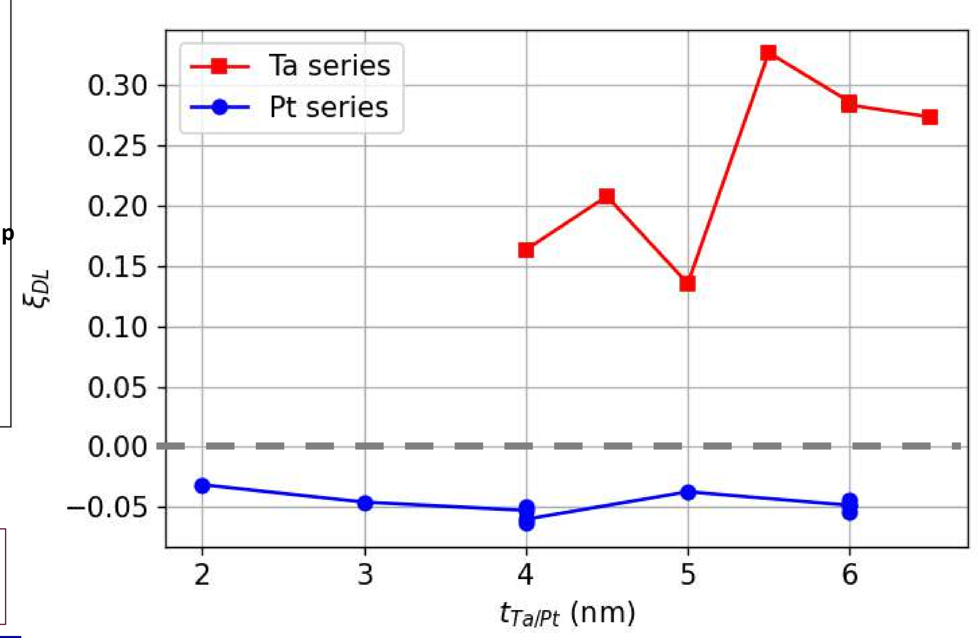


$$\xi_{DL} = \frac{j_S^{eff}}{j_C} = M_s t \frac{\mu_0 H_{DL}}{j_C} \frac{2\,e}{\hbar}$$





SOC directly controls the conversion mechanism



Greis Cipi, PhD student within the PEPR SPIN CHIREX framework at Laboratoire de Physique des Solides

EPR SPIN CHIREX aims to develop next-generation spintronic devices by using magnetic textures such as skyrmions and chiral domain walls. The project involves major French research institutions like CNRS, CEA, Centre de Nanosciences et de Nanotechnologies (Université Paris-Saclay), and Institut Jean Lamour (Université de Lorraine).

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FRANCE 2030 PROGRAMME DE RECHERCHE SPINTRONIQUE

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Ferromagnetic oxide nanosheets for Spintronics applications

Dorian MORLEY (dorian.morley@univ-rennes.fr), CNRS, 3rd year PhD Student in SPINMAT Project

IPR, CNRS, Rennes Université, UMR 6251: Pascal TURBAN*, Jean-Christophe LE BRETON*, Madeleine GHOBAR, Alain MOREAC, Bruno LEPINE
ISCR, CNRS, Rennes Université, UMR 6226: Valérie DEMANGE, Thierry GUIZOUARN, Mathieu PASTUREL, Yann THOMAS, Victor POREE
ScanMAT, CNRS, Rennes Université, UAR 2025: Ludivine RAULT, Loïc JOANNY, Francis GOUTTEFANGEAS
GeePs, CNRS, Université Paris-Saclay, UMR 8507: Sylvain LE GALL, Pascal CHRETIEN
OptiMAG, Brest University, UR 938: David SPENATO, David DEKADJEVI, Jean-Philippe JAY
CEMCA, CNRS, Brest University, UMR 6251: Alexandre LEBON

Carrier path – 3rd year PhD Student

Education:

- 2018 – Materials Sciences Technological degree (DUT) at Nantes IUT
- 2021 –Bachelor in Physics of Nantes Université
- 2023 – Master in Nanosciences of Rennes Université and Nantes Université

Skills :

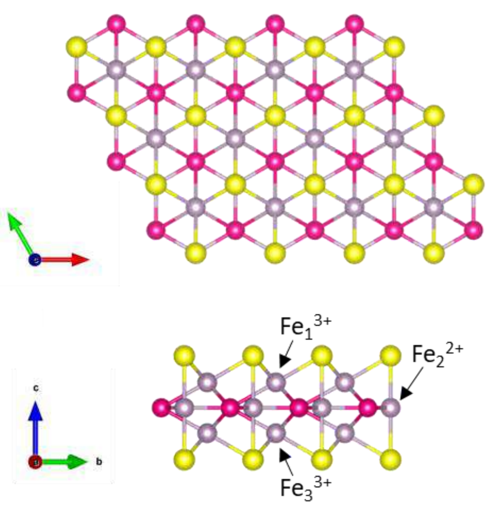
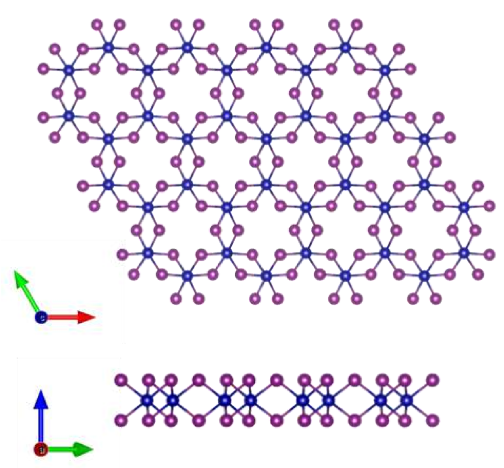
Linkedin:

- Magnetic characterizations
- Electrical measurements
- 2D Materials (Exfoliation, Transfer)
- Optical lithography
- Material synthesis and characterizations

Contact: dorian.morley@univ-rennes.fr

SPINMAT Project

Introduction of 2D magnetic materials as emerging solutions for spintronics devices.

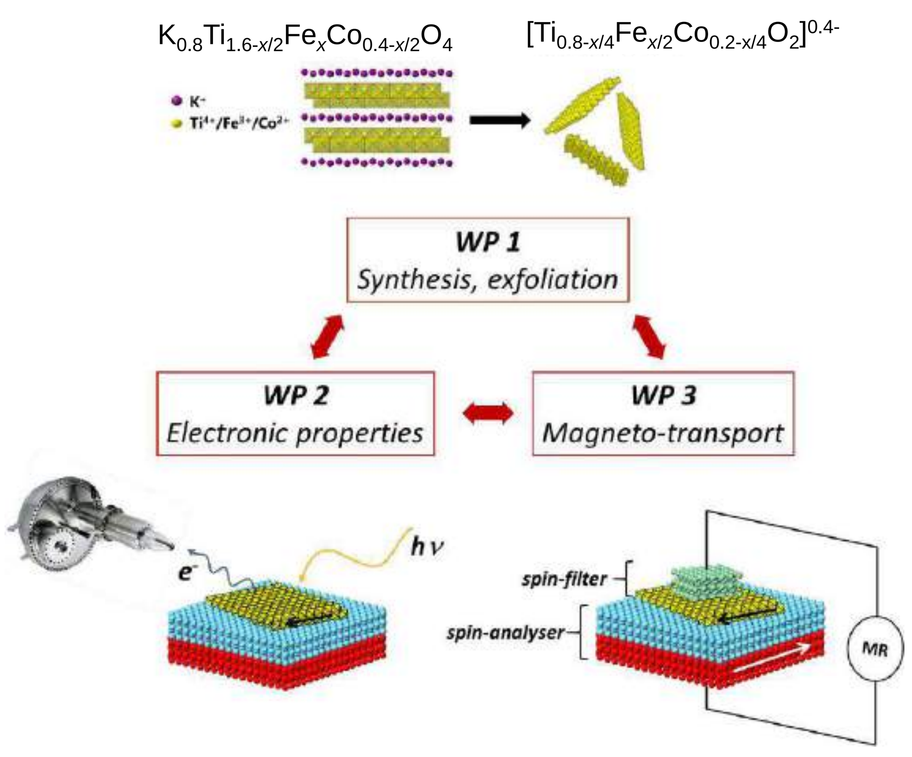
Fe_3GeTe_2		CrI_3	
	2D FM metal T_C (1L) = 130 K Tape exfoliation or MBE Air stability (1L) << 1 day		2D FM semiconductor T_N (1L) = 45 K Tape exfoliation Air stability (1L) few minutes

Huang, *Nature*, 2017 — Fei, *Nature Mater*, 2018

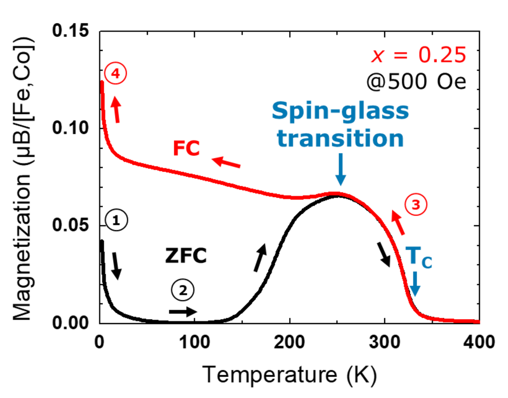
Our objectives in the SPINMAT project :

- Development of novel 2D ferromagnetic insulator with Curie point above room-temperature and air-stability
- Integration and test in MTJs → 2D spin-filter

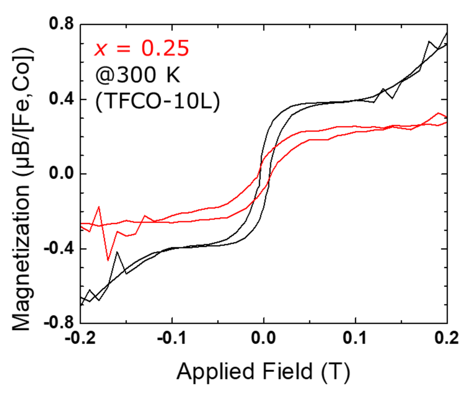
TFCO-ONS: a room-temperature 2D ferromagnet



SPINMAT + ONSET ANR Project



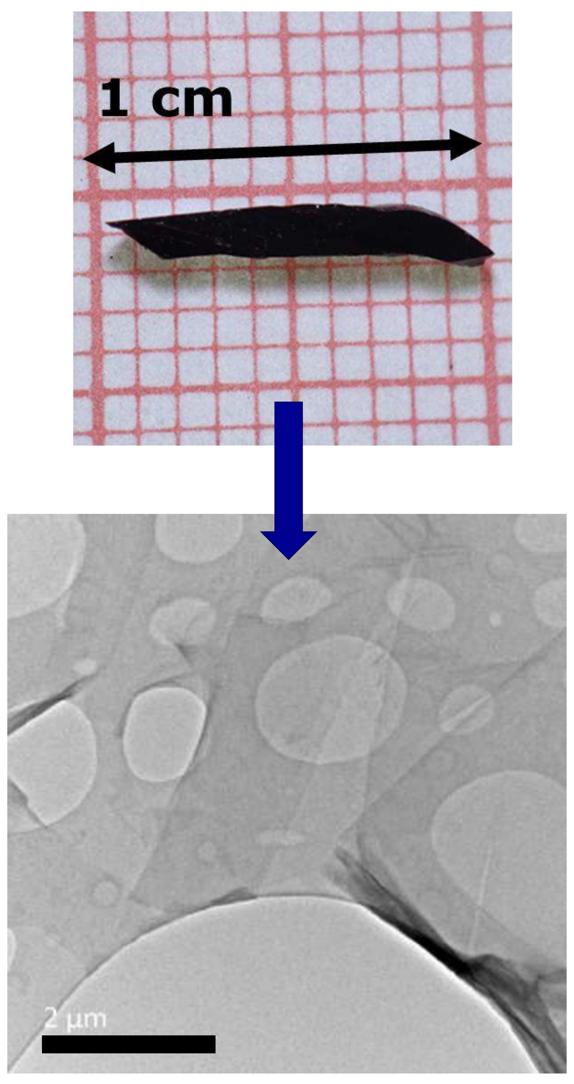
KTFCO: High-temperature Spin Glass



TFCO-ONS: Room-Temperature 2D Ferromagnet

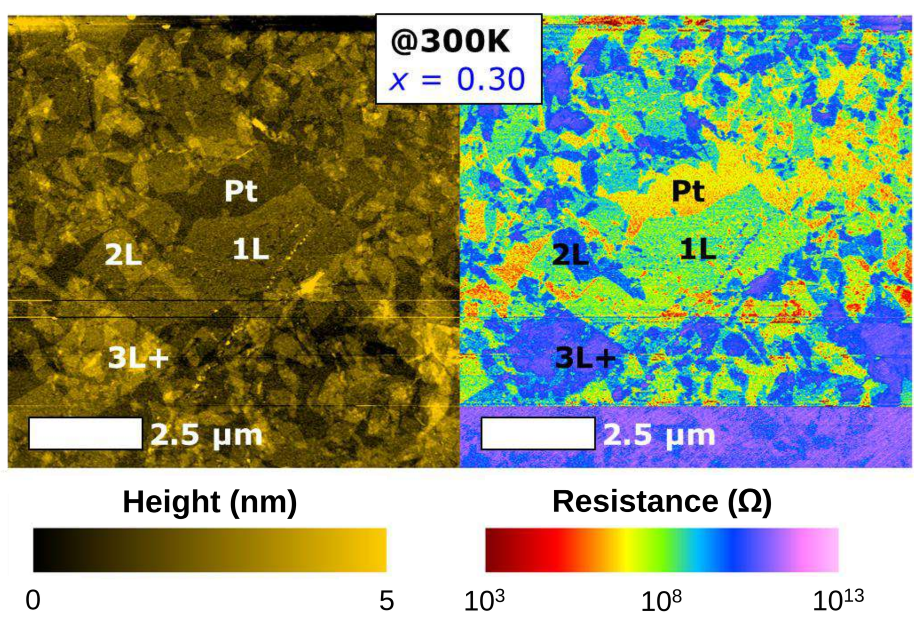
Latest results about the development of $K_{0.8}Ti_{1.6-x/2}Fe_xCo_{0.4-x/2}O_4$ layered single-crystals and $[Ti_{0.8-x/4}Fe_{x/2}Co_{0.2-x/4}O_2]^{0.4-}$ 2D materials

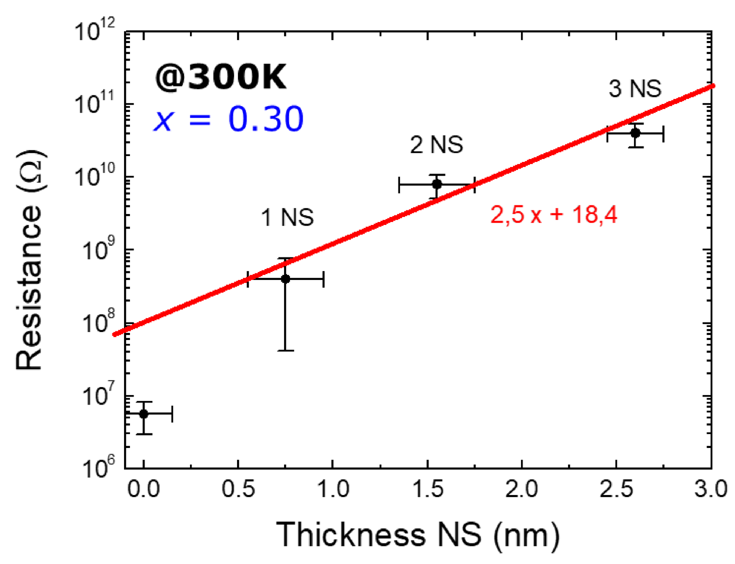
Solid-state reaction + Flux growth:



Lateral dimensions > 10 μm

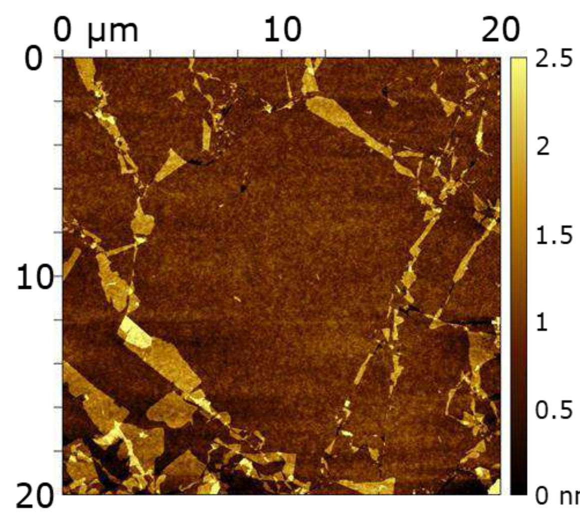
Insulating behavior:



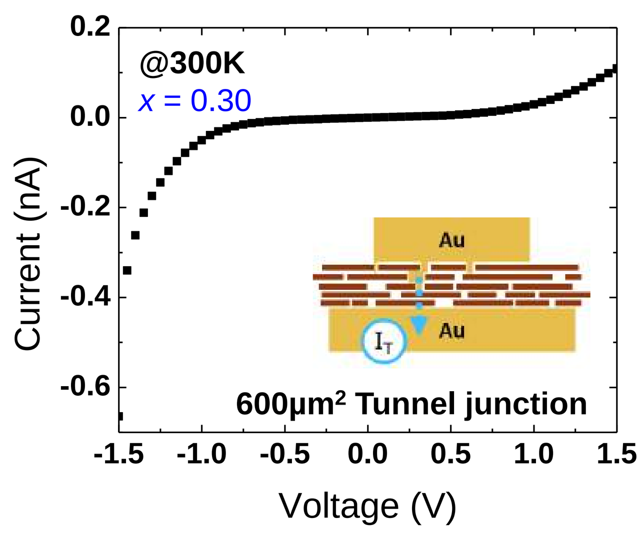


Semiconductor (1.6-1.9 eV gap) confirmed with STS

Layer by layer ONS transfer (drop casting):



ONS-based tunnel junctions:



Scan to discover PEPR SPIN website

The authors thank the France 2030 PEPR SPIN program in the framework of the SPINMAT project (ANR-22-EXSP-0007) and the French "Agence Nationale de la Recherche" (ANR) in the framework of the ONSET project (ANR-22-CE09-0010).

Local contacts: *Jean-Christophe LE BRETON (CNRS Researcher, IPR, Rennes) jean-christophe.lebreton@univ-rennes.fr
*Pascal TURBAN (Professor, IPR, Rennes) pascal.turban@univ-rennes.fr

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Towards Surface Acoustic Wave-driven Spin Wave emission for low-power magnonic devices

A. Sharma, **F. Millo, C. Gourdon, L. Thevenard, P. Rovillain, M. Marangolo**

Institut des Nanosciences de Paris, Sorbonne Université, France

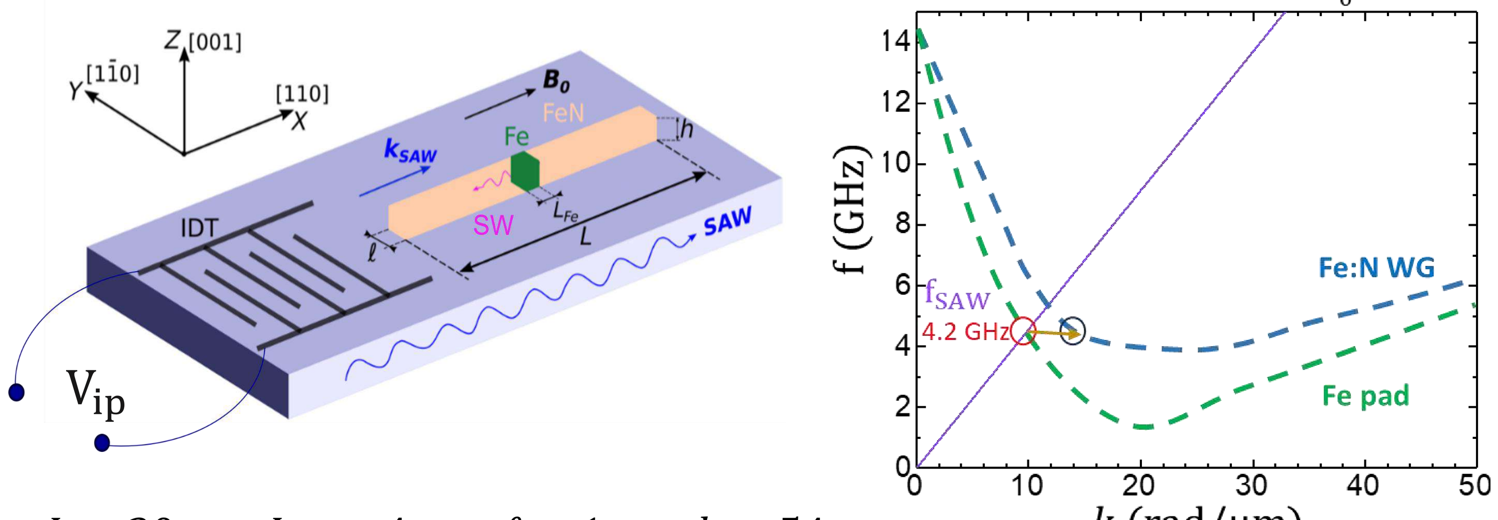
Objectives of my PhD:

- **Tuning of SAW-SW coupling via N-implantation in Fe thin films**
- **Fabrication of the state-of-art device for remote and resonant excitation of SWs**

My academic background

- **Masters in Physics**: Sorbonne Université, France (M2 Science des Matériaux et des Nano-Objets)
- **Bachelors in Physics:** Tezpur University, India

State-of-art device

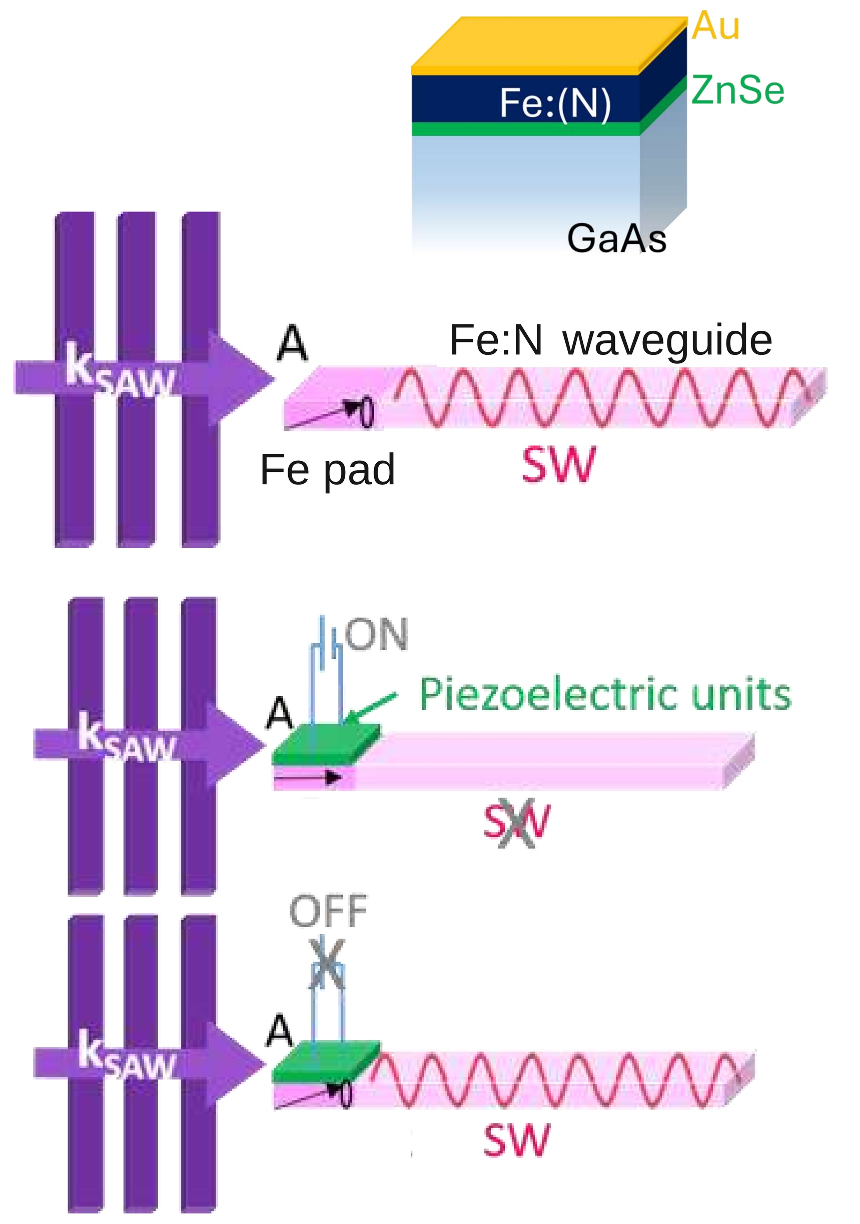


$L = 30\mu m;\ L_{fe} = 4\ \mu m;\ \ell = 1\ \mu m;\ h = 54\ nm$

To excite SW mode (f,k) only in Fe pad, not in Fe:N waveguide

Spin Waves for advanced signal processing (SWING)

To mitigate SW attenuation via SAW–SW hybridization

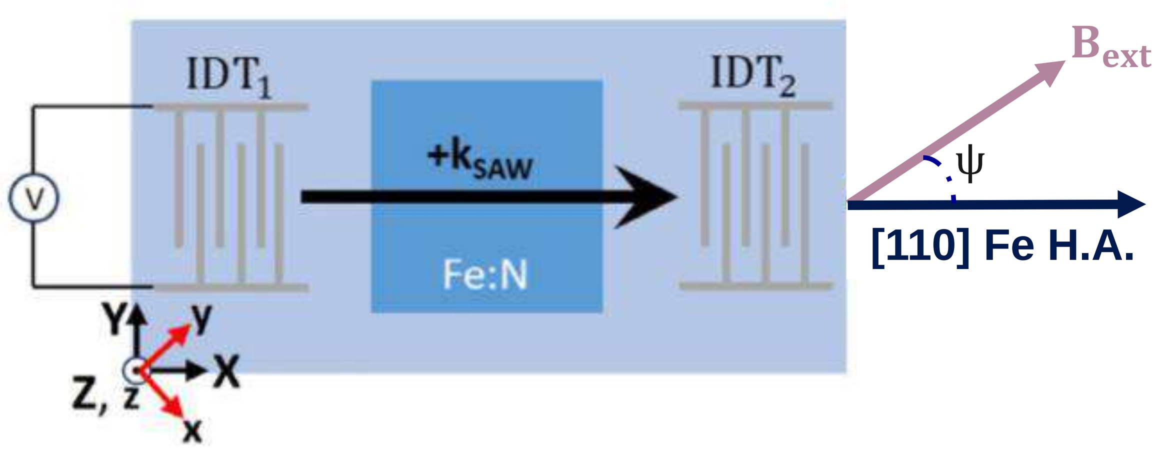


Why N-implantation?

- Preserves the epitaxy of Fe on GaAs
- Tunes the magnetic anisotropies of Fe → tuning of SAW-SW coupling

- Using SAWs to resonantly excite the Fe pad, injecting propagating SWs into the Fe:N waveguide (SW emitter)
- Using a piezoelectric layer to strain the Fe pad to switch SW emission OFF/ON

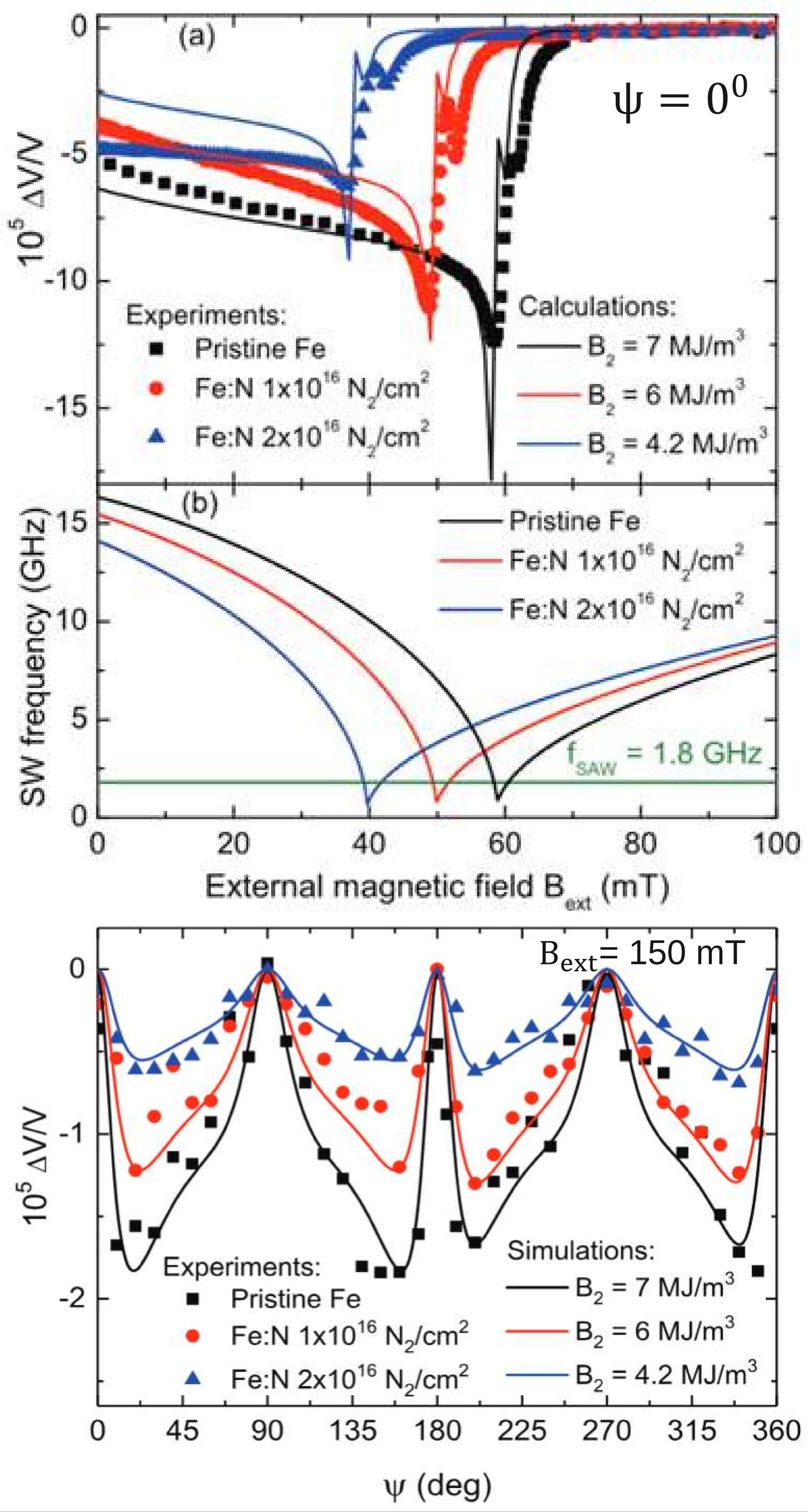
Tuning of SAW-SW coupling in Fe:N thin films & fabrication of the state-of-art device

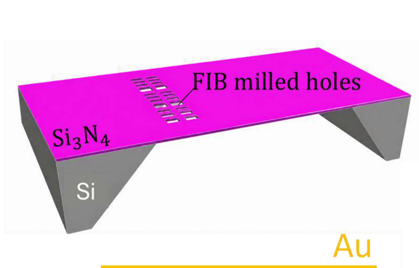


- Using SAW-based ferromagnetic resonance, we measure its relative velocity variation (ΔV/V) at IDT_2 [1]
- We use the model described in [2] to fit these measurements

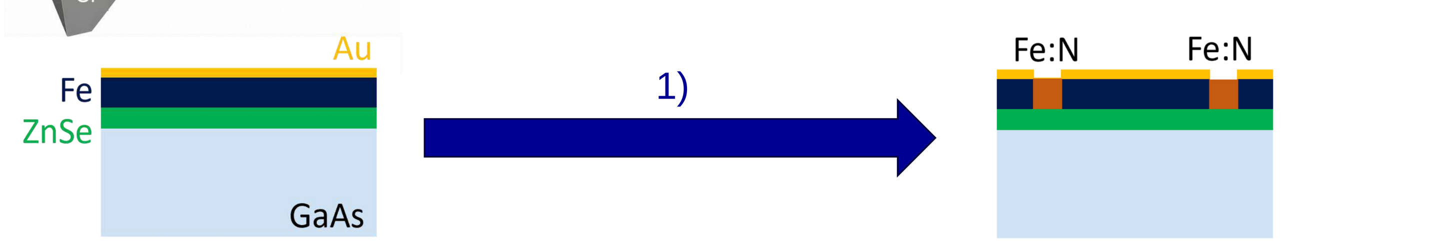
With increase of N-dose in Fe:

- SAW-SW resonance field decreases
- Magnetoelastic coupling decreases



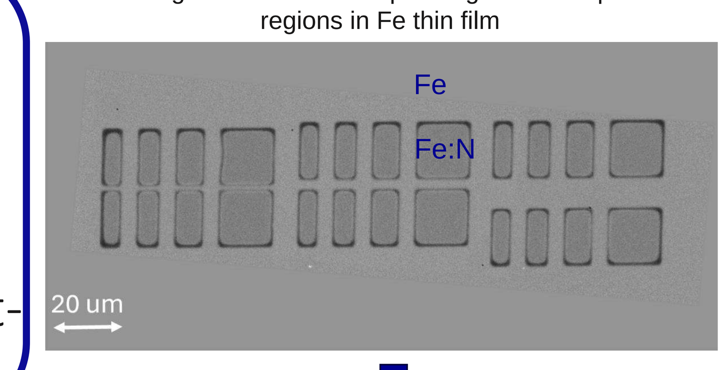


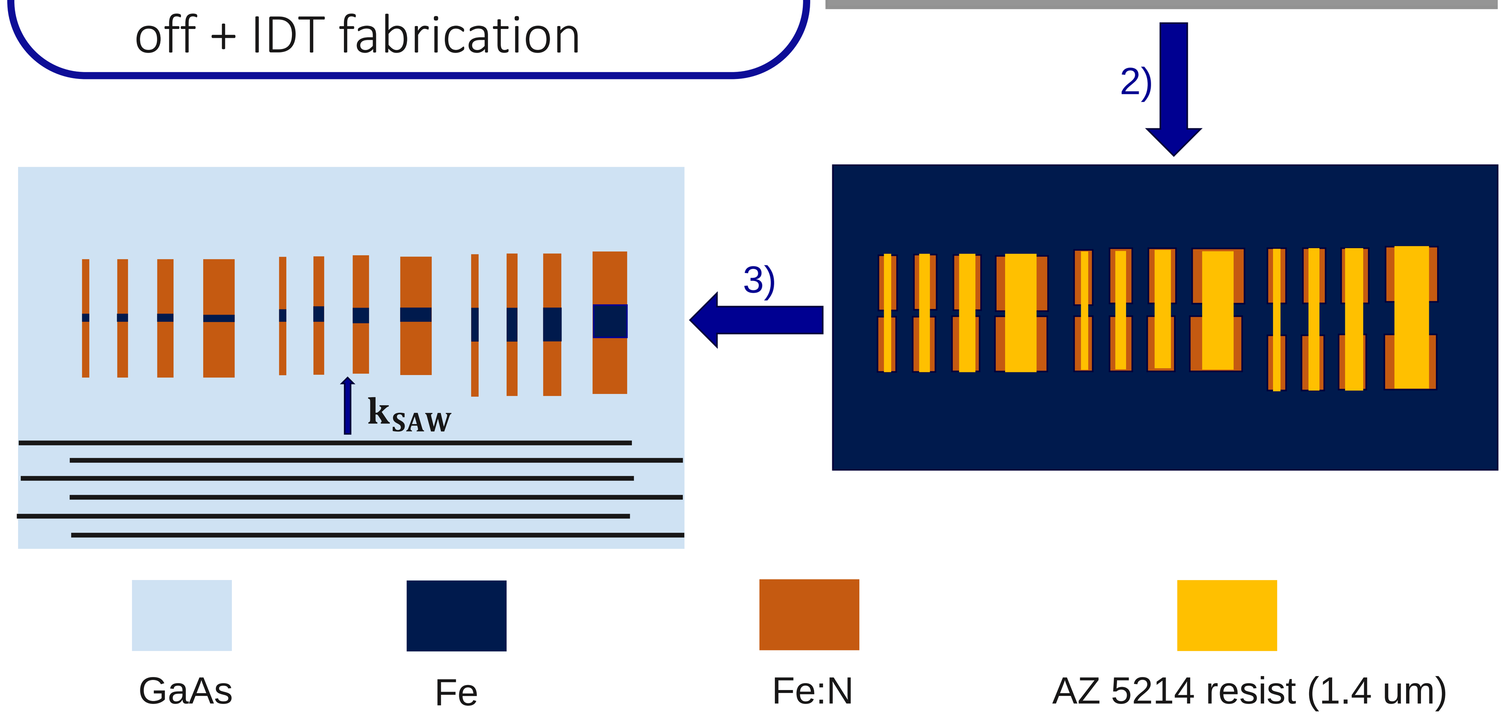
Focused ion beam-milled patterns on Si_3N_4 mask



1) Localized N-implantation using Si_3N_4 hard mask
2) Optical masks to define Fe/Fe:N conduits
3) Subsequent dry etching + lift-off + IDT fabrication

Scanning electron microscope image of the implanted regions in Fe thin film



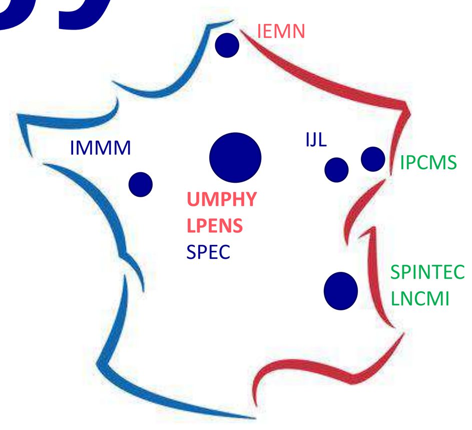


References:

1. A. Sharma *et al., Appl. Phys. Lett.* (2026)
2. P. Rovillain *et al., Phys. Rev. Applied* (2022)

anupam.sharma@insp.jussieu.fr

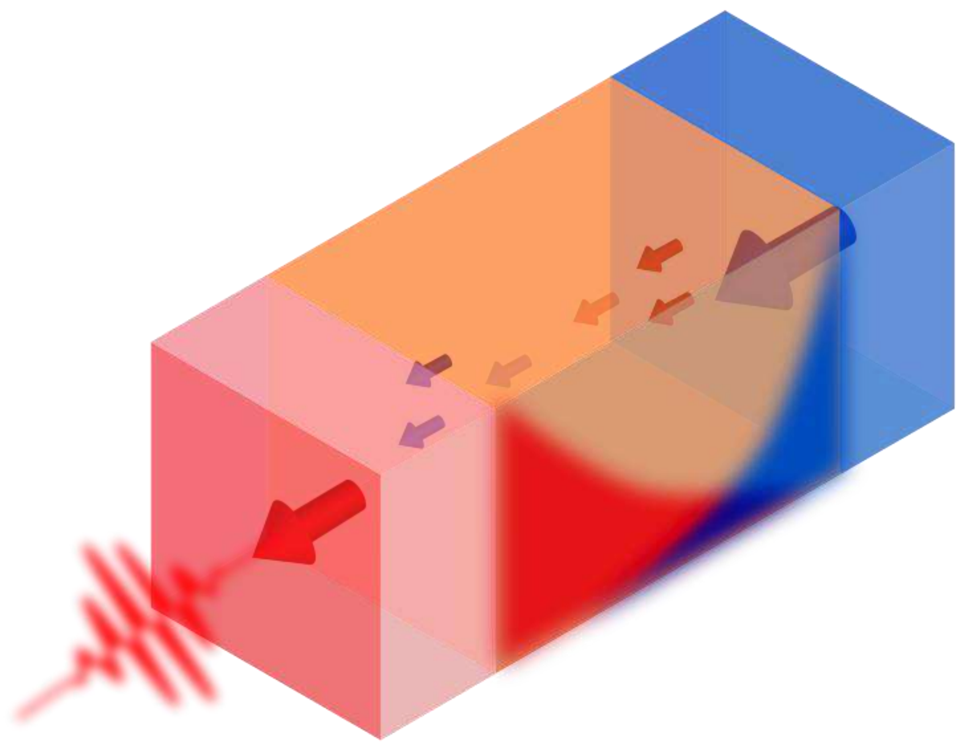
TOwArds Spin-based THz technology



Coordinateur **- Jon Gorchon (IJL Nancy)**

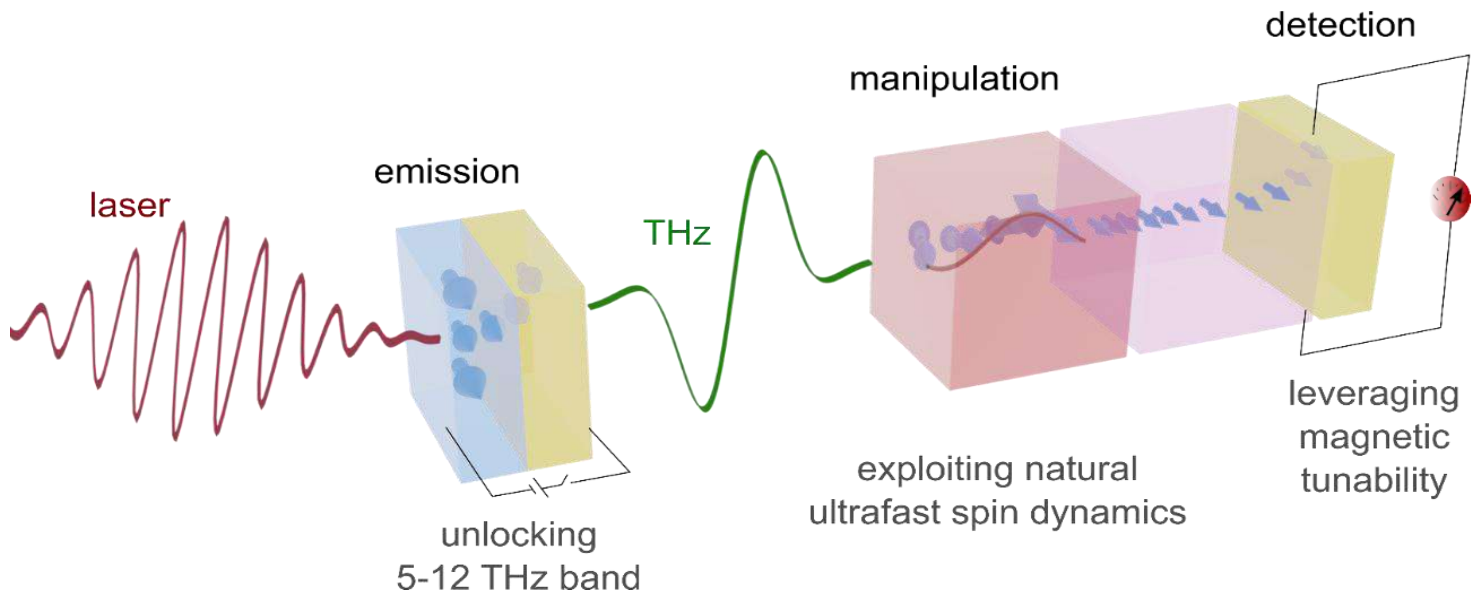
Partenaires et responsables scientifiques: **Pascal Ruello, IMMM (Le Mans), Michel Viret, SPEC, (Gif-sur-Yvette), Sukhdeep Dhillon, LPENS, (Paris, (Paris), Matthias Vanwolleghem, IEMN (Lille), Matthieu Bailleul, IPCMS, (Strasbourg), Vincent Baltz, SPINTEC, (Grenoble), Henri Jaffrès, UMPHy (Palaiseau), Anne-Laure Barra, LNCMI (Grenoble)**

Overview



This study clarifies many long-standing open questions, brings a clear pathway towards the optimization and extension of THz magnetic manipulation, and provides the new tools required for its analysis.

PEPR-TOAST



- ***Investigate and obtain proof of concepts for spin-based THz technologies that can be used to create ultrafast, energy-efficient devices.***

PhD Thesis

PhD candidate:

Harjinder Singh (IJL Nancy)

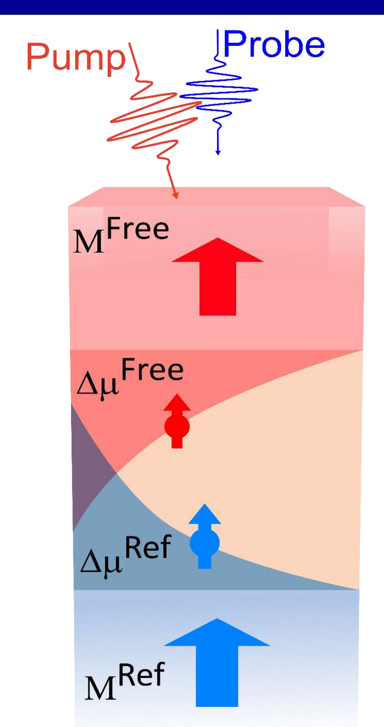
Objectives:

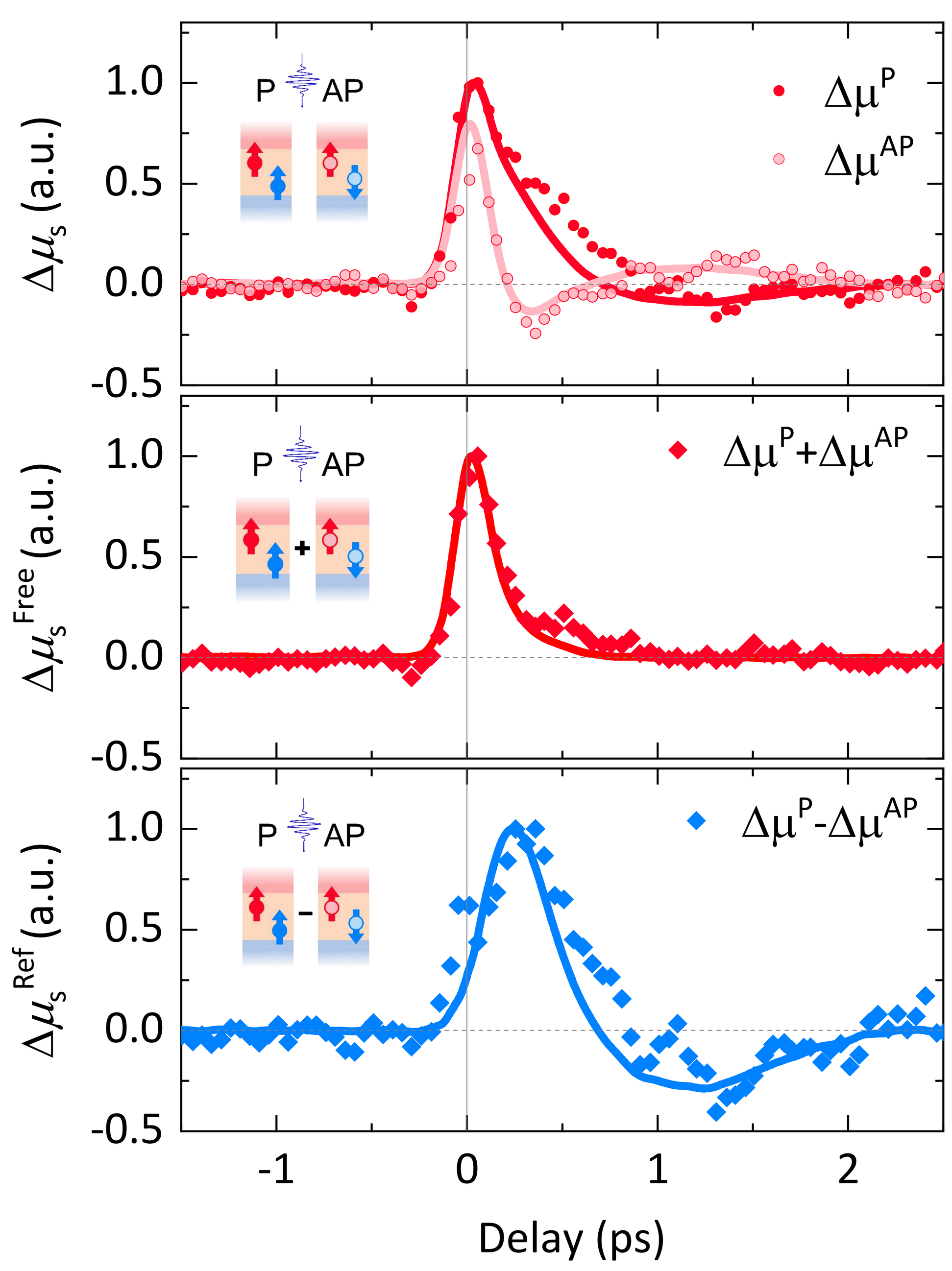
1) Optical control of magnetization using THz spin currents.

2) Spin-Orbit torque control of magnetization at THz frequencies.

Article: Ultrafast spin accumulations drive magnetization reversal in multilayers

Singh *et al.* PRL **136**, 056701 (2026)





Key takeaways:

- Time-resolved MOKE has the potential to be used for studying the dynamics of spin currents in complex multilayers such as anti-ferromagnets and altermagnets.
- THz spin currents play a direct role in determining the final magnetic state of a ferromagnetic spin-valve.
- In the future, it may be possible to fabricate devices that can write magnetic bits at THz frequencies.

PEPR website

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spin.ijl.cnrs.fr

High-throughput screening of 2D spintronic materials

Aurélien Manchon, coordinator SPINTHEORY

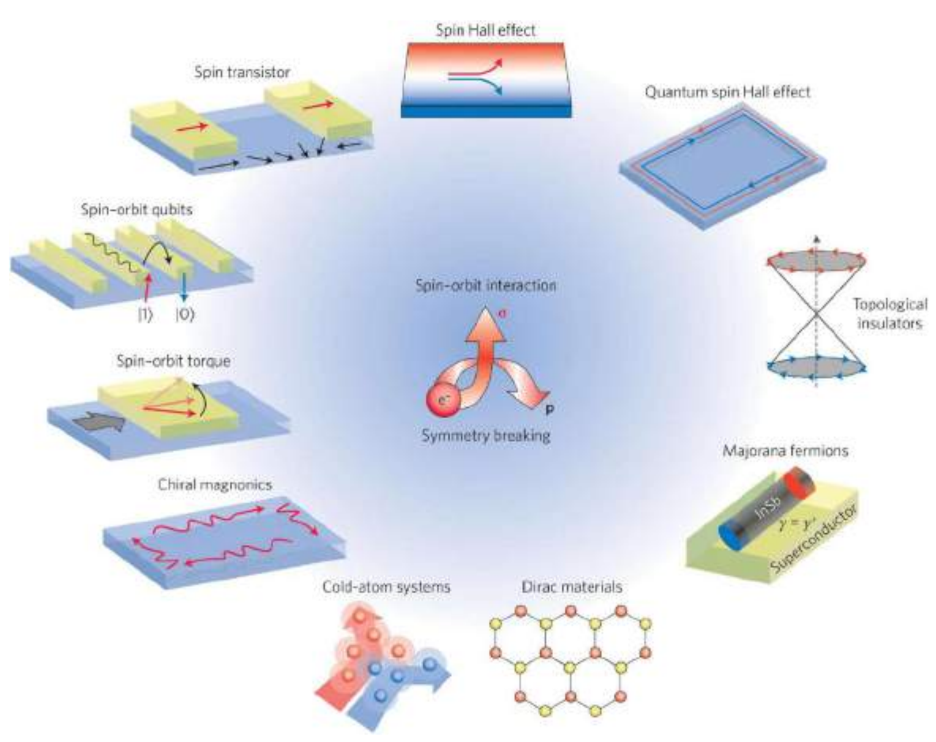
Supervisors: Thibault Sohier, Laboratoire Charles Coulomb; Mairbek Chshiev, SPINTEC

Career path

• PhD (2025–): High-throughput DFT for 2D spintronics (PEPR SPIN), Laboratoire Charles Coulomb

• Engineering Physics Degree (2022–2025): Institut National des Sciences Appliquées de Toulouse (INSA Toulouse)

High-throughput: spin-orbit coupling (SOC) in non-magnetic materials



[Manchon et al, Nature Materials **14**, 871 (2015)]

• MC2D database structures → classified by point group (PG) symmetry

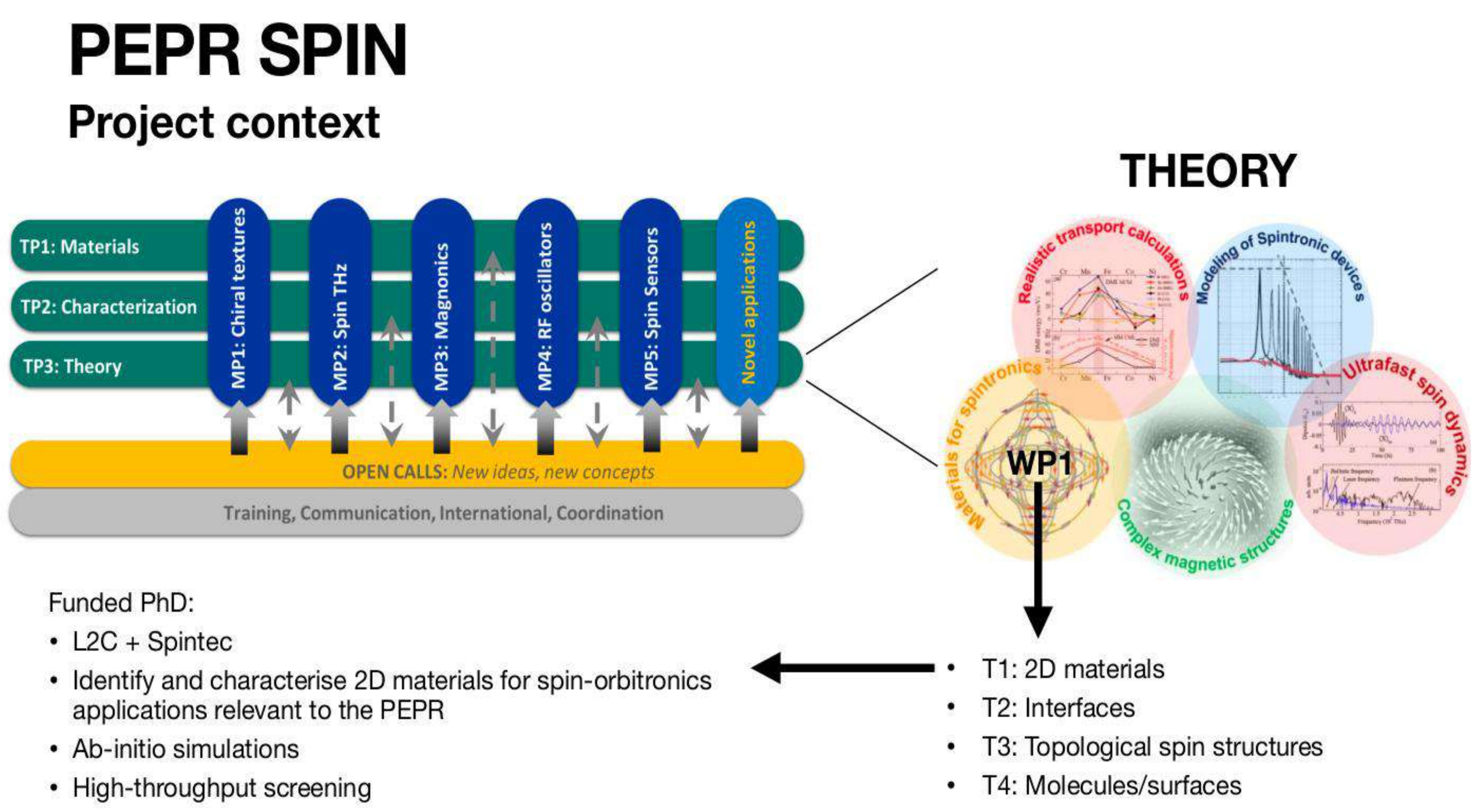
• Full relativistic (FR) DFT → SOC induced spin splitting strength

• Post-processing of FR-DFT → microscopic origin of spin splitting

• Physical explanation → clear strategies for materials/device design

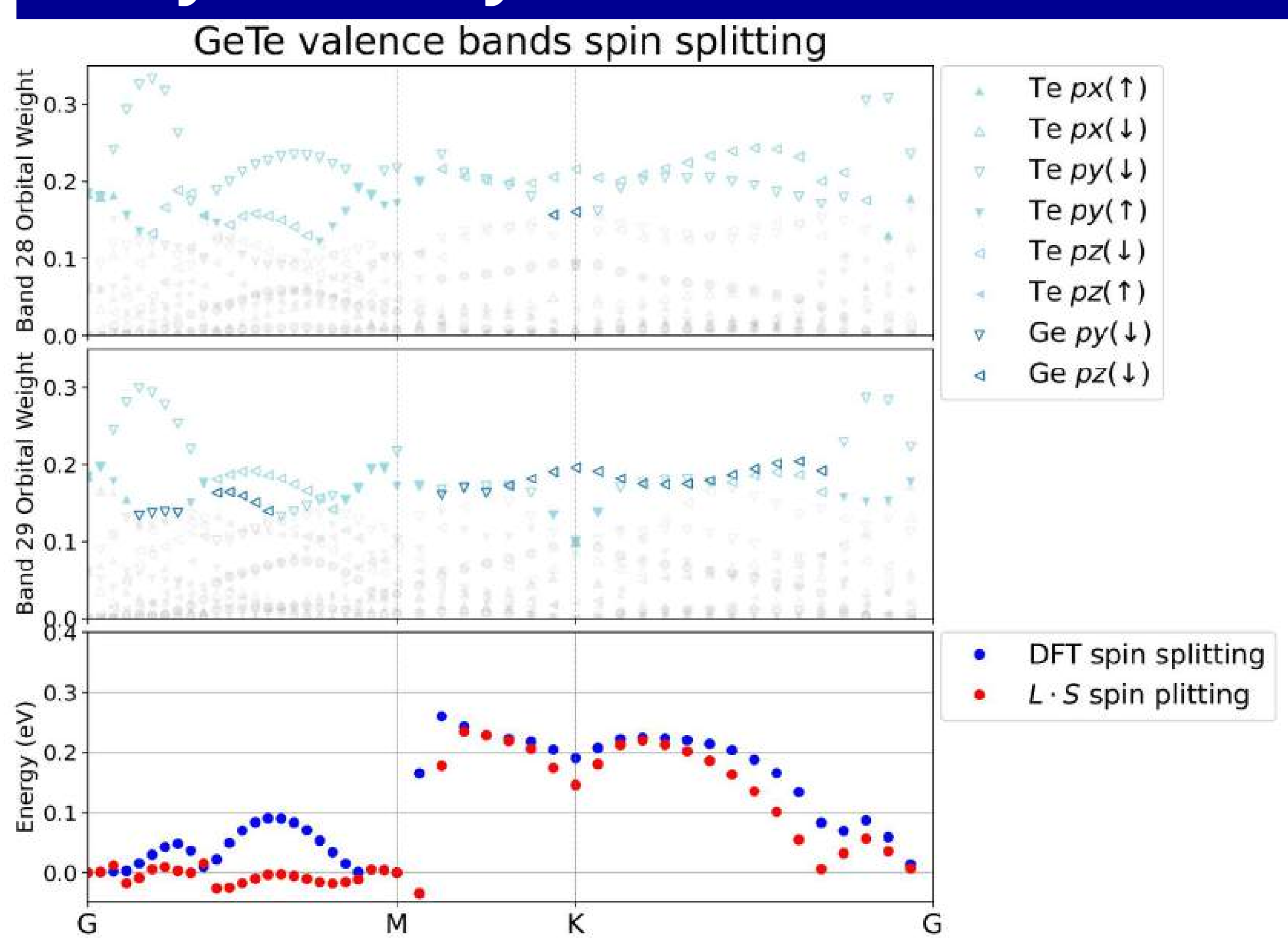
• Candidates for spintronic applications

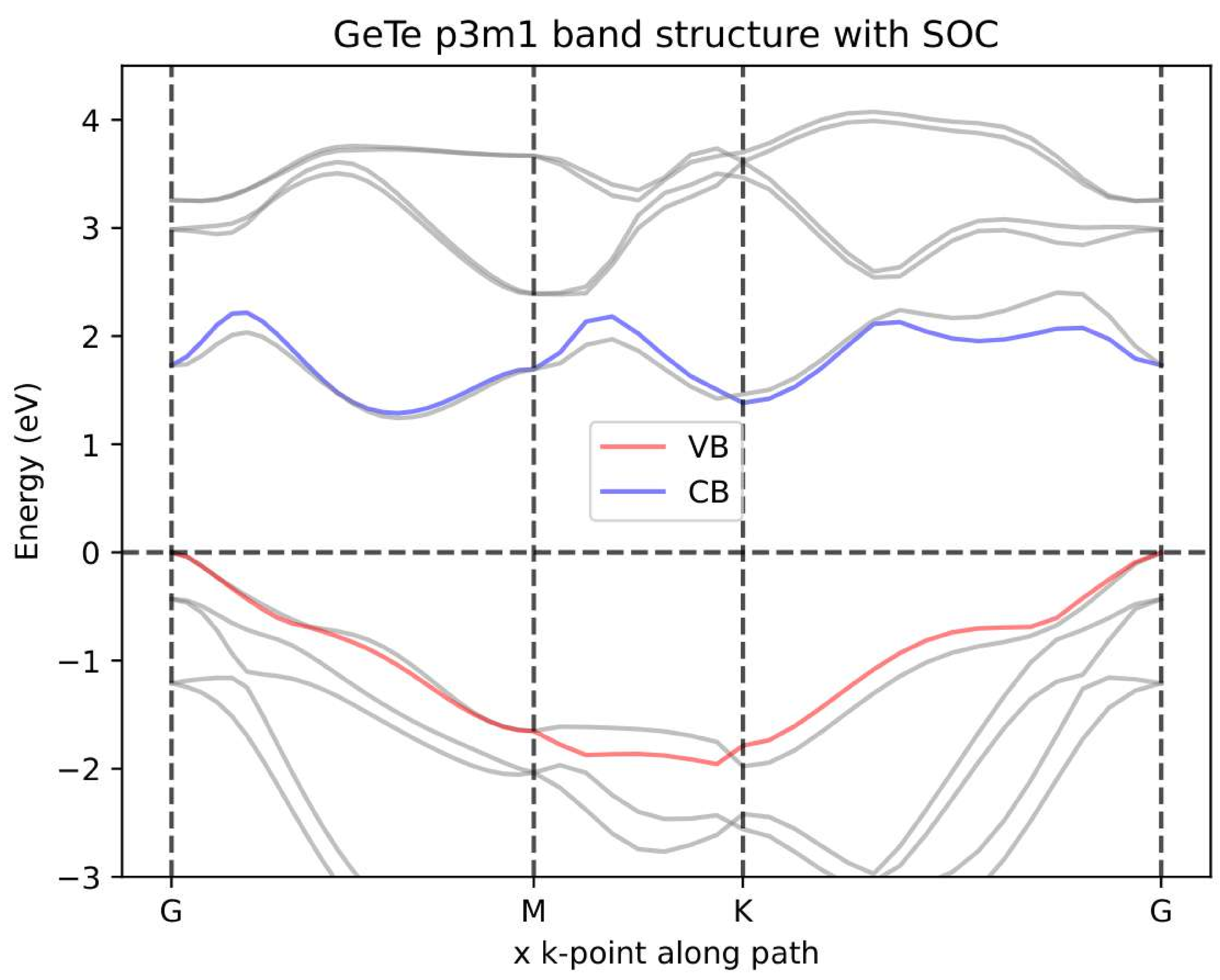
SPINTHEORY



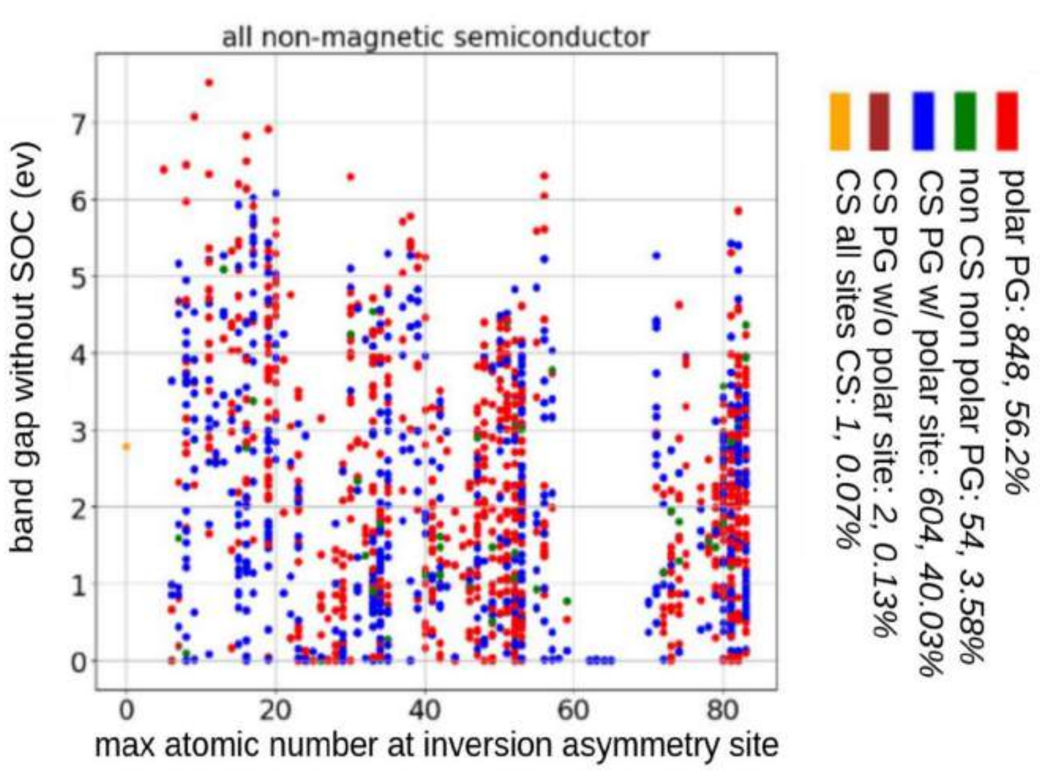
My PhD is part of the SPINTHEORY project (subproject T1: 2D materials), within workpackage 1: materials for spintronics.

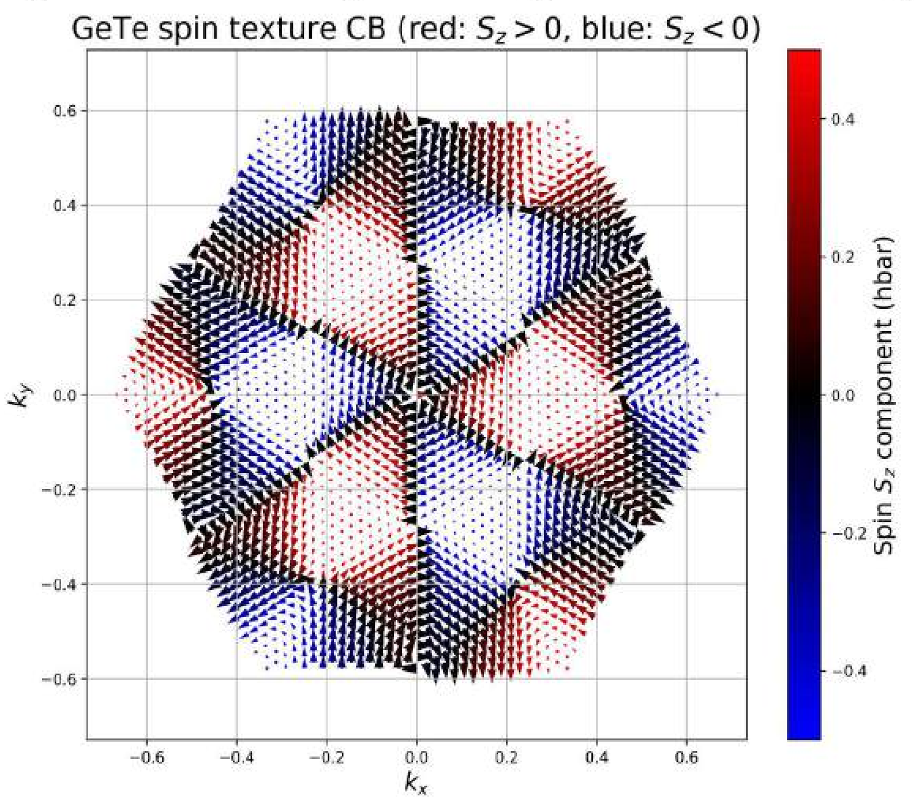
Symmetry classification and GeTe P3m1 case study





band gap & symmetry & atomic number metrics





- 848 materials with polar nature.
- GeTe (point group C3v): a good example for a case study with large spin splitting in the Brillouin zone (BZ) and Rashba effect in the conduction band (CB) at the Gamma (G) point.
- Spin splitting in valence bands 28, 29: generally, a greater projection on the heavy atom Te gives larger spin splitting. Exception: the G-M path, with an unknown effect.

Scan to discover the website

Junlin Yin, PhD student junlin.yin@umontpellier.fr

Complex dynamics in spin-torque oscillators for SpinCom project

Loukas KOKKINOS, PhD student
Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 91120, Palaiseau, France

Project partners : Joo-Von Kim (C2N), Ursula Ebels (coord. CEA SPINTEC), Vincent Cros (LAF) ,Gregoire de Loubens (CEA SPEC), Sebastien Petit-Watelot (IJL), Florence Podevin (TIMA), Damien Rontani (LMOPS)

My scientific background

M1 Internship at LPTMC

Subject: Study of hyperuniformity in non-euclidean geometries for supercooled systems

Methods: Theoretical/Numerical

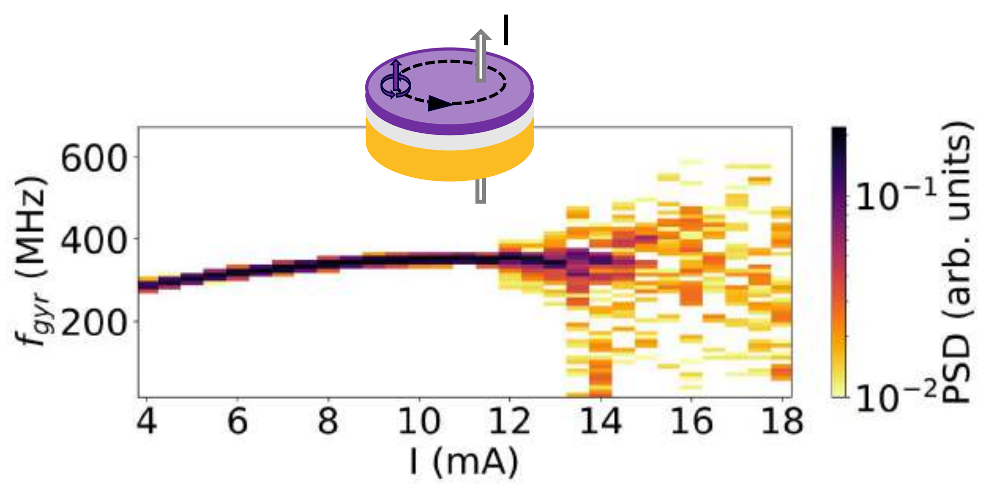
Key words: Condensed matter, statistical physics

M2 Internship at C2N

Subject: Dynamics in STVOs with non-uniform polarizer

Key words: Spintronics, magnetism

Methods: Theoretical/Numerical



SpinCom Project

RF Spintronics for Smart Communication (SpinCom)

Four work packages (WP)

WP1
- Building blocks and components
- New devices and optimization

WP2
- Detection and sensing
- RF power harvesting
- Wake-up receivers

WP3
- Random number generation
- Chaos generation
- Encryption

WP4
- Data and time series processing
- Unconventional computing

Personal involvement in the project

I'm involved mainly in work packages 3 and 4

My work consists in investigating spin-torque oscillators (STOs) looking for complex dynamics (such as chaos)

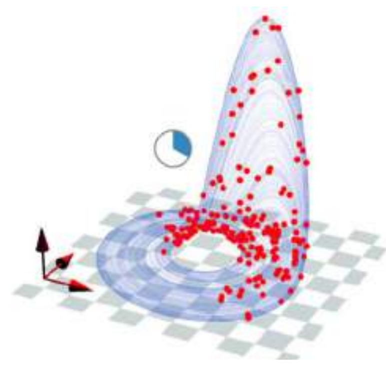
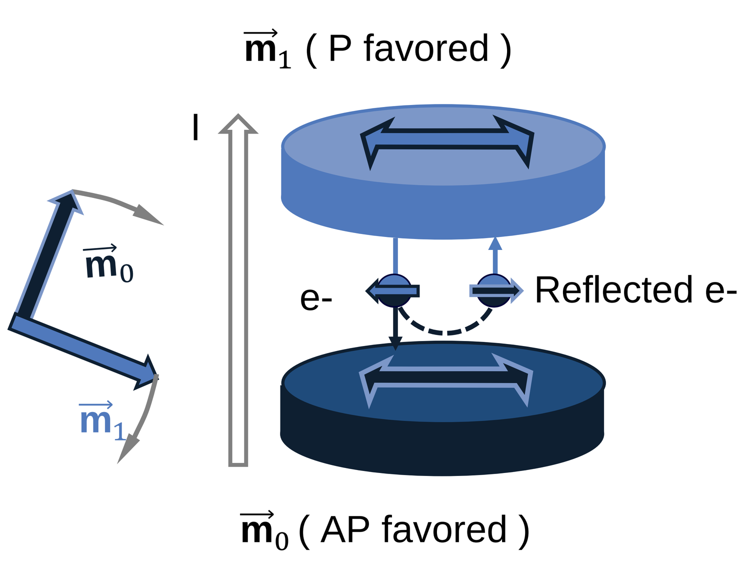


Image by J.V. KIM

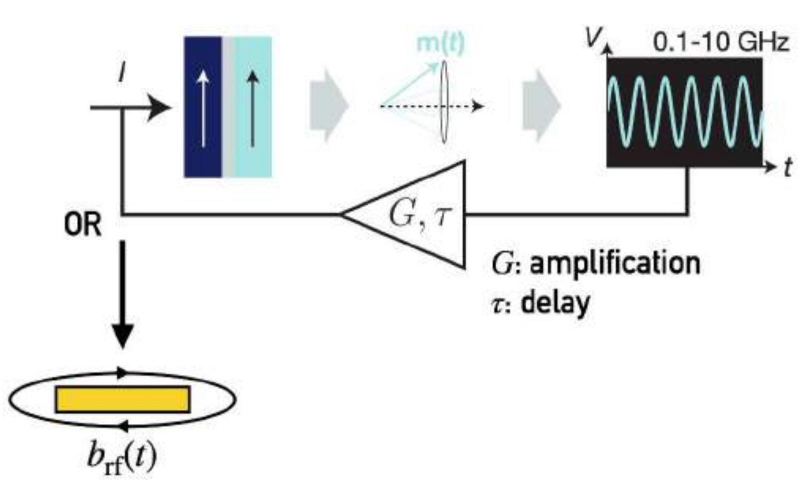
PhD topic: Complex dynamics in STOs for unconventional computing

- **Unconventional computing** …
  … to perform tasks not possible with conventional ways
  …often based **non-linear processes** such as chaos or stochasticity
- **STOs exhibit non-linear dynamics**
- **Numerical investigation** of non-trivial STVO set-ups
- **Generating complexity** by using **coupled STOs** by different means, such as …

Windmill dynamics



Delayed feedback



First results on windmill dynamics

Implementation of LLG equation for windmill dynamics on Mumax3 software

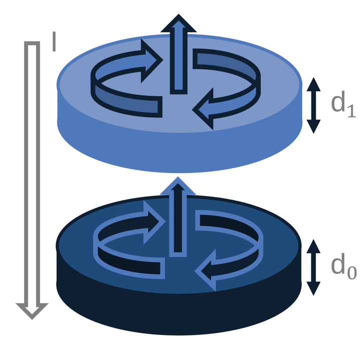
$$\frac{\partial \vec{m}_1}{\partial t} = -\gamma\,(\vec{m}_1 \wedge \mu_0\,\vec{H}_{eff,1}) + \alpha \vec{m}_1 \wedge \frac{\partial \vec{m}_1}{\partial t} + \gamma\,\beta_1 \vec{m}_1 \wedge (\vec{m}_1 \wedge \vec{m}_0)$$

$$\frac{\partial \vec{m}_0}{\partial t} = -\gamma\,(\vec{m}_0 \wedge \mu_0\,\vec{H}_{eff,0}) + \alpha \vec{m}_0 \wedge \frac{\partial \vec{m}_0}{\partial t} - \gamma\,\beta_0 \vec{m}_0 \wedge (\vec{m}_0 \wedge \vec{m}_1)$$

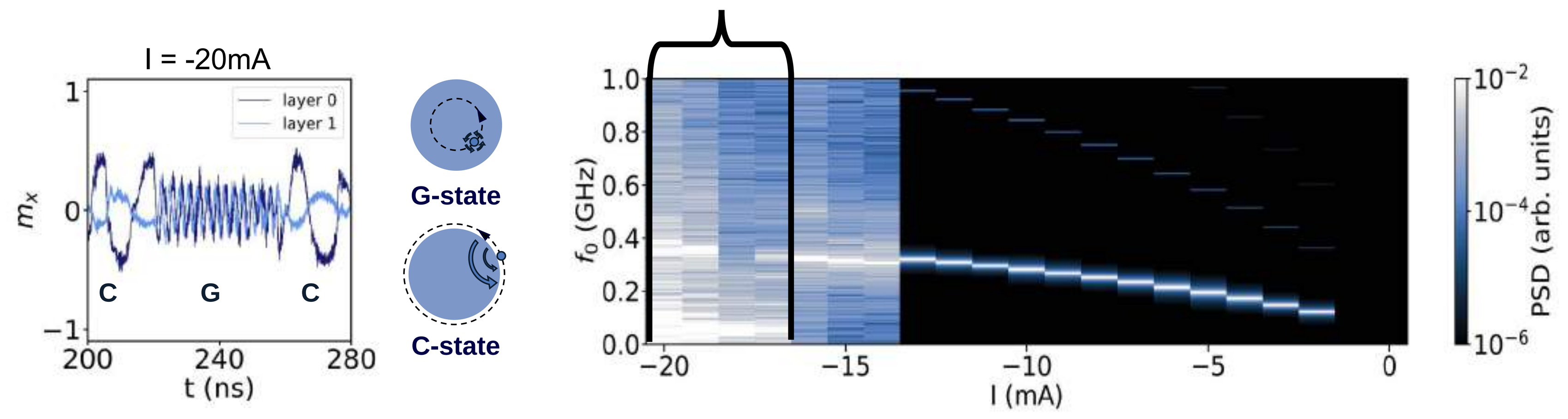
with $\beta_i = \dfrac{\hbar\, I\, P}{2\,\pi\, R_{disk}^2 M_{s,i}\, d_i\, |e|}$

Studying two layers in identical vortex magnetic state

Asymmetrical thickness between layers, $d_1 = \zeta\, d_0$, with $\zeta > 1$



Obtained some interesting non-linear dynamics (stochastic switching)



Scan to discover the website

The Priority Research Program for SPIN (PEPR) is an exploratory program within the framework of the France 2030 investment plan.
It aims to develop a new generation of components for a more frugal, agile, and sustainable digital world. With a funding of 38 million euros over eight years, the SPIN Research Program is intended to contribute to accompanying a new cycle of innovation in spintronics.

Spintronic innovations for a frugal, agile, and sustainable digital future

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

FRANCE 2030 PROGRAMME DE RECHERCHE SPINTRONIQUE

anr cnrs cea

Voltage-driven control of exchange bias field in Pt/Co/CoO thin films via magneto-ionic effects

Project coordinator: Stefania Pizzini, CNRS Institut Néel (e-mail: stefania.pizzini@neel.cnrs.fr)

Agnieszka Klimeczek[1], Maurizio De-Santis[1], Frédéric Gay[1], Laurent Ranno[1], Jan Vogel[1], Aurélien Masseboeuf[2], Anne D. Lamirand[3], Stefania Pizzini[1]

1 Université Grenoble Alpes, CNRS, Institut Néel 2 Université Grenoble Alpes, CNRS, CEA, SPINTEC 3 Université Lyon, Ecole Centrale de Lyon, CNRS, INSA Lyon, Université Claude Bernard Lyon

Career path & PhD project

After finishing my degree in Physics at AGH University in Kraków, Poland, I moved to Institut Néel in Grenoble to pursue a PhD under the supervision of Stefania Pizzini and Laurent Ranno.

My PhD work is carried out within the PEPR-SPIN CHIREX project and I study the voltage-driven manipulation of magnetic properties in ultra-thin films based on Pt/Co.

PEPR-SPIN CHIREX

CMOS structures suffer from relatively low operational speed and volatility, requiring continuous power to retain information.

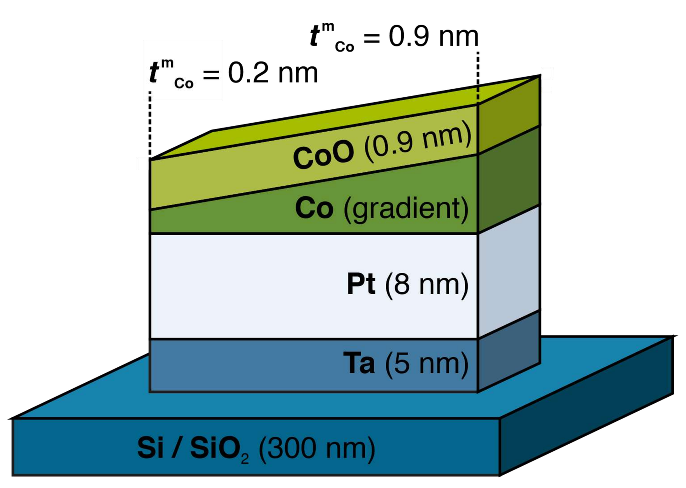
PEPR-SPIN CHIREX addresses these limitations by exploiting topological spin structures, such as magnetic skyrmions, as robust, energy-efficient information carriers. The project focuses on their controlled creation, manipulation, and detection for next-generation data processing and storage.

Oxygen magneto-ionics as a way to electrically and reversibly tune exchange bias

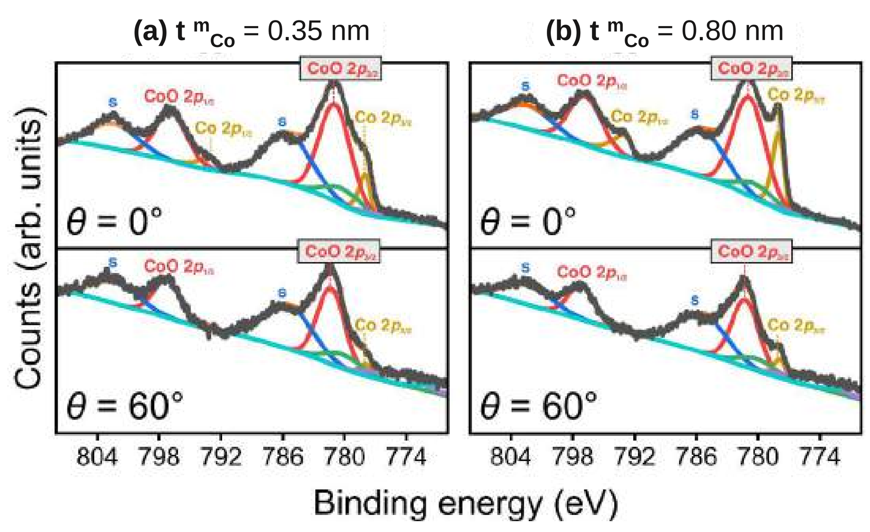
INTRODUCTION

Electric-field control of magnetic anisotropy is critical for low-power spintronics. We achieve this via voltage-driven interfacial oxidation by magneto-ionic effects that tune the perpendicular magnetic anisotropy, the coercivity and the exchange bias field in Pt/Co/CoO ultra-thin films.

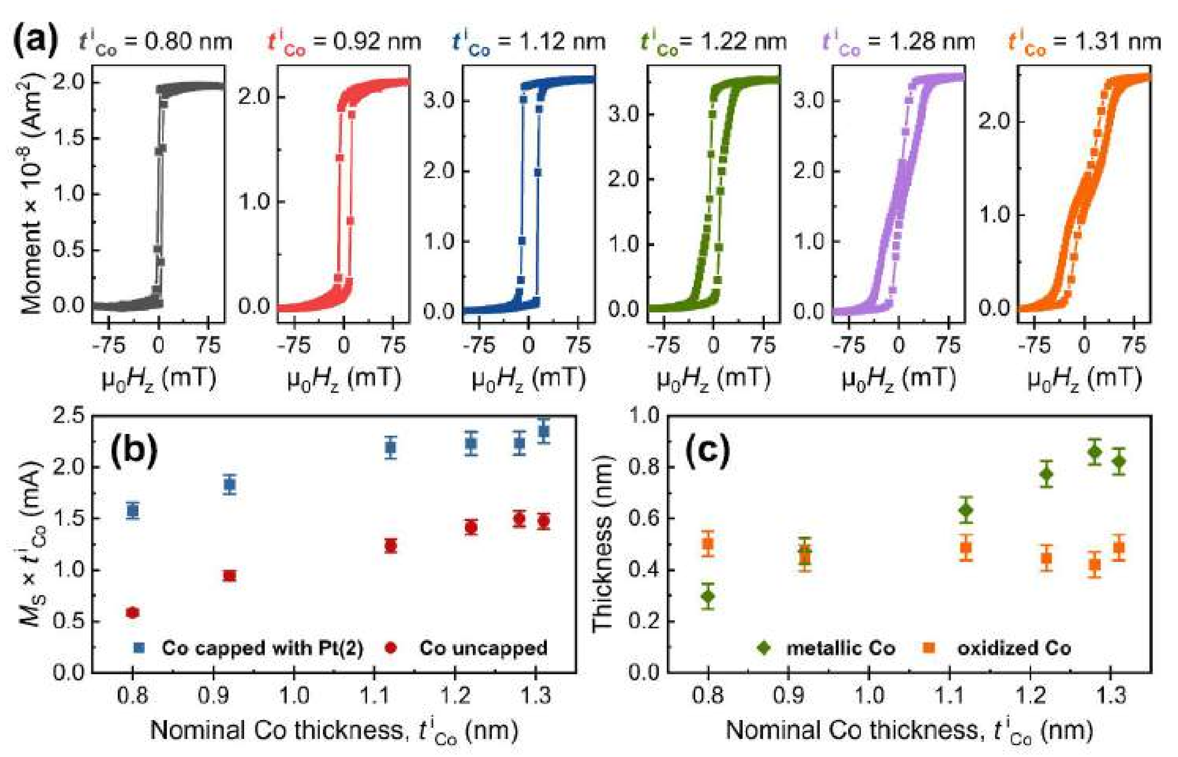
(a) System: Pt/Co/CoO trilayers with native oxide and a gradient of Co



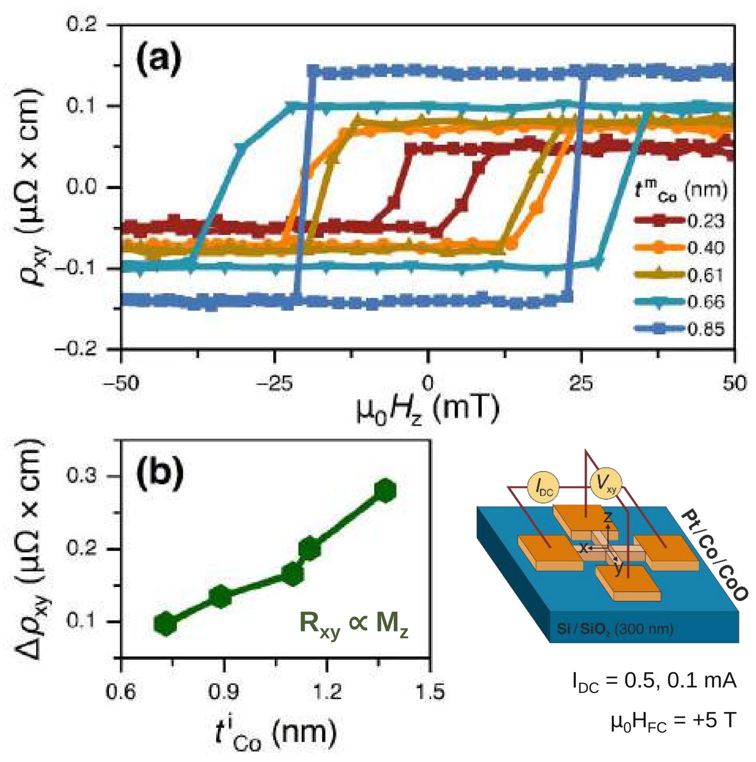
(b) Determining the oxide: XPS measurements at the Co 2p edge indicate that the native oxide is predominantly CoO



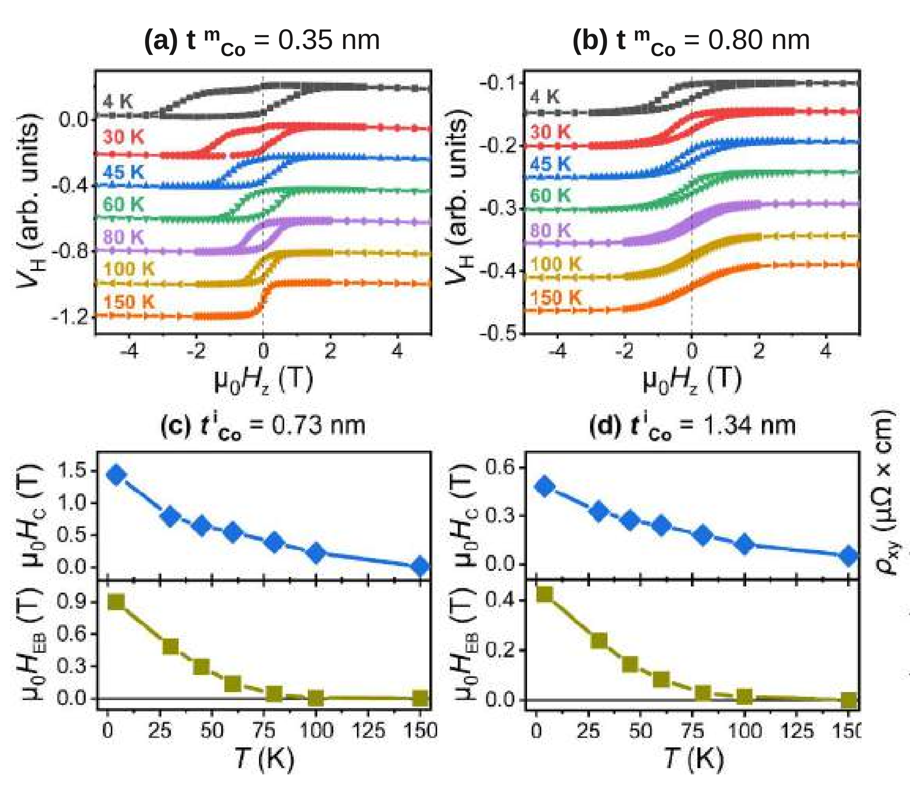
(c) Magnetic characterization: VSM-SQUID shows PMA with a transition to an in-plane easy axis around 1.1 nm of as-deposited Co



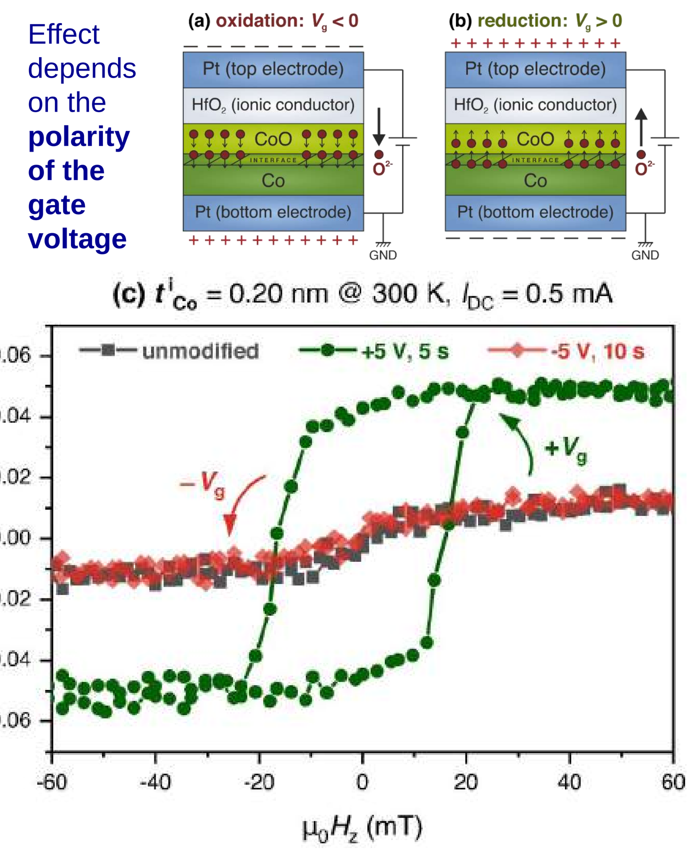
(d) Magneto-transport measurements @ RT: amplitude of hysteresis cycles measured with AHE scales as a function of metallic Co volume



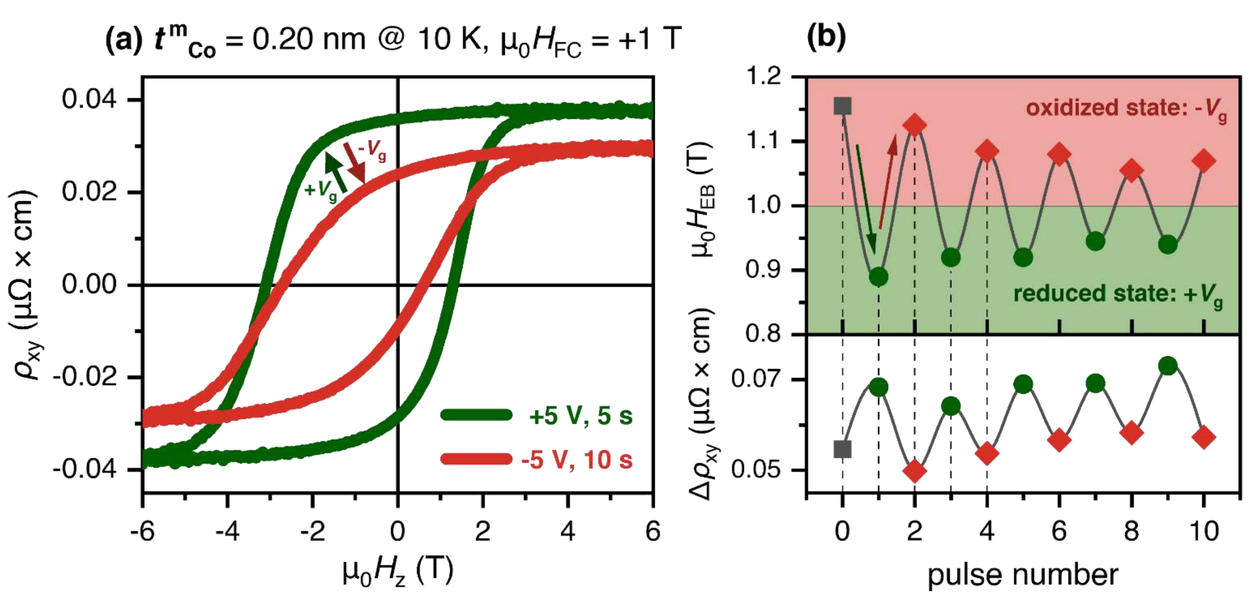
(e) Is the nature of the oxide antiferromagnetic? Magneto-transport measurements @ LT reveal a large perpendicular exchange bias of almost 1 T @ 4 K



(f) Magneto-ionics: applying a gate voltage increases anisotropy and the AHE signal



(g) Exchange bias: electrical switching between an initial 1.2 T "high-exchange-bias field" and 0.9 T "low-exchange-bias-field" through a controlled reduction/oxidation of the ferromagnetic interface



SUMMARY: We show that voltage-driven oxygen migration produces large, reversible changes in perpendicular exchange bias via interfacial oxidation control, providing a route for electrically programmable magnetic interfaces

1	Trilayers with native Co oxide and PMA despite 1-2 MLs of unprotected Co	2	Large perpendicular exchange bias for 0.2 nm of metallic Co that reaches ~ 1 T @ 10 K	3	Amplitude of AHE as a proxy for checking the metallic Co thickness	4	Electrical and reversible way to control exchange bias through magneto-ionics

Klimeczek et al., Appl. Phys. Lett. 127 (2025), Smardz et al., J. Appl. Phys. 71, 5199 (1992), Dieny et al., Rev. Mod. Phys. 89, 025008 (2017), Nakajima et al., Phys. Rev. Lett. 81, 5229 (1998), Song et al., J. Alloys Compd. 696, 315 (2017), Fassatoui et al., Small 17, 2102427 (2021).

Agnieszka Klimeczek, PhD Student within the PEPR SPIN CHIREX framework at CNRS Institut Néel in Grenoble

PEPR SPIN CHIREX aims to develop next-generation spintronic devices by using magnetic textures such as skyrmions and chiral domain walls. The project involves major French research institutions like CNRS, CEA, Centre de Nanosciences at de Nanotechnologies (Université Paris-Saclay), and Institut Jean Lamour (Université de Lorraine).

Epitaxial fluorides for van der Waals magnetic tunnel junctions (MTJs)

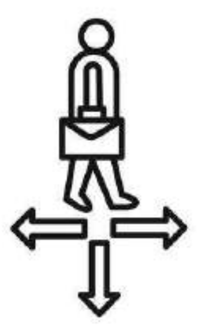
Davide Benettin, Ph. D. student

F. Ibrahim, A. Marty, I.G. De Moraes, M. Chshiev and F. Bonell

Univ. Grenoble Alpes, CEA, CNRS, Grenoble INP, SPINTEC, 17 rue des Martyrs, Grenoble, France

My career path

- **05/2023** – Graduation at Politecnico di Milano (PoliMi) with master thesis - *Effect of graphene in Ge-based non-local architecture for spin transport*
- **06/2023 - 09/2024** - Internship at PoliFab (structure for micro and nano-fabrication of PoliMi) - *Molecular beam epitaxy of FerroElectric Rashba SemiConductor (FERSC) for logic in-memory applications*
- **09/2024 – 09/2027** - Ph.D. at Spintec – CEA Grenoble – *Spintronics devices based on epitaxial 2D magnets*
- **01/2028** - Looking for a Postdoc…



2D magnets for van der Waals MTJs

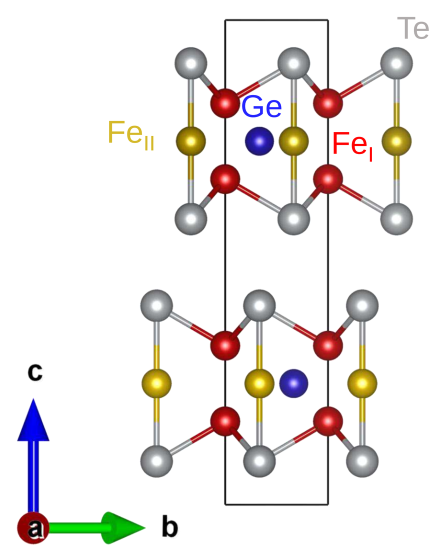
- Molecular beam epitaxy to grow cm^2 scale epitaxial van der Waals magnets to be used as electrodes in MTJs

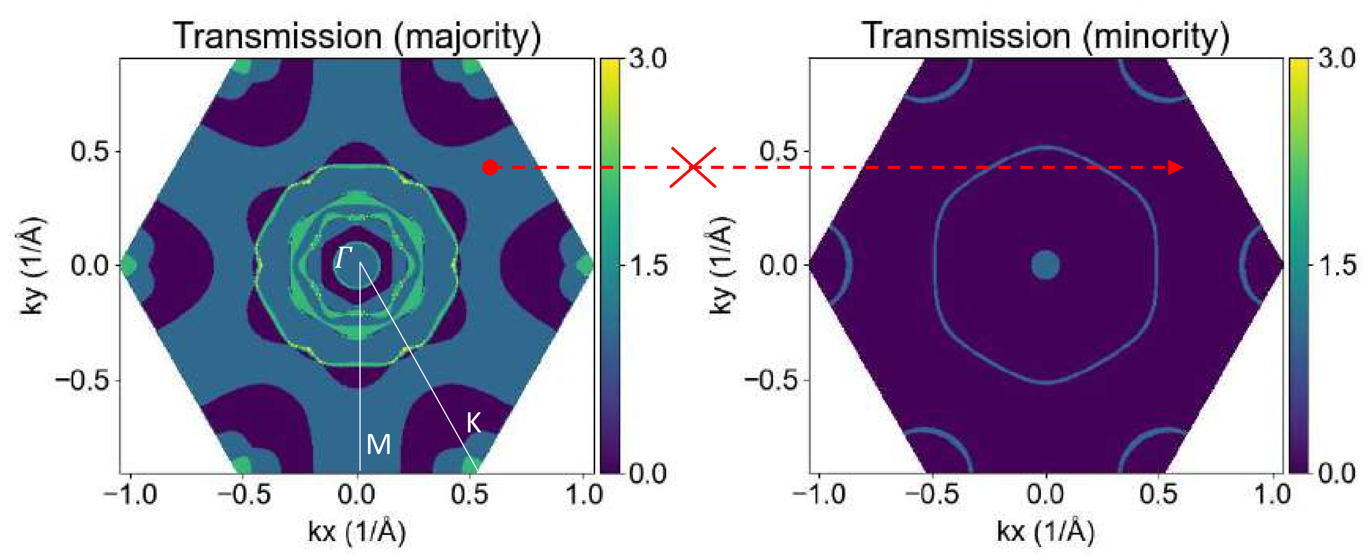
Molecular Beam Epitaxy (MBE) → Sub-nm thickness control; Fine tuning of composition; Ultra-high vacuum

- $Fe_{n=3,5}GeTe_2$: family of 2D magnets with high T_C and tunable anisotropy with Fe-content

→Small overlap of spin ↑ and ↓ states → large Tunneling MagnetoResistance (TMR)

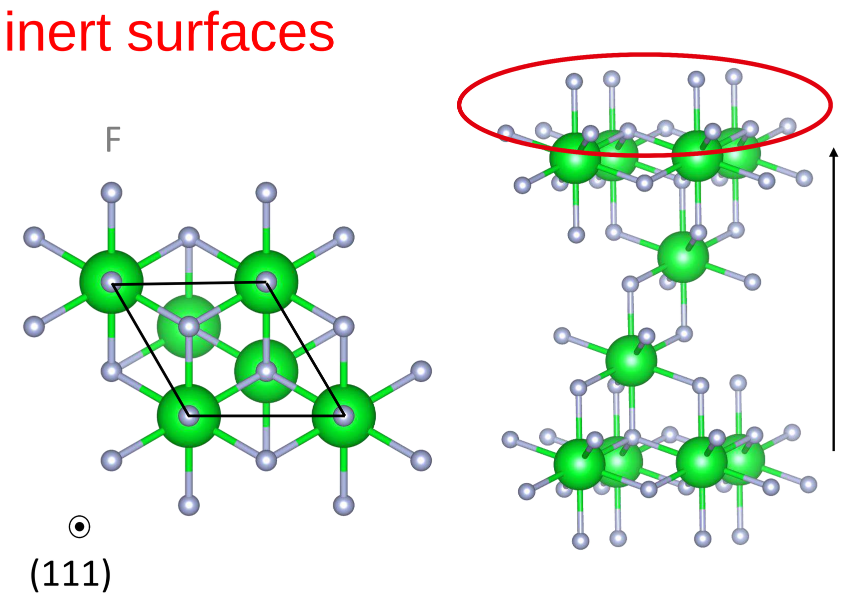
→Need to consider filtering action of the insulating barrier





Epitaxial alkaline earth fluorides

Cubic crystals with hexagonal lattice in (111) planes and F-terminated inert surfaces



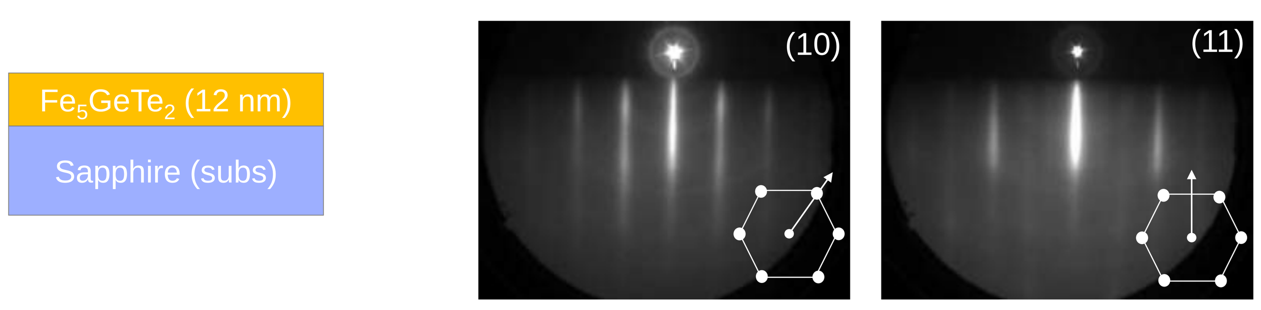
Compatible with 2D heterostructures

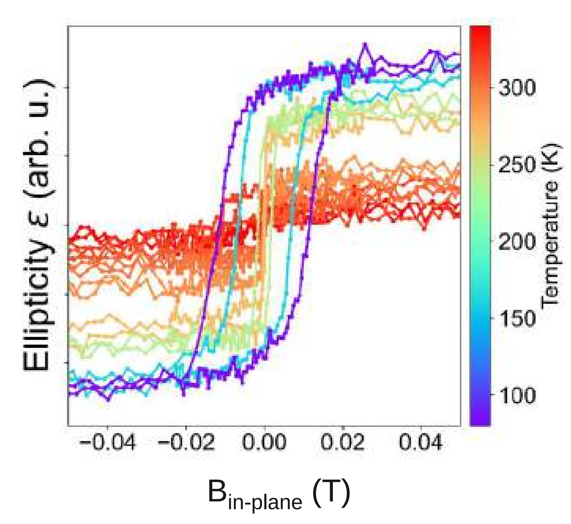
Material	In-plane lattice parameter [Å]	Lattice mismatch with Fe_3GeTe_2
CaF_2	3.866	-3%
SrF_2	4.040	+1.2%
$Fe_{3,5}GeTe_2$	3.991	-

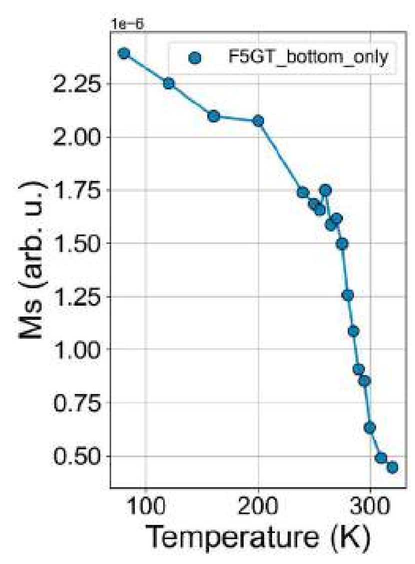
Solid solution of CaF_2 and SrF_2 to achieve perfect lattice matching ➡ $Ca_{0.3}Sr_{0.7}F_2$

Fully epitaxial 2D MTJ

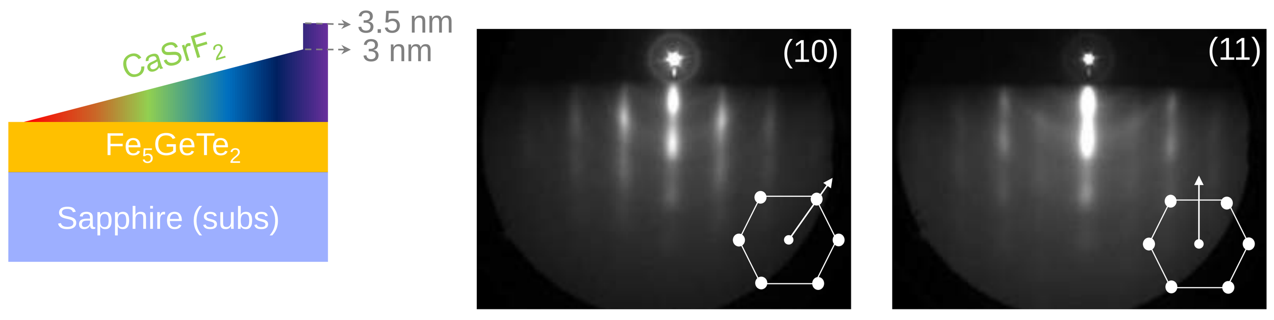
- Growth of Fe_5GeTe_2 on sapphire substrates

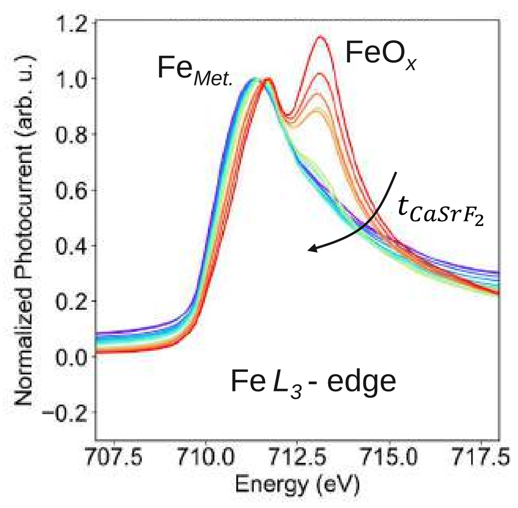






- Epitaxial $(Ca,Sr)F_2$ on Fe_5GeTe_2

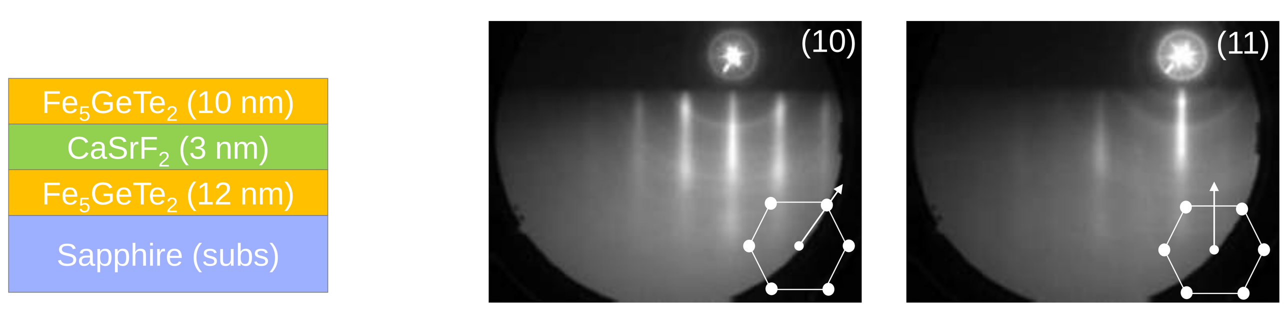




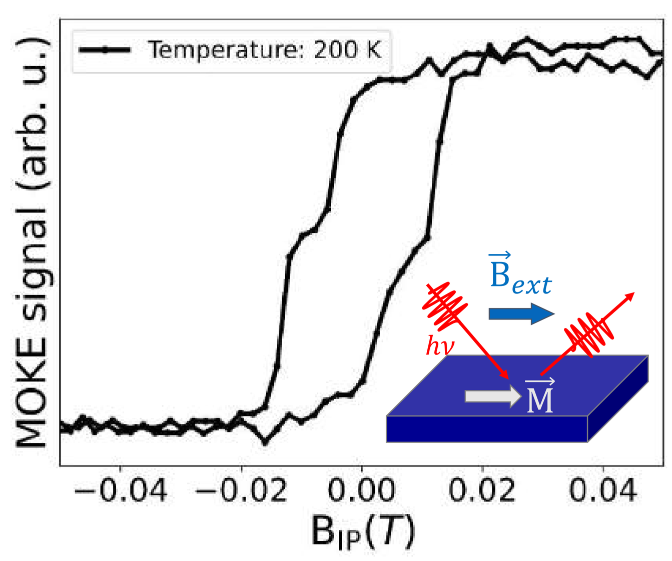
X-ray Absorption Spectroscopy (XAS) on a wedge of $(Ca,Sr)F_2$ on Fe_5GeTe_2

Continuous for $t_{CaSrF_2} > 2$ nm

- Fully epitaxial van der Waals MTJ



RHEED pattern of top Fe_5GeTe_2 electrode



Two electrodes are uncoupled through a 3-nm thick $(Ca,Sr)F_2$ barrier

The Priority Research Program for SPIN (PEPR) is an exploratory program within the framework of the France 2030 investment plan. It aims to develop a new generation of components for a more frugal, agile, and sustainable digital world. With a funding of 38 million euros over eight years, the SPIN Research Program is intended to contribute to accompanying a new cycle of innovation in spintronics.

Author's contact

davide.benettin@cea.fr

Oxide-based heterostructures for orbitronics

Project Coordinator: Aurélien MANCHON, CINaM, Aix-Marseille Université, CNRS

Scientific responsable: Daniele PREZIOSI, IPCMS, Université de Strasbourg, CNRS

Career path

2025 - Current

Ph.D. student
IPCMS-CNRS (Strasbourg, France)
Thesis: Oxide-based heterostructures for orbitronics

2025

Research fellowship
CNR - Istituto Nanoscienze (Modena, Italy)

2022-2024

Master's Degree in Chemical Sciences
University of Modena and Reggio Emilia (Italy)
Thesis: Plasmonic copper nanoparticles coupled with copper oxides as photocathodes with high solar light absorption efficiency

2018-2021

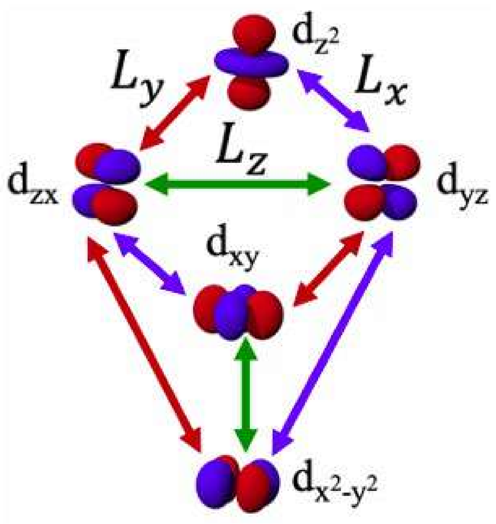
Bachelor's Degree in Science and Technology of Chemistry and Materials
University of L'Aquila (Italy)
Thesis: Synthesis and characterization of innovative materials for space applications

OXIMOR

A key advantage of orbital currents over spin currents is their efficient generation in materials lacking heavy elements. Moreover, preliminary experimental results demonstrate that orbital currents can substantially reduce the critical current required to operate magnetic memories.

OXIMOR proposes to bring orbitronics to maturity by demonstrating the **control of orbital transport** via the modulation of the electron's orbital character.

We will investigate orbital transport **in oxide heterostructures with tunable crystal field potential.** These systems, already at the forefront of spin-orbitronics but totally unexplored for this purpose at the time being, present a number of properties that could be modulated to generate and control orbital currents for low-power spintronics.



Thesis project

The project will investigate strongly correlated **transition metal oxides** (such as manganites and ferrites), combined with materials exhibiting **low spin–orbit coupling** (such as copper or infinite-layer nickelates).

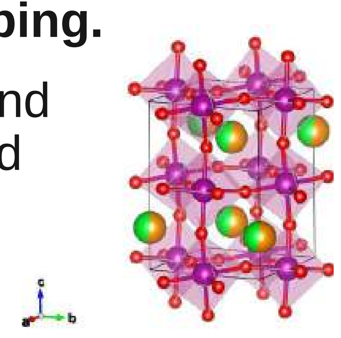
The main objective is to harness crystal field effects and orbital textures to study orbital transport phenomena. These properties will be actively controlled through external fields and heterostructure engineering, enabling the exploration of novel electronic functionalities.

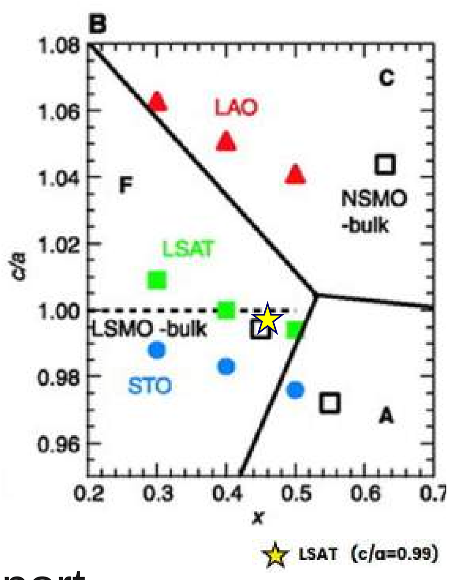
In TMOs the crystal field quenches the orbital moment by lifting the orbital degeneracy.
The main challenge of this PhD is to preserve the degeneracy in order to promote the orbital functionalities.

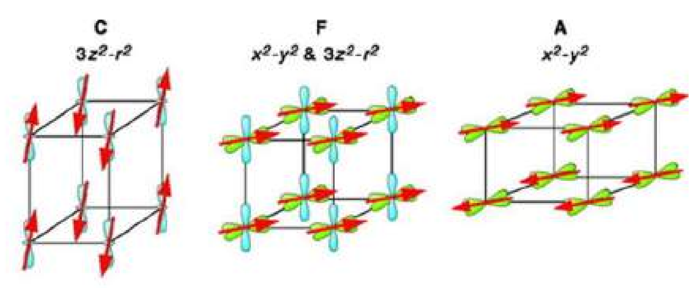
Preliminary results

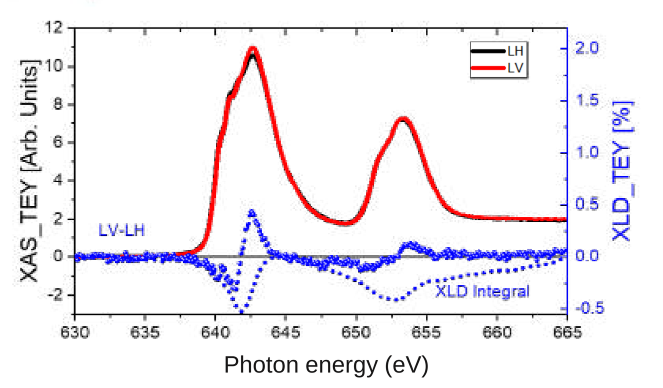
$Nd_{1-x}Sr_xMnO_3$ are highly sensitive to structural modification of their orbital character, which can be tuned via **strain** (c/a ratio modulation) or **Sr-doping.**

The combination of Sr-content (x=0.45) and epitaxial strain from a LSAT substrate lead to a homogeneous occupation of both Mn $3dx^2$-y^2 and $3z^2$-r^2 orbitals and a ferromagnetic state (F-type).



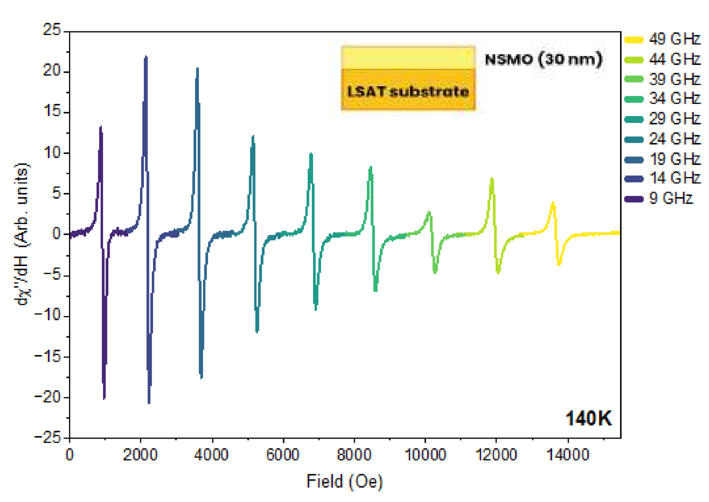


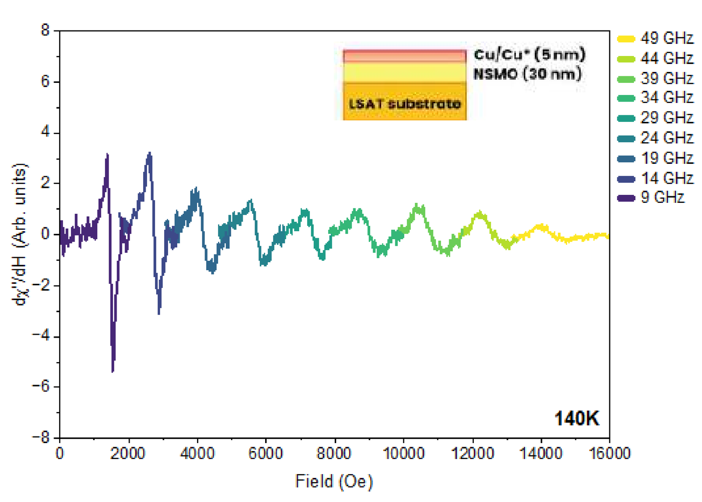


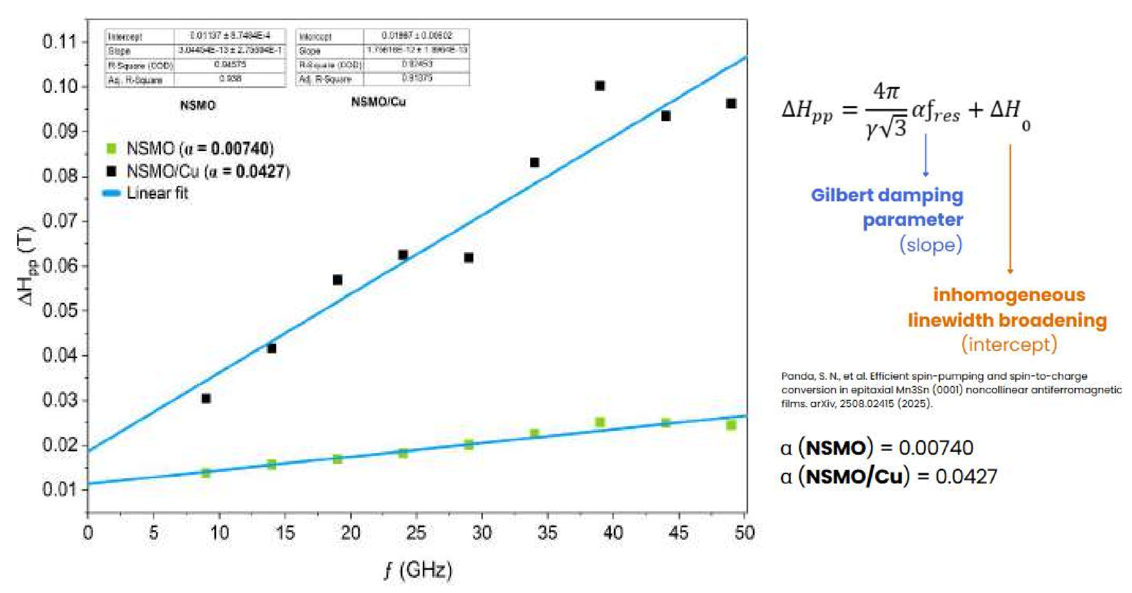


A vanishing X-ray linear dichroism (XLD) integral indicates **orbital degeneracy**, a prerequisite for orbital transport.

Ferromagnetic resonance (FMR)







Naturally oxidized Cu layer (Cu/Cu*) is used to investigate magnetic property modifications and enable inverse Orbital Hall Effect (iOHE) detection.

The disparity in alfa suggests the presence of a spin/orbital-pumping effect.

Scan to discover the website

The Priority Research Program for SPIN (PEPR) is an exploratory program within the framework of the France 2030 investment plan. It aims to develop a new generation of components for a more frugal, agile and sustainable digital world. With a funding of 38 million euros over eight years, the SPIN Research Program is intended to contribute to accompanying a new cycle of innovation in spintronics.

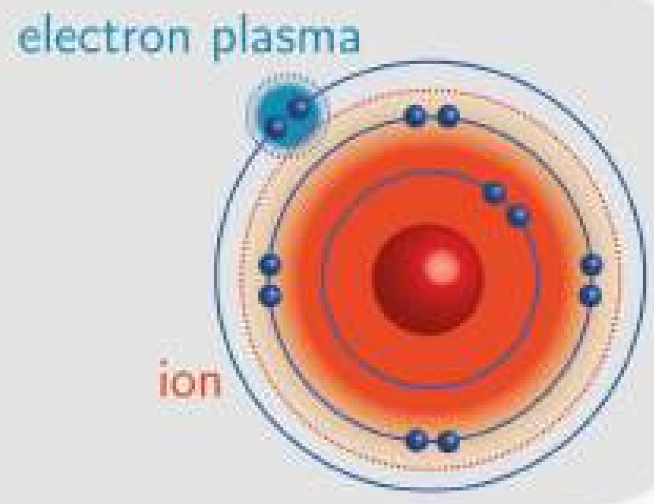
Ultrafast electron-magnon interactions in a ferromagnetic structure

Benjamin Bakri[1], Giovanni Manfredi[1], Paul-Antoine Hervieux[1]

[1]Université de Strasbourg, CNRS, Institut de Physique et de Chimie des Matériaux de Strasbourg

Specificities

- Early stage of the ultrafast demagnetization process (around 10 fs): before spin-orbit coupling, electron-phonon and magnon-phonon interactions [1]
- Non-thermalized electrons: distributions resolved in space and energy
- The semi-classical spin-Vlasov-Poisson-Landau-Lifshitz system models the electrons and the magnetic ions [2]



Electron-Magnon Interaction

Electrons

Spin-Vlasov-Poisson: charge + spin distributions

$$\frac{\partial f_0}{\partial t} + v\frac{\partial f_0}{\partial x} - \frac{1}{m_e}\frac{\partial V_{tot}}{\partial x}\frac{\partial f_0}{\partial v} - \frac{\mu_B}{m_e}\frac{\partial \boldsymbol{B}_{tot}}{\partial x}\cdot\frac{\partial \boldsymbol{f}}{\partial v} = 0$$

$$\frac{\partial \boldsymbol{f}}{\partial t} + \underbrace{v\frac{\partial \boldsymbol{f}}{\partial x} - \frac{1}{m_e}\frac{\partial V_{tot}}{\partial x}\frac{\partial \boldsymbol{f}}{\partial v}}_{\text{advection}} - \underbrace{\frac{\mu_B}{m_e}\frac{\partial \boldsymbol{B}_{tot}}{\partial x}\frac{\partial f_0}{\partial v}}_{\text{Zeeman effect}} - \underbrace{\frac{2}{\hbar}\mu_B \boldsymbol{B}_{tot}\times\boldsymbol{f}}_{\text{spin precession}} = 0$$

- Electrons of the conduction band (s-orbital)
- Resolution in position and velocity
- Inherited from Wigner equation [2]

$V_{tot} = V_H + V_X$ Hartree + Exchange potential

$\boldsymbol{B}_X = -\frac{e^2}{4\pi\varepsilon_0}(n_\uparrow{}^{1/3} - n_\downarrow{}^{1/3})\frac{\boldsymbol{m}}{||\boldsymbol{m}||}$ Exchange magnetic field

- Exchange corrections from DFT: Local Density Approximation [3]

Coupling fields

Mean Field Approximation

$\boldsymbol{B}_{tot} = \boldsymbol{B}_{ions} + \boldsymbol{B}_X$ experienced by electrons

$\boldsymbol{B}_{ions} = -\frac{Kn_i}{2\mu_B}\boldsymbol{S}$ produced by ions

$\boldsymbol{B}_{elec} = -\frac{K}{2\mu_B}\int \boldsymbol{f}\,\mathrm{d}v$ produced by electrons

Ions

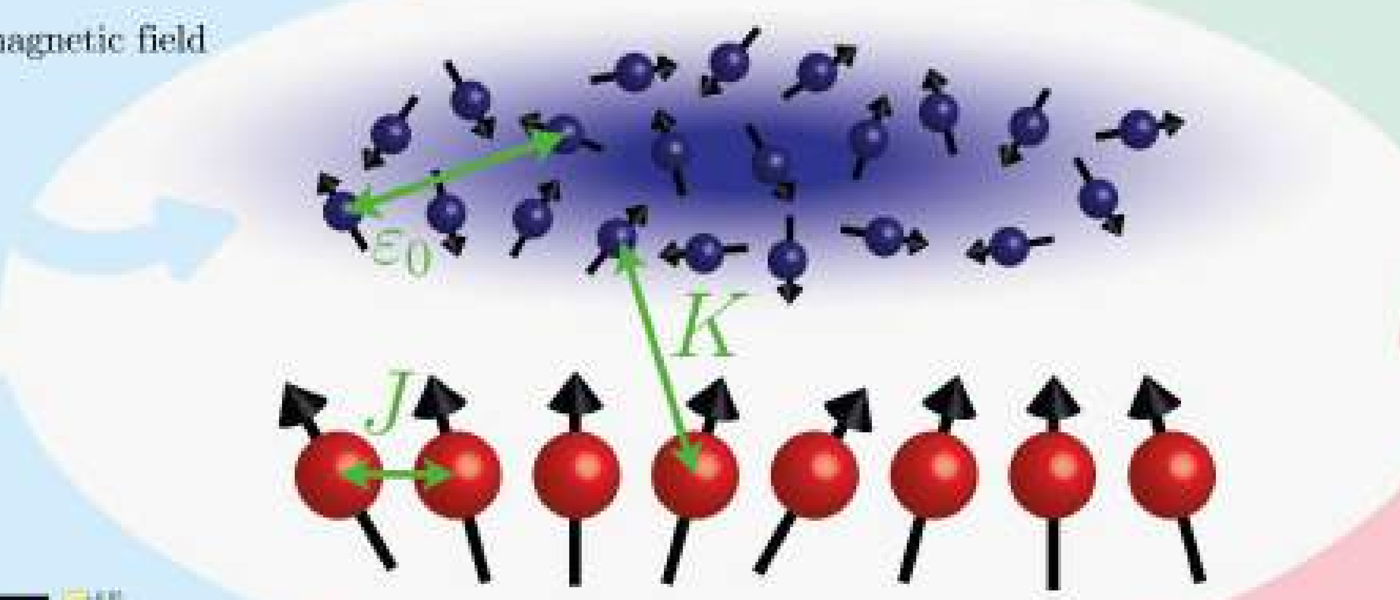
Landau-Lifshitz equation

$$\frac{\partial \boldsymbol{S}}{\partial t} = \frac{a^2 J}{\hbar}\boldsymbol{S}\times\frac{\partial^2 \boldsymbol{S}}{\partial x^2} - \frac{\mu_B}{\hbar}\boldsymbol{S}\times\boldsymbol{B}_{elec}$$

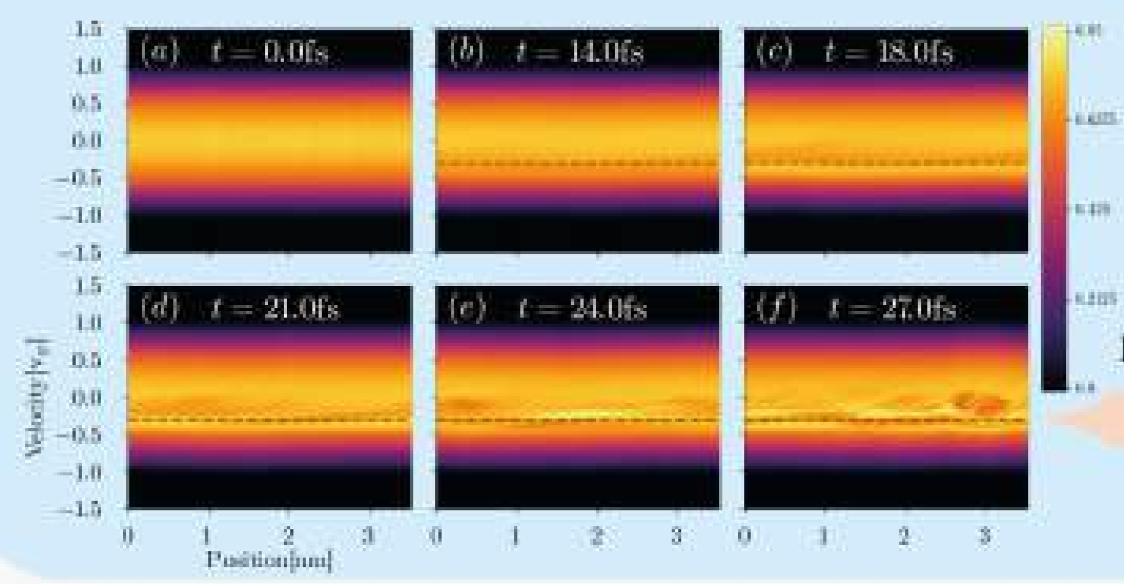
- Magnetic sites (d-orbital)
- Vectorial field
- Magnetic ion-ion + ion-electron interactions
- No velocity dependence (the lattice is fixed)
- No phonons: low time scale (<ps) [1]
- Inherited from the Heisenberg Hamiltonian

$$H_{Heisenberg} = -J\sum_i \boldsymbol{S}_i\cdot\boldsymbol{S}_{i+1} - \mu_B\sum_i \boldsymbol{B}_{elec}\cdot\boldsymbol{S}_i$$

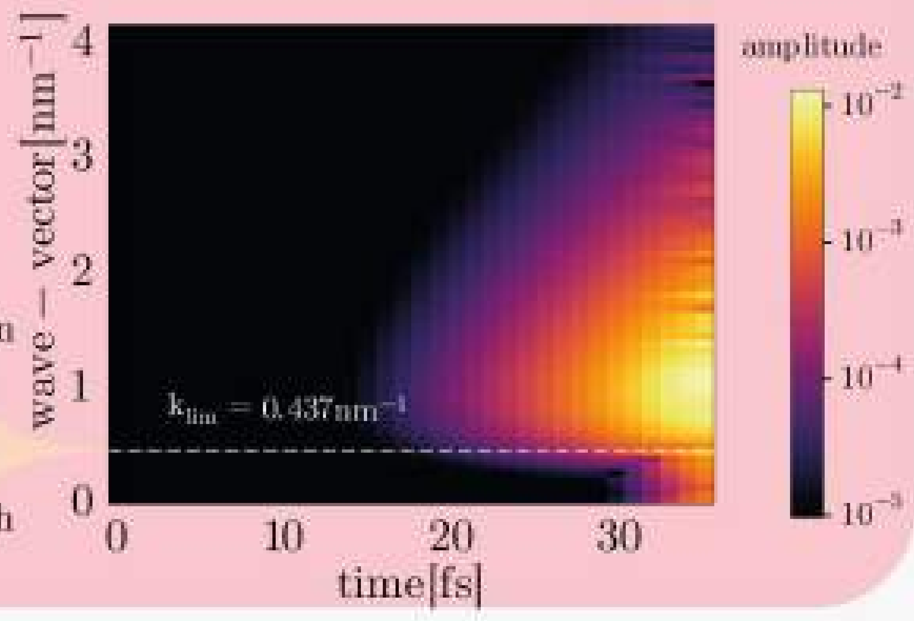
- Nearest neighbor interaction + external magnetic field
- No Gilbert damping: emergent property



Phase space of electrons



Magnon spectrum



Numerical simulations

Electrons		Ions
Low temperature Fermi-Dirac distribution	initial state	Ferromagnetic state + uniform magnon distribution at low amplitude (1e-7)
Resonant velocity		Threshold in wave-vector
Formation of vortices + resonant peak	unstable regime	Exponential growth rate + wave-length threshold

Resonance

Analytical calculations

Dispersion relation

$$D(\omega,k) = \omega - \omega_0 - \frac{Z\eta}{2}\frac{\omega_L}{S_0} - \frac{\omega_L^2}{2n_iS_0}\frac{\left(\frac{\hbar k}{2m_e}I_0 - I_z\right)}{1 + \frac{\alpha d}{m_e}kI_0}$$

$\omega_L = \frac{Kn_iS_0}{\hbar}$

$\omega_0 = \frac{a^2J}{\hbar}k^2$

η = initial electron spin polarization

$I_0(\omega,k) = \int \frac{\frac{\partial f_0^{(0)}}{\partial v}}{kv - \omega + \omega_L}\mathrm{d}v$

$I_z(\omega,k) = \int \frac{f_z^{(0)}}{kv - \omega + \omega_L}\mathrm{d}v$

- no electron-magnon interaction
- electron mean field equilibrium
- Zeeman effect
- electron spin precession
- electron-electron magnetic exchange

$$\omega_r = \omega_0 + \frac{Z}{2S_0}\omega_L(\eta - \eta_{eq})\left(1 - \frac{q}{2}\ln\left|\frac{1+q}{1-q}\right|\right)$$

$$\omega_i = \begin{cases}\pi\frac{Z}{2S_0}\omega_L(\eta_{eq} - \eta)\frac{q}{2} & \text{for } q < 1\\ 0 & \text{for } q > 1\end{cases}$$

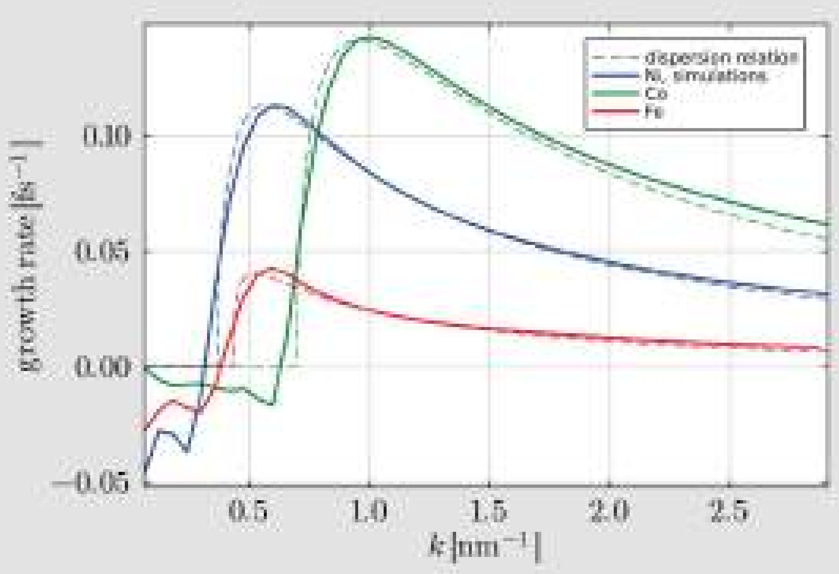
$\eta_{eq} = \frac{3}{4}\frac{\hbar\omega_L}{E_F} = \frac{3}{2}\frac{\mu_B B_0}{E_F}$

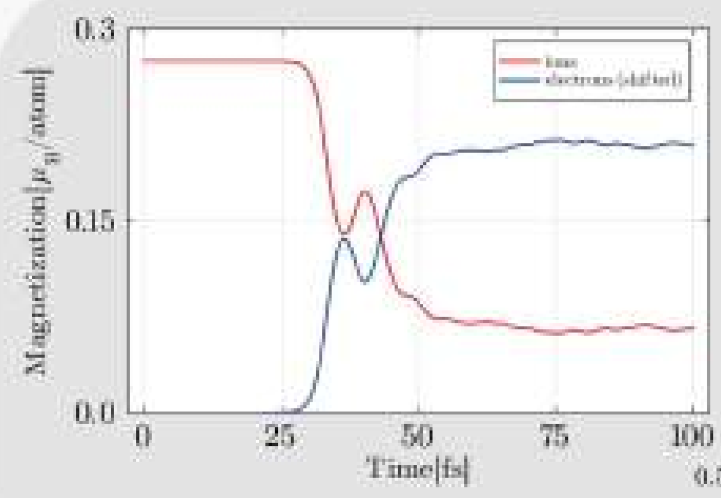
$q = \frac{\omega_L}{kv_F} \approx \frac{v_r}{v_F}$

Hypothesis:

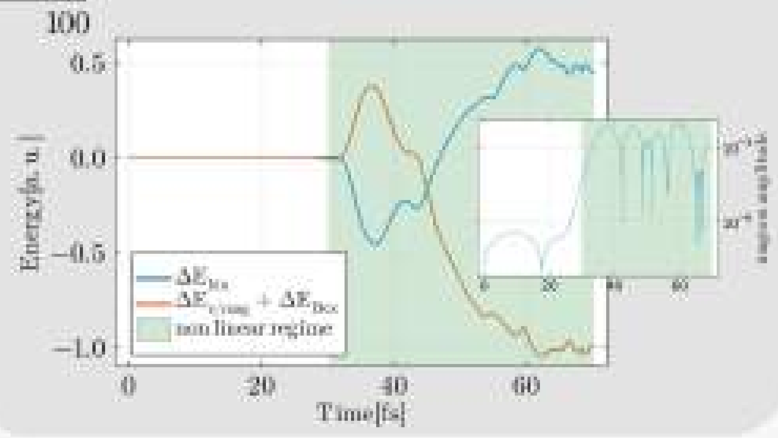
$\eta \ll 1$; $\omega_0 \gg \omega_L \gg \omega$

- Vanishing of the resonance when the resonance velocity exceeds the Fermi velocity





- electron-magnon interaction in unstable regime
- magnetic exchange between the two populations
- mediated by the resonance: magnetic energy transferred into kinetic energy



Conclusion

- Magnetic transfert before the UDM
- No net loss of magnetization: the sVPLL system is Hamiltonian (energy and angular momentum conservation)
- Ab-initio induced Gilbert damping in the stable regime

[1] J-Y. Bigot, M. Vomir, E. Beaurepaire. Coherent ultrafast magnetism induced by femtosecond laser pulses, *Nature Phys 5, 515-520* (2009).
[2] J. Hurst, O. Morandi, G. Manfredi, P-A. Hervieux. Semiclassical Vlasov and fluid models for an electron gas with spin effects. *Eur. Phys.J. D. 68, 176* (2014)
[3] J.P. Perdew, A. Zunger. Self-interaction correction to density-functional approximations for many-electron systems. *Phys. Rev. B 23, 5048* (1981)
[4] B. Bakri, N. Crouseilles, P-A. Hervieux, G. Manfredi. Wave-particle interactions in a spin polarized plasma. *Phys. Plasmas 33, 022111* (2026)

Complex Dynamics of Spintronic oscillators for Random Numbers Generation and Secure Communications

COLIN Pacôme - PhD Student – Institut Jean Lamour – Nancy

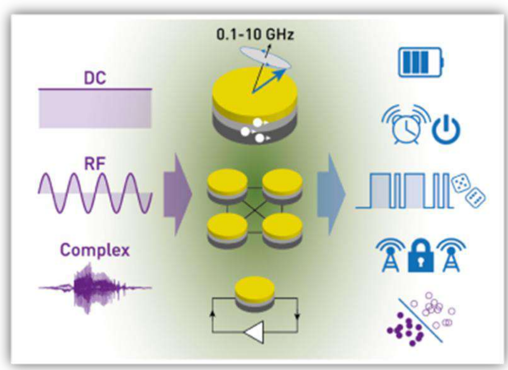
Under the supervision of S. JOVANOVIC[1] and S. PETIT-WATELOT[1]

Career Path

- **PhD Candidate in Physics | Institut Jean Lamour | Nancy** *(2025-202*)*
  Internship | Second Year of Master Degree | Institut Jean Lamour | Nancy *(2025)*
  Complex Dynamic of Spintronic Oscillators in the case of True Random Numbers Generation
- **Internship | First Year of Master Degree | LPCT | Nancy** ***(****2024)*
  Dynamic Quantum Phase Transitions
- **Internship | Bachelor | LPCT | Nancy** *(2023)*
  Electromagnetism in Curved SpaceTime
- **Dormitory Supervisor | Lycée Stanislas / Lycée Jean Prouvé (***2020-2025)*
- **Metrology Technician | Eiffage Route/Crown Bevcan | Nancy/Frouard** *(2019-2020)*
- **Internship Erasmus | Glyndwr University | Wrexham | Wales** *(2018)*

SPINCOM Project

The SPINCOM project is part of the French PEPR SPIN research program dedicated to advanced spintronics technologies. It focuses on developing radio-frequency spintronic devices based on spin-torque nano-oscillators (STNOs) for low-power, secure wireless communications and fast data processing in IoT and edge-computing applications.



The project aims to exploit the nonlinear and multifunctional dynamics of nanoscale magnetic tunnel junctions to improve energy efficiency, RF energy harvesting, data security, and real-time signal classification. Researchers are also studying complex phenomena such as synchronization, chaos, and coupled oscillator dynamics to design compact and intelligent communication hardware.

My Thesis Project

Actually, **cryptography algorithms are based** on **pseudo random number generation**, which implies **biases**. However, **chaotic physical source of entropy** can be used to generate uncorrelated **True Random Numbers (TRNG)**.

Chaos Characterization

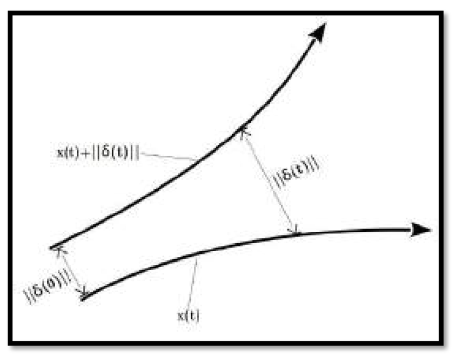
Chaos is defined by the **sensitivity to initial conditions** : two nearby trajectories will expentionnally diverges

$$||\delta_i(t)|| = ||\delta_i(0)||e^{\lambda_i t}$$

λ_i **coefficient are called the Lyapunov exponents.**

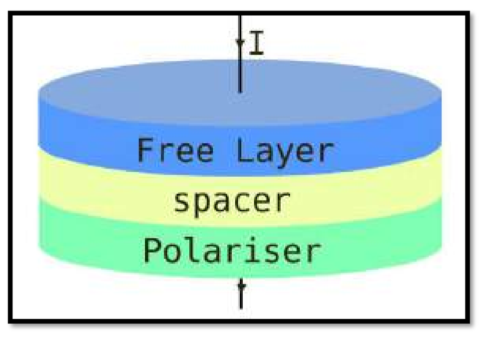
If all λ_i **< 0** → System exhibits **periodic dynamics.**

If at least one λ_i **> 0** →System exhibits **chaotic dynamics**.



Spin Torque Nano Oscillators

Spin-torque nano-oscillators (STNO) are **CMOS-compatible nanoscale devices** that operate at frequencies close to the GHz and can exhibit **chaotic behavior** under certain **operating conditions**.

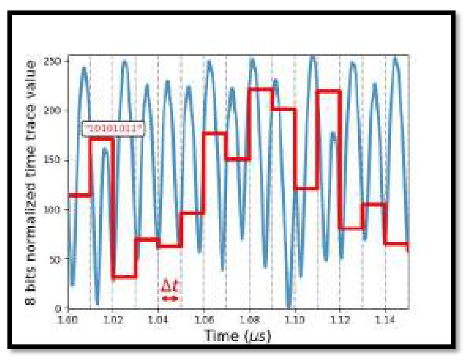


Idealized STNO schematic

Is it possible to exploit the complex dynamics of STNOs to generate True Random Numbers, from acquisition to post-processing?

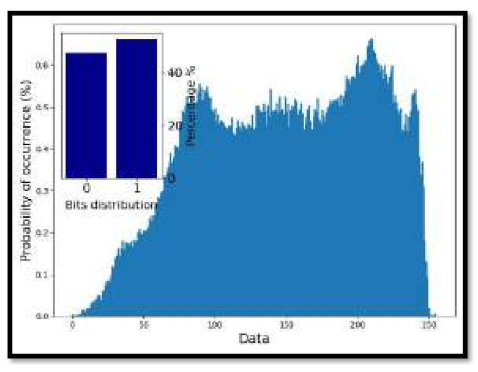
Preliminary Results

Chaotic signal digitalization



8 bits sampling of the time trace

The study by **A. Kolli[2]** shows that, in **high-power ferromagnetic resonance (FMR),** under certain conditions the dynamics can become **chaotic** with $\lambda_{max} = 1.55$ GHz.



8 bits numbers distribution of the system

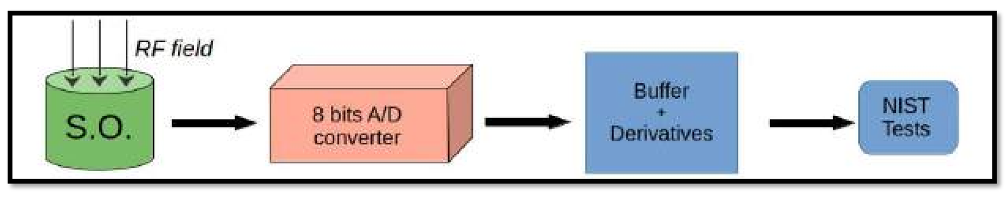
Parameters :

- $\langle m_z \rangle$ dynamic component sampling.
- 8 bits Analogic-Digital Converter
- *Frequency sampling* f_s = 100 MHz

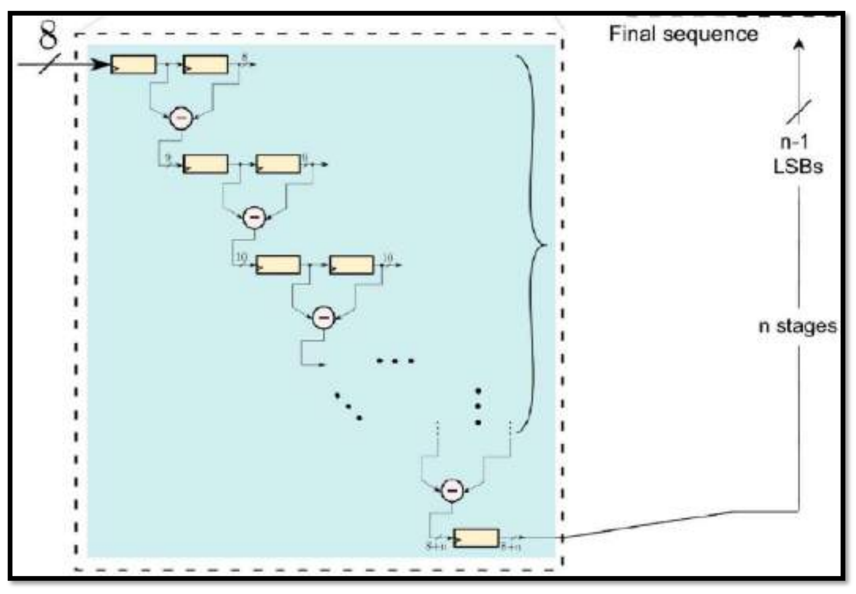
Randomness tests do not pass.

Post-processing derivatives protocol for biases attenuation

- **Sequence of derivative stages** between acquisition and randomness testing.
- Two adjacent 8-bit are **subtracted**.
- **Sign extension** is applied to avoid overflow.
- 2 following 9-bit output are again subtracted.
- **Process repeated N times**.
- Arbitrary number of **Least Significant Bits** n_b retained.

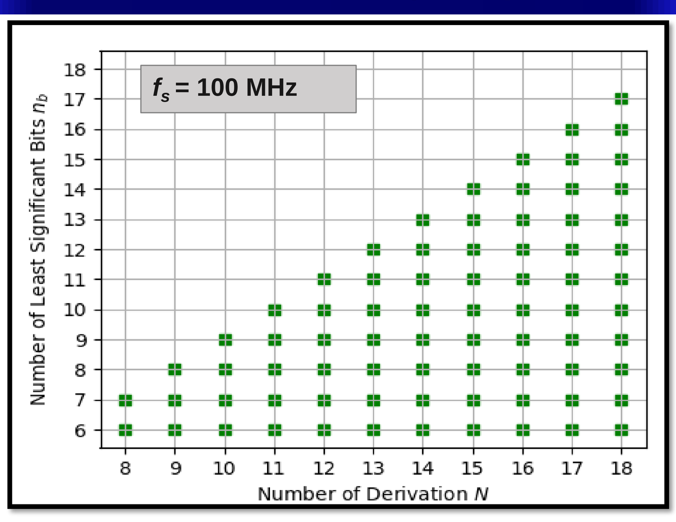


Bias attenuation acquisition device



N derivatives stages schematic.

Randomness test after post-processing



NIST tests for various values of N and n_b

Green points → random bitstream,

red points → non-random bitstream.

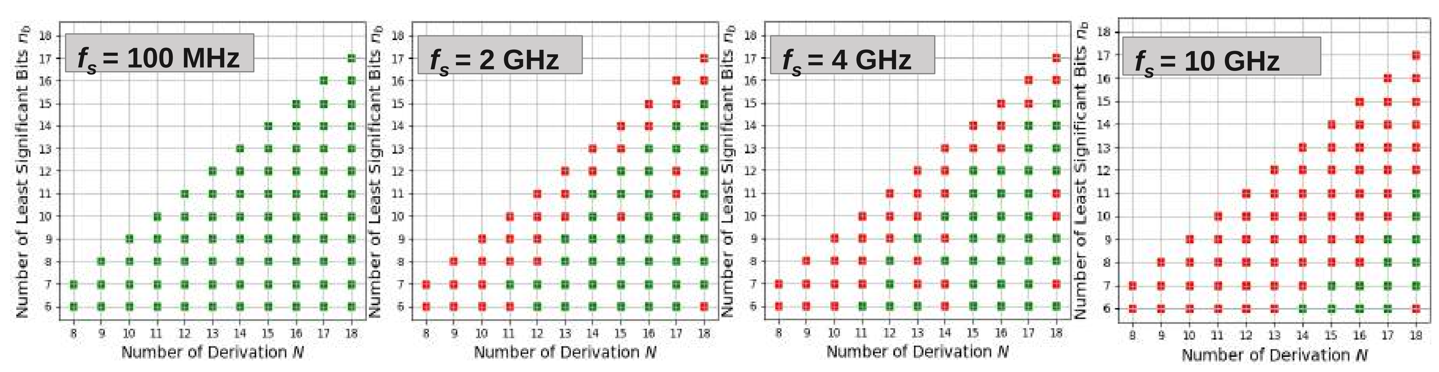
After post process with **N=9, n_b=6** bits distribution $\Delta_{0,1}$**= 0.017% → Bias Reduction.**

Two following numbers are **uncorrelated** :

Random Bitstream for all parameters

Sampling frequency influence

If $f_s > \lambda_{max}$ **= 1.55 GHz :** Two following numbers before derivatives are correlated → randomness tests should be valid until f_s.



If the sampling frequency $f_s < \lambda_{max}$**, the randomness tests are validated. However, the derivative protocol can be applied at higher frequencies although over a more restricted range of parameters.**

Scan to discover the website

[1] ***Institut Jean Lamour****, CNRS-Université de Lorraine, Campus Artem, 2 allée André Guinier, 54011 Nancy*

[2] **Service de Physique de l'Etat Condensé** Bât. 772, Orme des Merisiers, CEA Saclay, F-91191, Gif sur Yvette, France

Spintronics innovations for a frugal, agile, and sustainable digital future

Spin Transfer Torque Magnetic Field Sensing

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Career path

Nanoscience and Nanotechnology : UAB Universitat Autònoma de Barcelona; Universitat de Barcelona

Bachelor thesis : ICMAB Institut de Ciència de Materials de Barcelona (Excelencia Severo Ochoa)

Internship: Futurechromes — ICN2 Institut Català de Nanociència i Nanotecnologia

T. Zakusylo et al., Mater. Horiz., 2024, 11, 2388

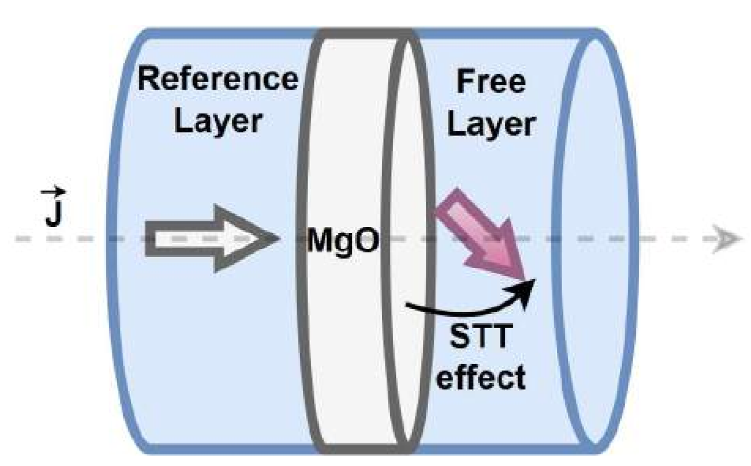
ADAGE project

ADAGE — Augmented Magnetic Sensing is a targeted project within spintronic innovations for energy efficient, agile and sustainable digital applications. It aims to develop a new generation of spintronic magnetic sensors that are more **sensitive**, **energy- efficient**, **agile** and **versatile**, by combining nanomagnetism, advanced nanofabrication, new materials and electronic architectures.

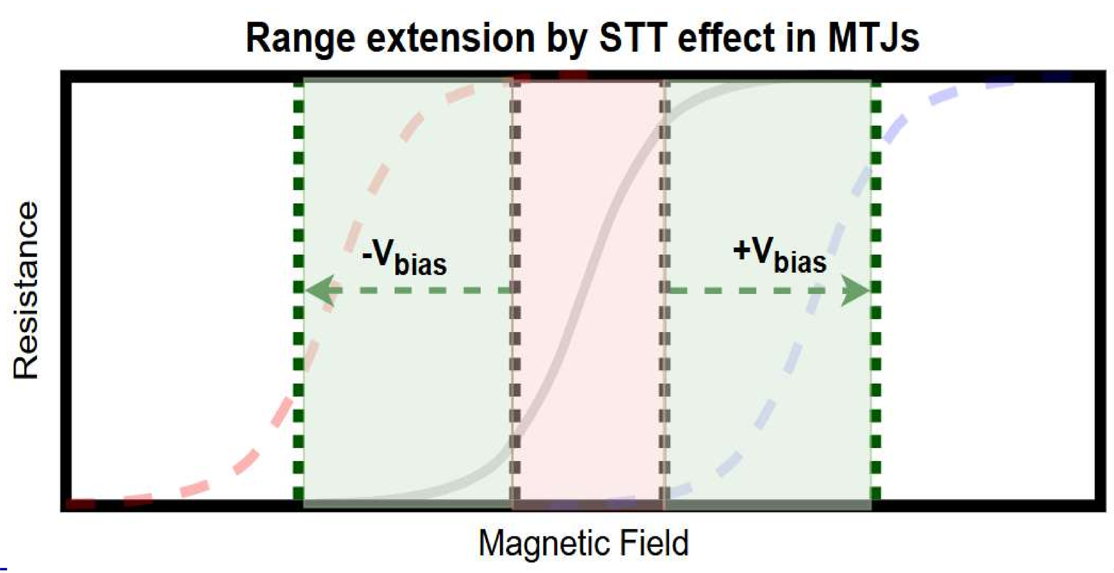
A key objective of ADAGE is to create **intelligent magnetic sensors** with adjustable properties such as range, linearity and directivity. These sensors are designed to adapt their configuration during operation, optimizing detection depending on the application and measurement conditions.

Thesis description

- The objective of the project is to develop a **compact**, **energy-efficient** and **tunable** spintronic sensors.
- **Spin-transfer torque** is exploited as electrical tuning mechanism allowing the shift of the sensor transfer curve.
- As a result the **operating range is extended without** the need of **external coils.**

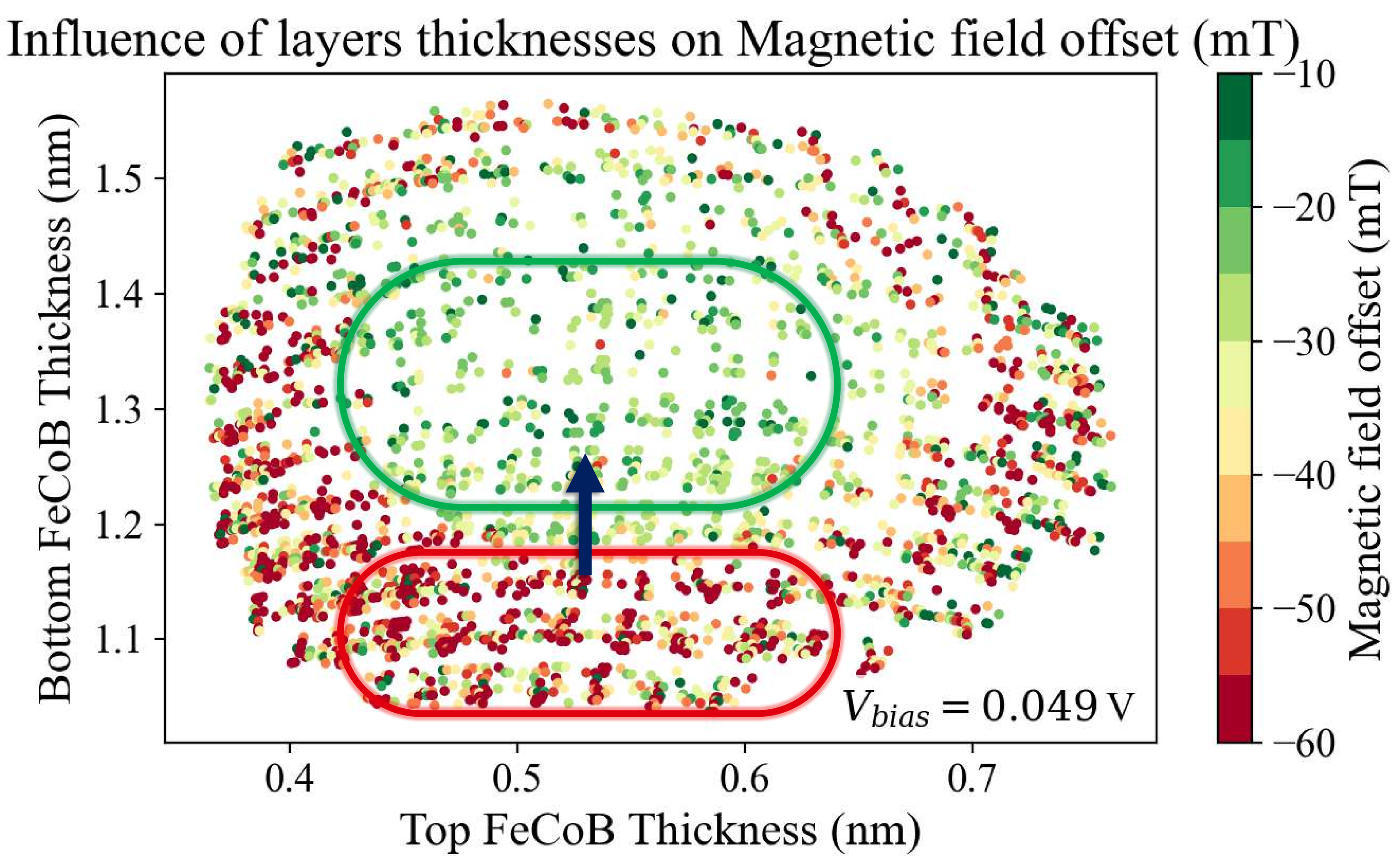


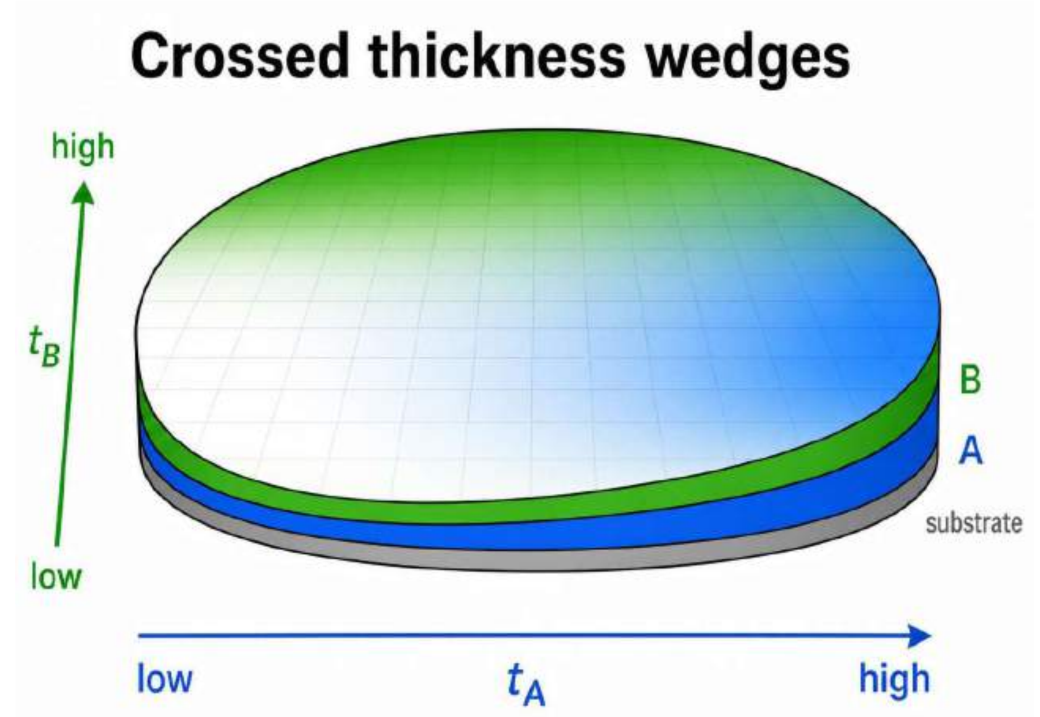
Switchable by magnetic field and current



Preliminary results / Highlights

- Crossed wedge wafers allow full stack mapping
- Wafer maps reveal offset, linearity and range trends
- **Problem:** Initial stack showed a **large offset**

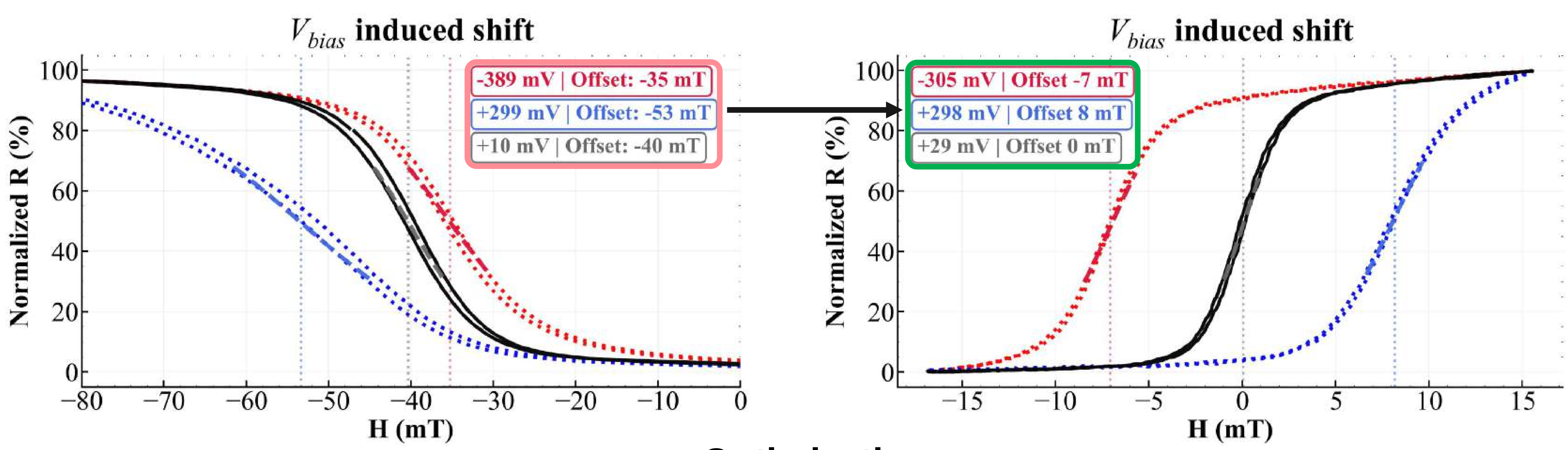




Optimization proposal:

Thicker Bottom FeCoB Layer

(Reference Layer)



Asymmetric with large offset — Optimization / Thicker RL → **Symmetric without offset**

The Priority Research Program for SPIN (PEPR) is an exploratory program within the framework of the France 2030 investment plan.

It aims to develop a new generation of components for a more frugal, agile, and sustainable digital world. With a funding of 38 million euros over eight years, the SPIN Research Program is intended to contribute to accompanying a new cycle of innovation in spintronics.

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Generation of chaotic signals with spin-torque vortex oscillators

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(1) Université Grenoble Alpes, CEA, CNRS, Grenoble INP, SPINTEC, France
(2) Université de Lorraine, CNRS, Institut Jean Lamour, Nancy, France

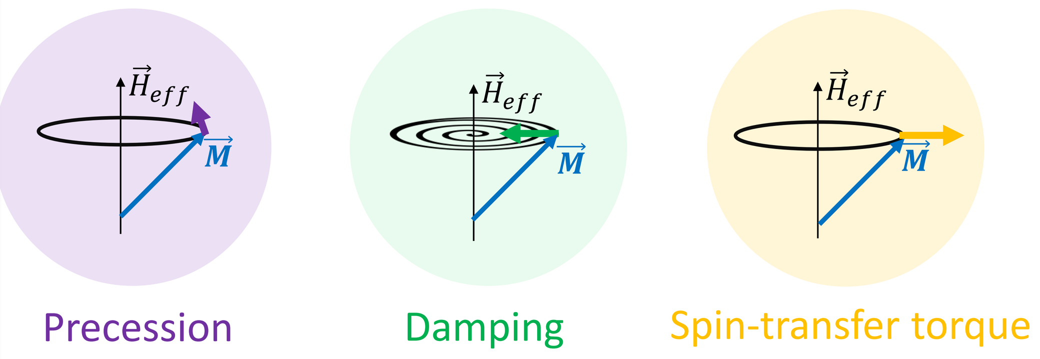
ABSTRACT

- Secure communication is a key requirement for wireless sensor networks and communicating objects. To ensure the data encryption, we need encryption keys that are inaccessible to anyone except the intended receiver. The use of true random numbers is a very promising approach to achieve this by providing unpredictable sequences.
- True random numbers can be generated through physical processes such as thermal noise or chaotic signals. Among these, spin-torque vortex oscillators (STVO) are promising candidates for chaos generation due to their intrinsic non-linear properties.
- Here we investigate the dynamics of an STVO under self-delayed feedback as a route to chaos.

Spin-torque vortex oscillators

Landau-Lifshitz-Gilbert-Slonczewski equation: Describes the dynamics of the magnetization $\vec{M}$.

$$\frac{d\vec{M}}{dt} = -\Upsilon\vec{M}\times\vec{H}_{eff} + \frac{\alpha}{M_s}\vec{M}\times\frac{d\vec{M}}{dt} + \frac{\Upsilon\alpha J}{M_s}\vec{M}\times(\vec{M}\times\vec{P})$$

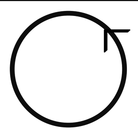


Existence of a critical current I_c :

For $I < I_c$: Damping > STT

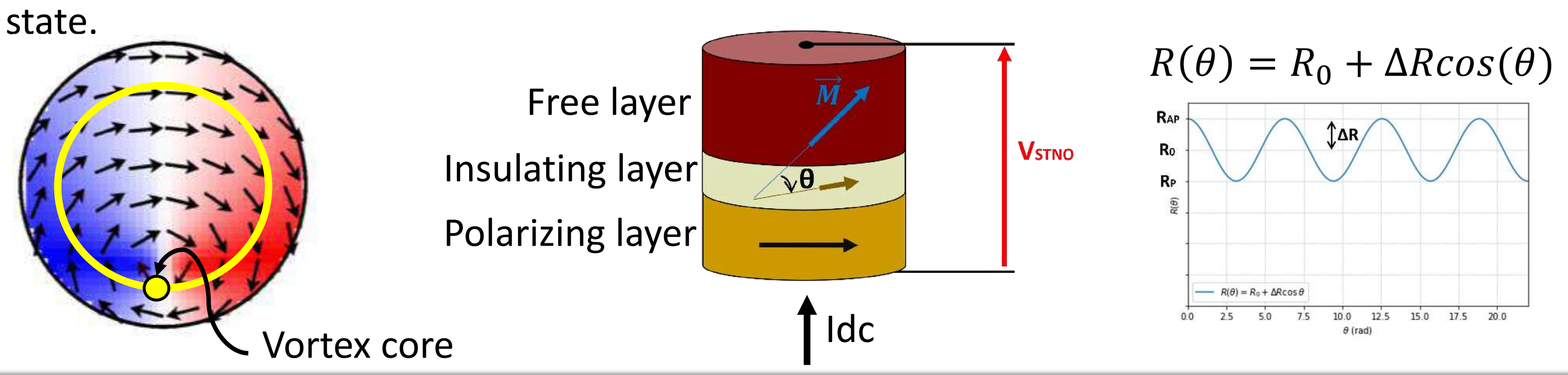
Relaxation of $\vec{M}$ along its equilibrium position.

For $I > I_c$: STT > Damping



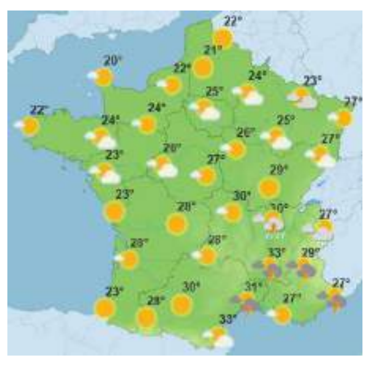
Steady state oscillations on a limit cycle.

STVO: Injection of a dc current I_{dc} generates an RF signal via steady-state magnetization oscillations of the vortex free layer. The tunnel magnetoresistance is used to read the dynamical state.

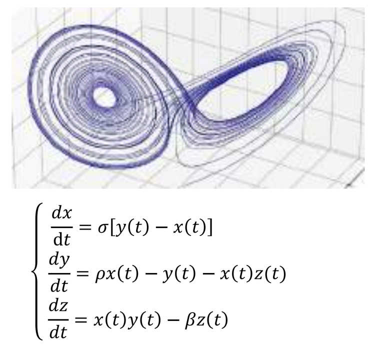


Chaotic systems

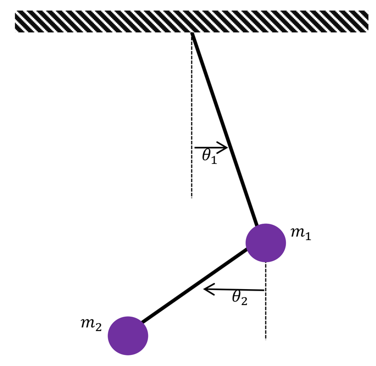
Examples of chaotic systems:



Weather



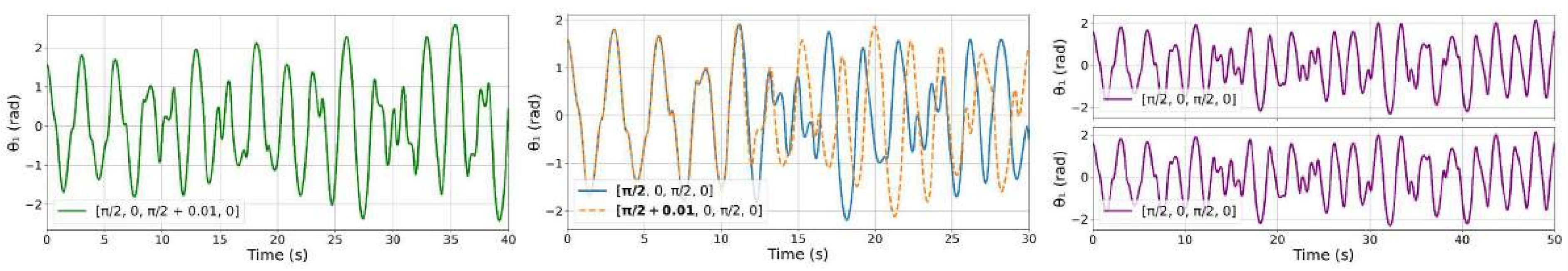
Lorenz attractor



Double pendulum

Properties of chaotic systems:

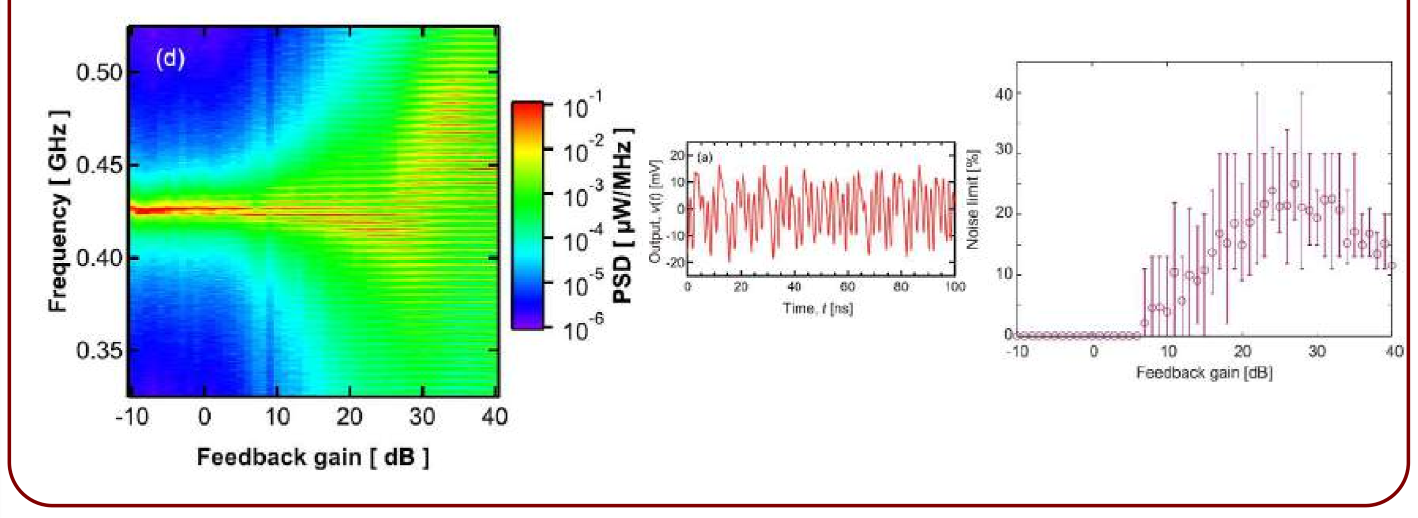
Simulation of the double pendulum with initial conditions: $[\theta_1, \frac{d\theta_1}{dt}, \theta_2, \frac{d\theta_2}{dt}]$



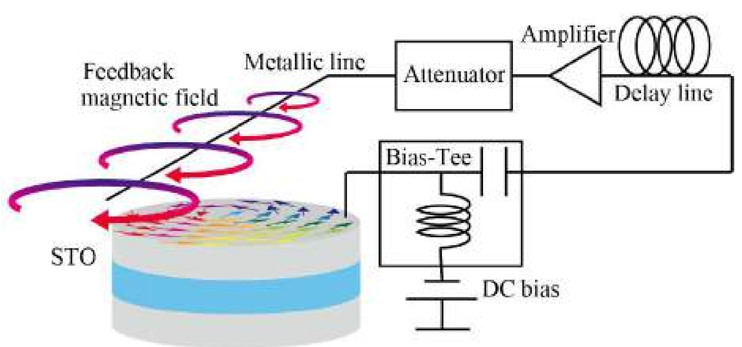
Aperiodic: never repeats — Sensitive to initial conditions — Deterministic: no randomness

Studies from literature:

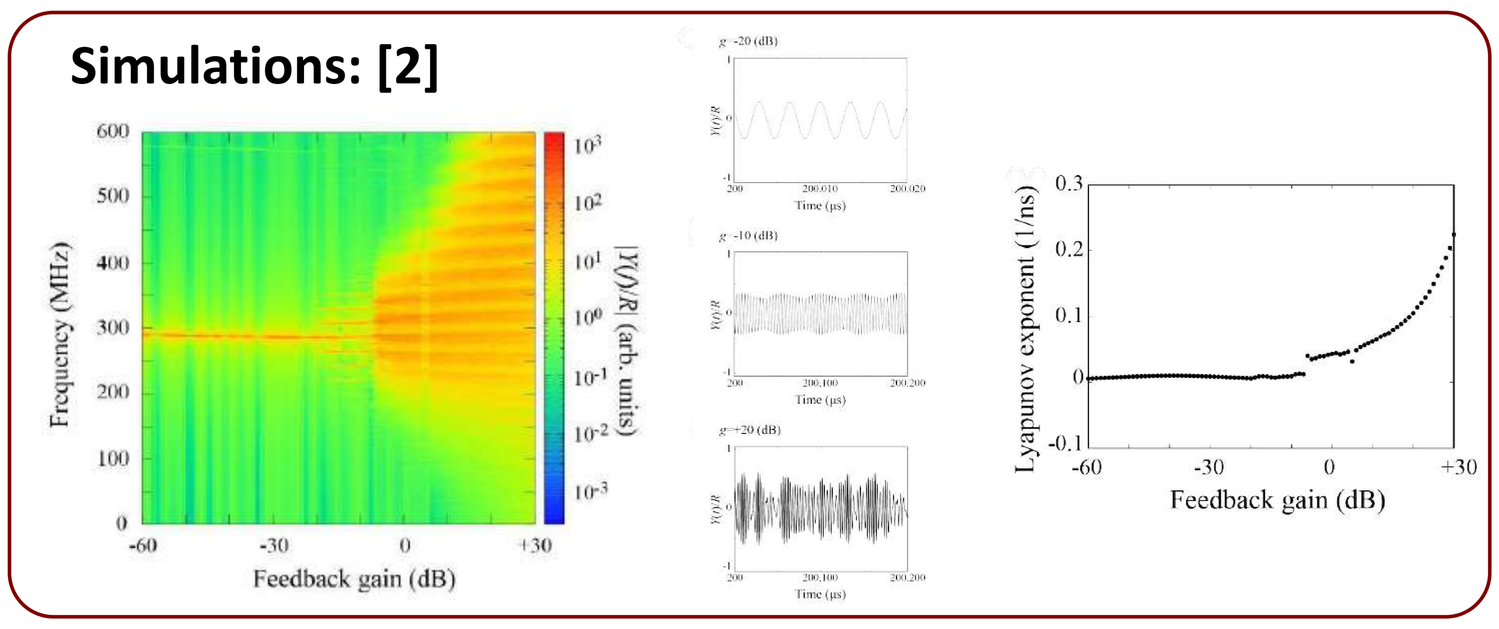
Experiments: [1]



Setup:



Simulations: [2]



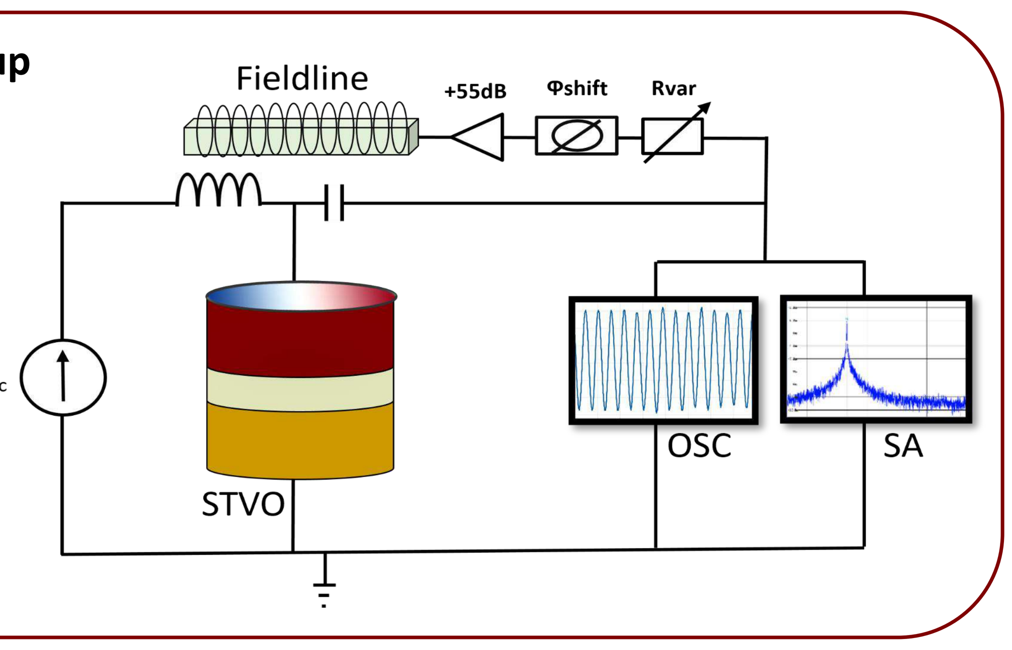
First results with magnetic delayed feedback

Experimental setup

→ Feedback control:

Φ_{shift}: shifting the phase

R_{var}: adjusting feedback strength



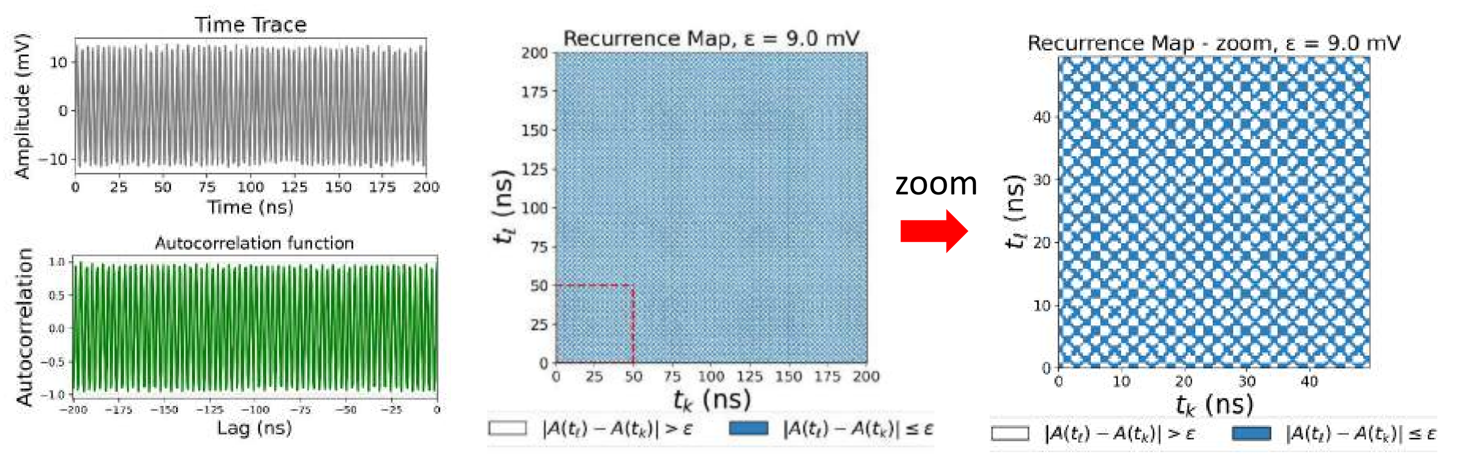
Analysis techniques

Recurrence maps: show how the system revisits similar states in space.

Auto-correlation function: measures how the signal relates to itself over time

Currently developped: Reconstruction of the attractor, derivation of the Lyapunov exponents, noise titration.

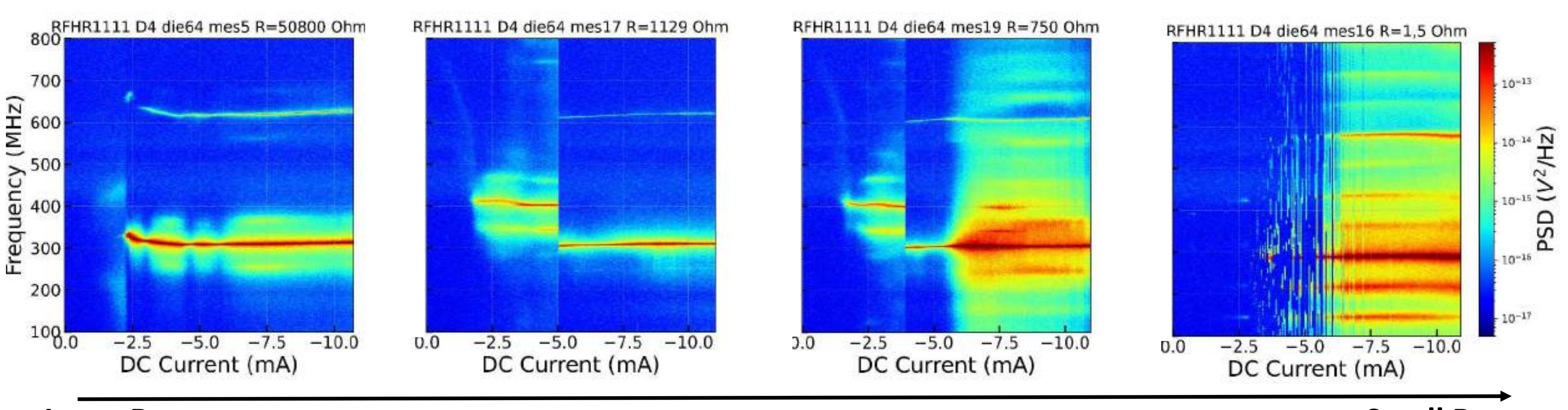
Results for low auto-coupling: $R_{variable}$ = 50 800 Ohm



→ Sinusoidal time-trace
→ Sinusoidal $R_{AA}(\tau)$

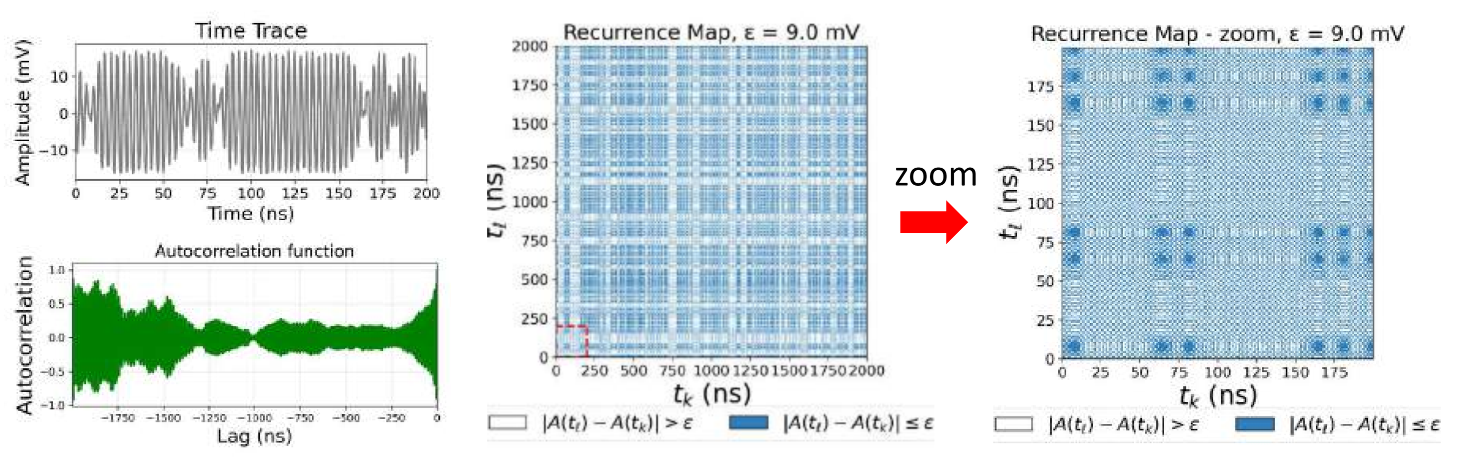
→ Periodic patterns in both full and zoomed maps

Spectra when changing the coupling strength through R



Large R → Small R

Results for high auto-coupling: $R_{variable}$ = 1.8 Ohm



→ Irregular time-trace
→ Fluctuating $R_{AA}(\tau)$

→ Complex patterns in both maps and auto-similarities

CONCLUSIONS

- *Complex signals that could lead to a chaotic dynamic were generated using a magnetic-fieldline feedback setup. This experiment allowed us to understand the physics behind delayed autofeedback and to establish a process for analyzing chaotic signals through time traces that will be useful for further studies.*
- ***Perspectives: Further investigations will include unidirectional and bidirectional coupling of one or two STVOs, as well as exploring resonance phenomena and other STVO configurations.***

REFERENCES

1. A. Kamimaki, PhysRevResearch 3, 043216 (2021)
2. T. Taniguchi, PhysRevB 109, 214412 (2024)

ACKNOWLEDGEMENTS

PEPR SPIN – SPINCOM ANR-22 EXSP-0005 : This PhD takes is funded by the SpinCom project of the PEPR Spin aiming to develop innovative, energy efficient and secure solutions for wireless communications and edge computing
ANR SpinIm (ANR-22-CE24-0004).
CEA programme FOCUS NUMERIQUE FRUGAL

FRANCE 2030 PROGRAMME DE RECHERCHE SPINTRONIQUE

SPINTEC channels
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FRANCE 2030 PROGRAMME DE RECHERCHE SPINTRONIQUE

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FERROELECTRIC OXIDES FOR ULTRA LOW POWER SPINTRONIC APPLICATIONS

Christian Diehl NGOMA MANICKA, PhD Candidate, CRISMAT CNRS

Julien VARIGNON, Sébastien PETIT, Wilfrid PRELLIER – CRISMAT UMR 6508 ENSICAEN CNRS UNICAEN

Career path

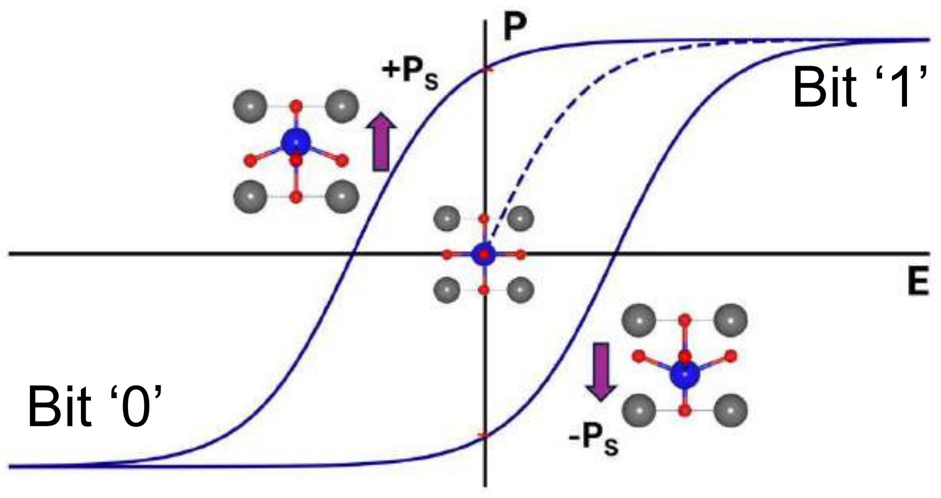
- **2016-2018:** CUPGE, Cergy-Paris Université, FR
- **2019**: Bachelor in Mathematics and Physics, CY Cergy-Paris Université, FR
- **2024**: Master in Physics and Modelisation, CY Cergy-Paris Université, FR
- **2025**: PhD Candidate, CRISMAT, Caen FR

Spinmat project

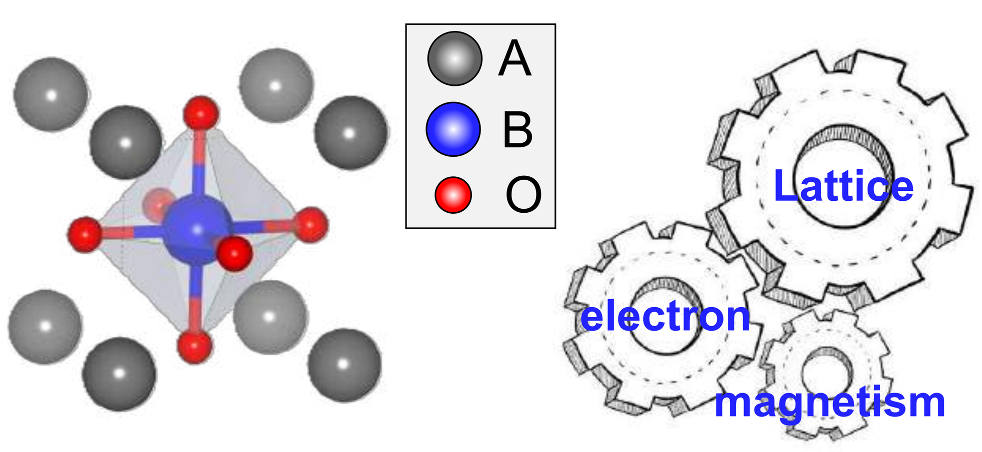
SPINMAT is a targeted project of the **PEPR Spintronics** program. Its ambition is to build a national platform with unique capabilities for the design and production of new spintronic materials. The project addresses **three major challenges**: **low energy consumption**, **spin-charge conversion**, and the development of reconfigurable and **neuromorphic architectures**. It relies on five pillars, from optimizing existing materials to introducing emerging solutions such as **multifunctional oxides**, 2D magnetic materials, and topological insulator-based heterostructures.

PhD project

In the quest for low-power electronic devices, **ferroelectric** (FE) materials offer a highly promising route: reversing a spontaneous polarization P_s requires far less energy than switching a magnetization. Coupling FE with electronic and magnetic properties thus emerges as a powerful lever to design energy-efficient compounds capable of addressing today's climate and economic challenges.



The **goal** of the PhD is to **identify/design** compounds **combining FE and magnetism**, based on ABO_3 perovskite oxides. Studies are carried out with **electronic structure calculations**, possibly **combined** with **systematic methods** such as high-throughput, machine learning or genetic algorithm.



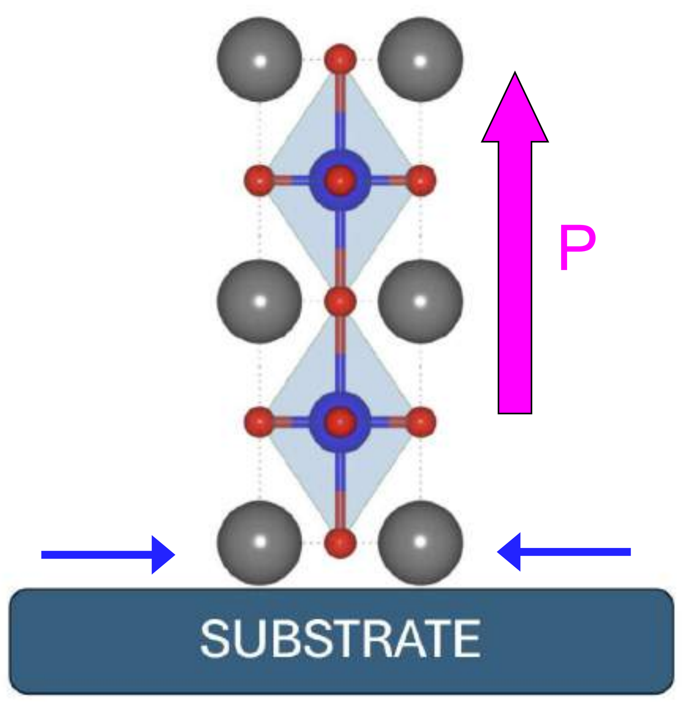
"Epitaxial strain-induced ferroelectricity: why some oxides respond and others don't"

Most ABO_3 perovskites are PE ∀ T. **Epitaxial strain** η is usually used to **engineer FE**. Yet it **works** rarely in magnetic ones. Why?

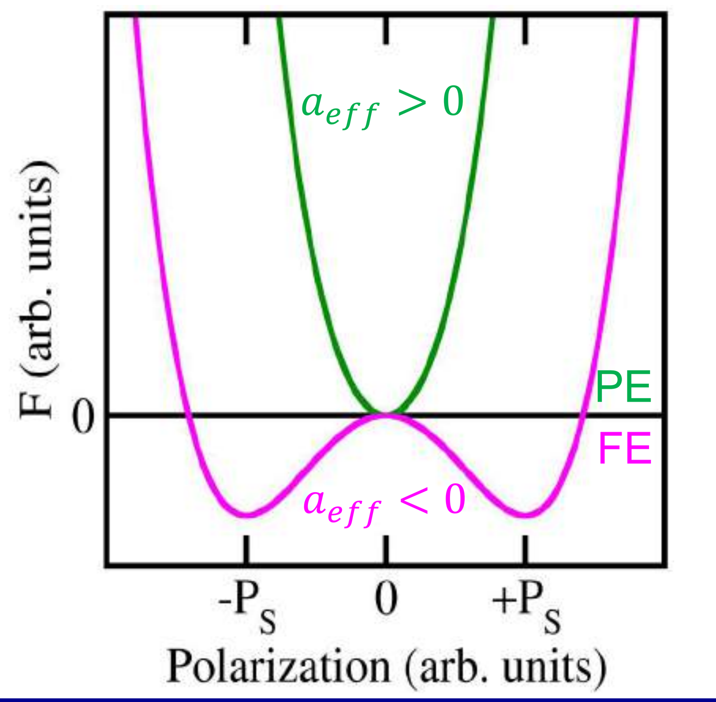
➢ **Rationale** the **role of η** on the emergence of **FE** between ≠ ABO_3 thin films.

Test 2 ≠ compounds $Ca^{2+}Ti^{4+}O_3$ & $Y^{3+}Sc^{3+}O_3$ (d^0 configuration) with a compressive strain η. Results are mapped on a Landau model of F

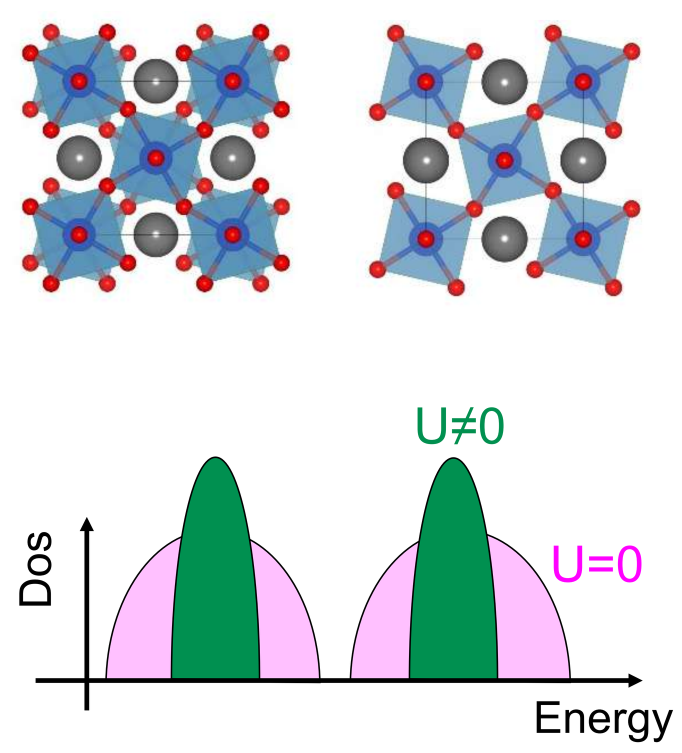
strain η



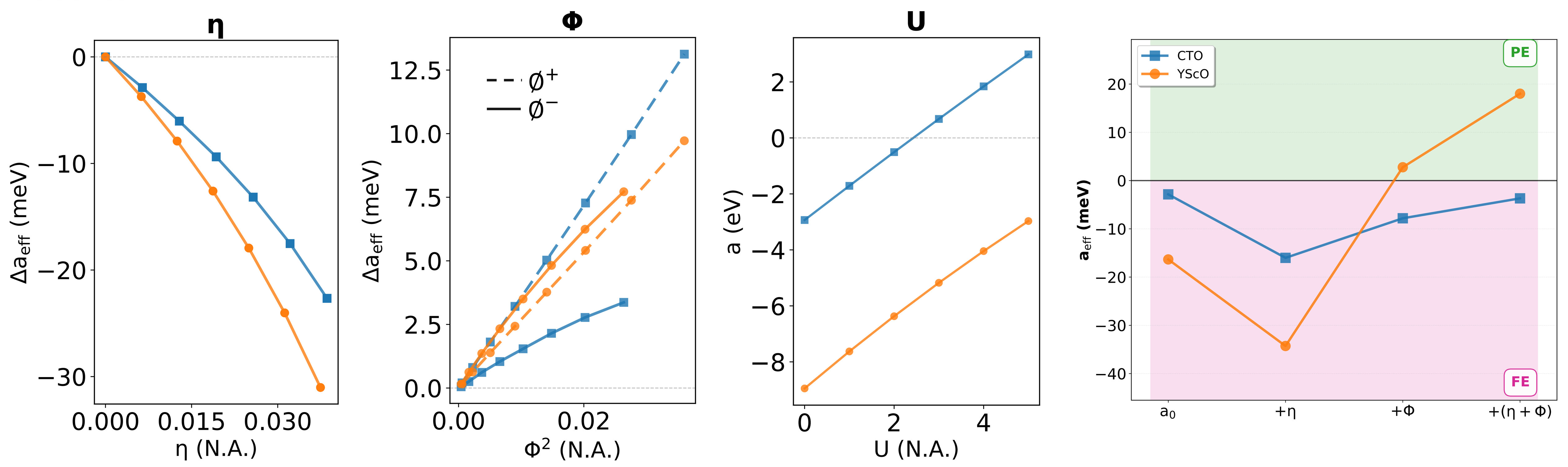
$$F \propto a_{eff}P^2 + bP^4$$
$$a_{eff} = f(\eta, \emptyset, U \dots), (b > 0)$$



Rotations ∅



Results:



✓ **η favors FE** ∀ ABO_3

✓ **∅ and correlation U**, both producing localized electronic structures -- **kills FE**

➢ **Competition between η and** ∅ + U governs whether a given ABO_3 compound undergoes a FE transition — a balance directly controlled by the choice of A & B

Scan to discover the PEPR spin website

Work supported by (i) the *Programme et Équipements Prioritaires de Recherche* (PEPR) through the SPINMAT project, (i) the Normandy Region through the RiN project « *Ferroelectric Oxides for Spintronics* » (OFERS) & the *Contrat Plan État–Région* (CPER) PROPRE project « *Research of Materials with Record Properties* ».

Scan to have contact informations

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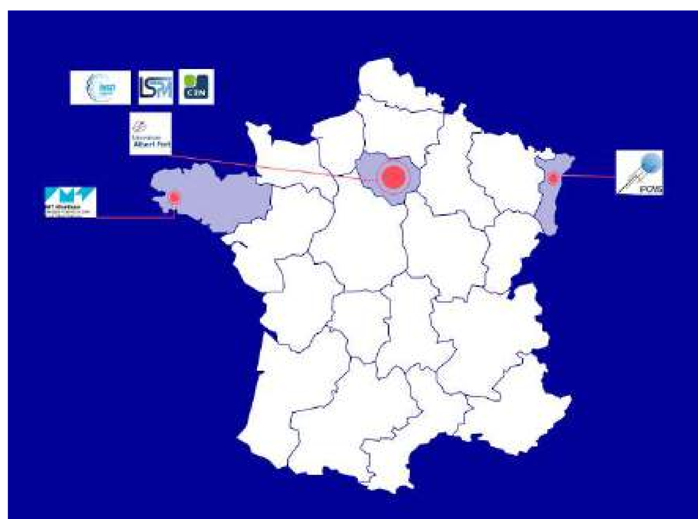
FRANCE 2030 PROGRAMME DE RECHERCHE SPINTRONIQUE

Investigation of spin wave propagation in topological magnonic nanostructures

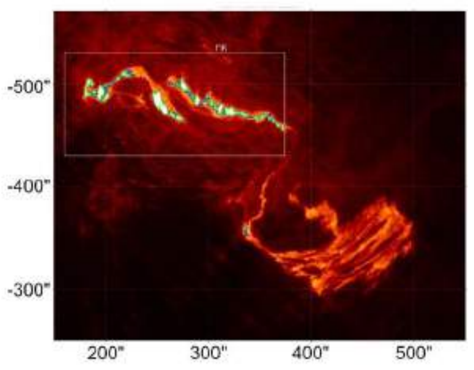
Greeshmani Doddi

Supervisors: **Abdelmadjid Anane**, **Ping Che**

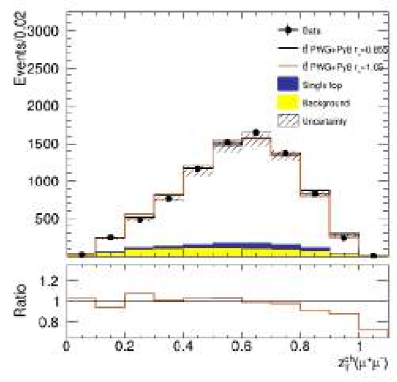
Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, Palaiseau, France



My Academic Journey



X-class solar flare ribbons (2014)



Probing b-quark fragmentation from CERN data

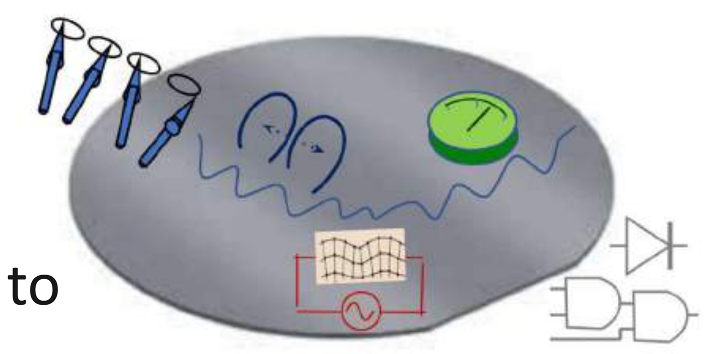
Bachelors: NIT Calicut, India in Engineering Physics.

Masters: Sorbonne Université - Nuclear Particle, Astroparticle & Cosmology (**NPAC**).

Masters 2: Sorbonne Université - Sciences des matériaux et nano-objets (**SMNO - Nanomat**).

Spin Waves for Signal Processing (SWING)

The SWING project is part of **magnonics**, which exploits spin waves (magnons) for next-generation information technologies using their phase and amplitude for coding.



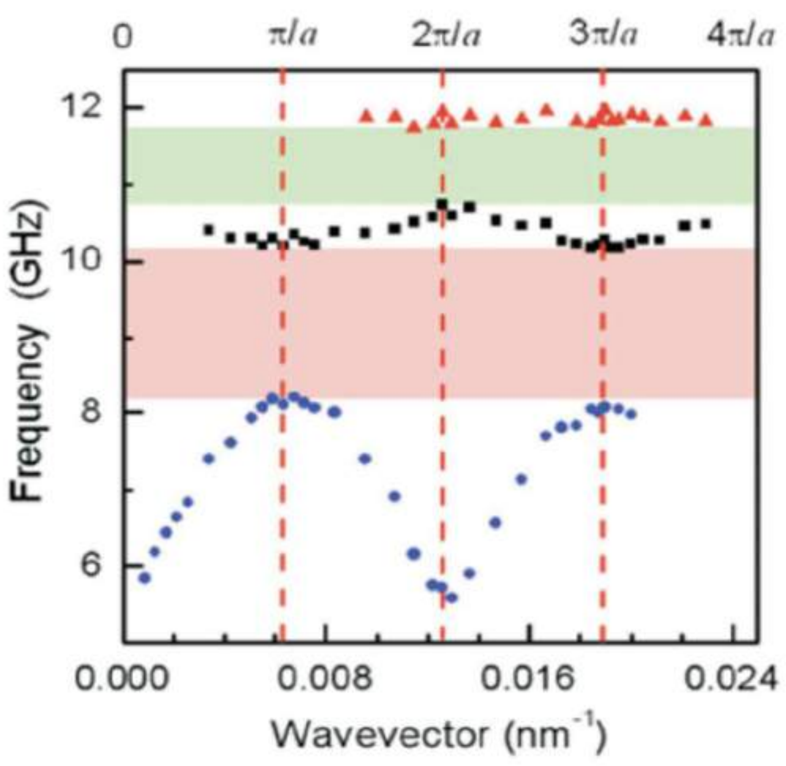
Interactions between spin waves and complex magnetic structures studied to develop key components for future Magnonic circuits.

Reconfigurable Magnonic Crystal formed by stripe domain textures in BiYIG

Goal: Bismuth-doped Yttrium Iron Garnet (BiYIG) exhibits perpendicular magnetic anisotropy (PMA) with $H_K \approx M_{sat}$ The competition between different magnetic energies leads to non-uniform magnetic textures such as topological bubbles. We study spin-wave propagation through these textures in a 20 nm BiYIG thin film.

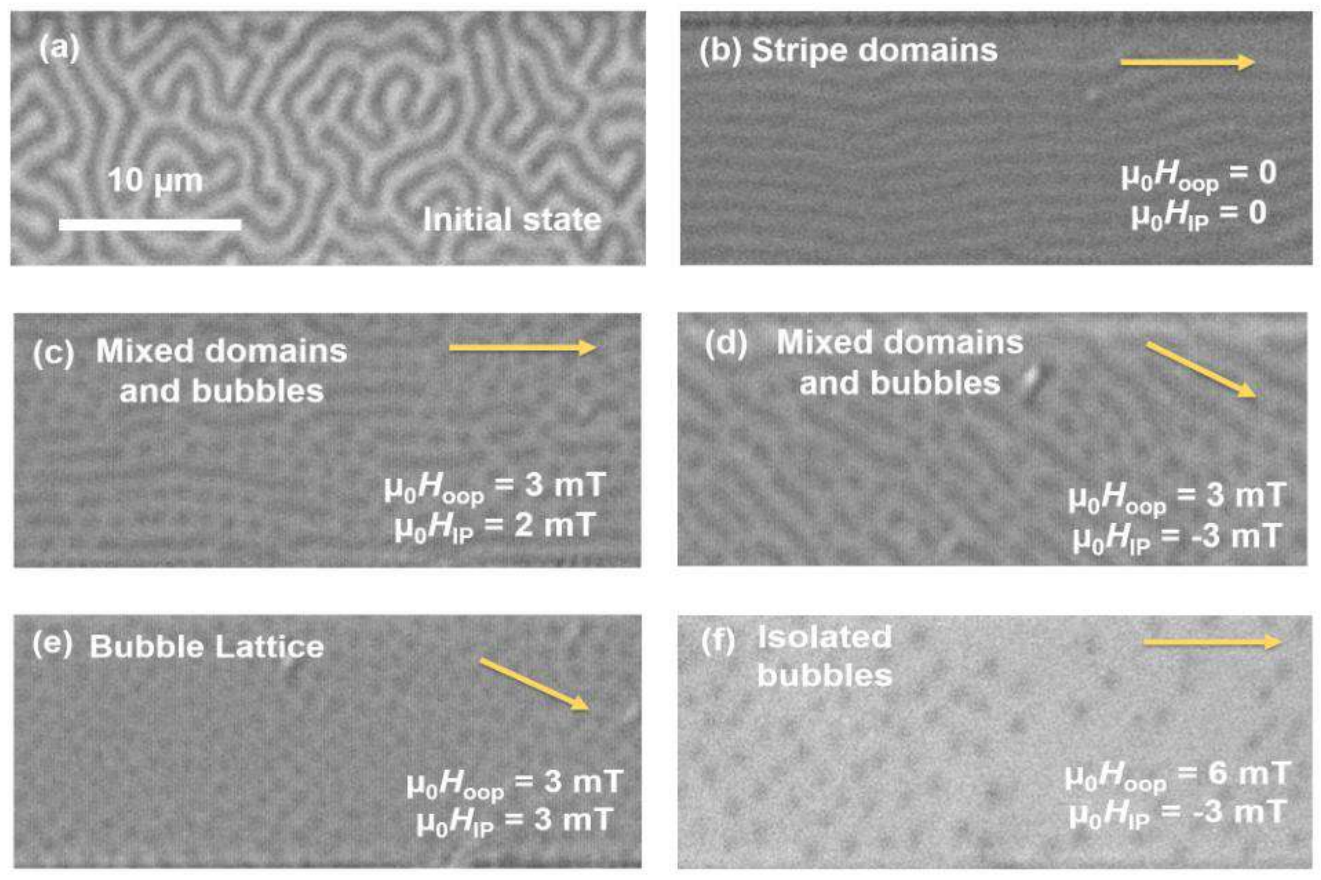
Magnonic Crystal

Periodic variation of magnetic properties.
Band gap at $k = \pm \pi/a$ (λ =2a)



Using MOKE, the several magnetic phases created are imaged:

- Striped domain lattice
- Topological bubble lattice
- Mixed state of domains & bubbles

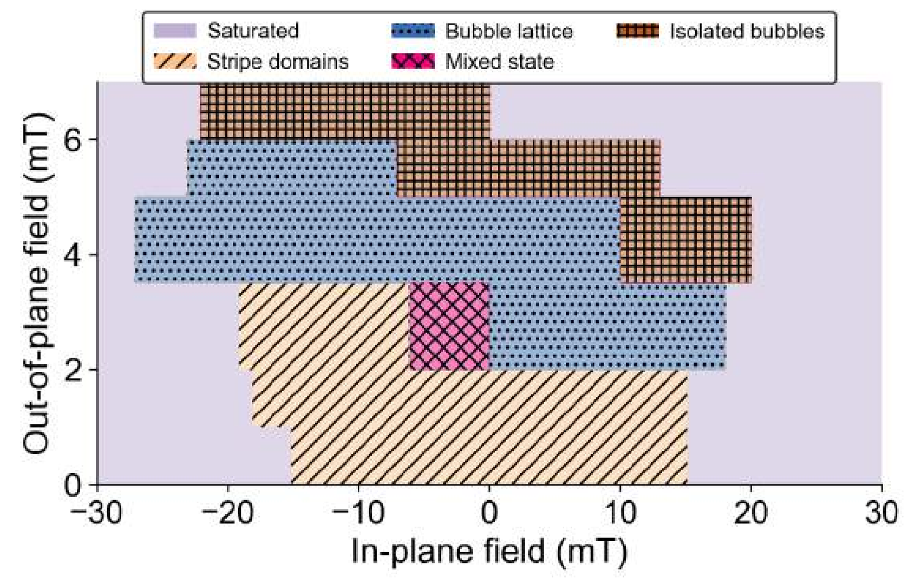


MOKE images at different applied field values

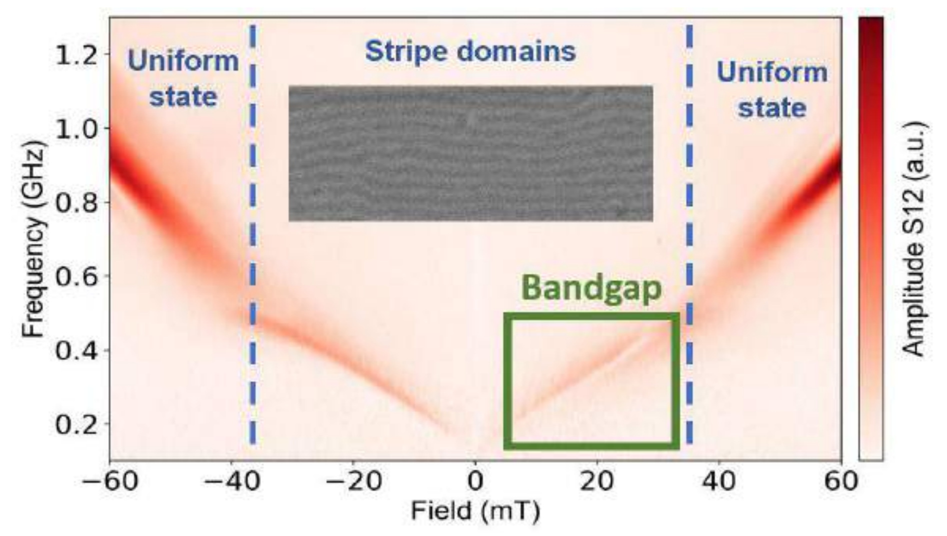
Results: Field-dependent bandgaps observed in spin-wave transmission across stripe domains.

Frequency bandgap can be tuned easily with applied external field.

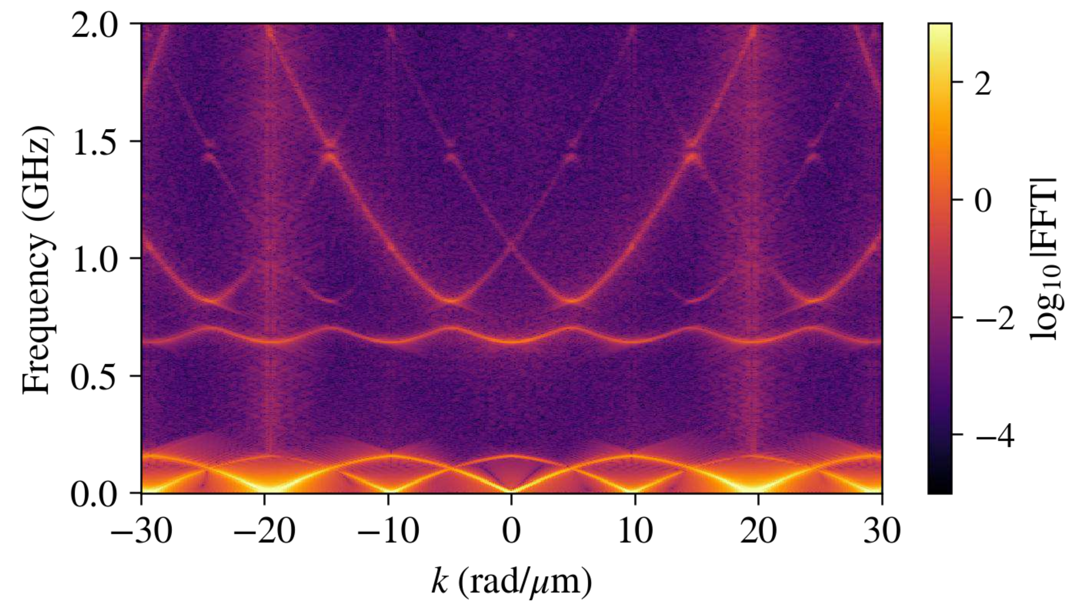
MuMax3 simulations also show bandgaps in the SW dispersion relation, confirming magnonic crystal behavior.



Magnetic Phases - $\mu_0 H_{OOP}$ & $\mu_0 H_{IP}$



Experiment - Transmission spectrum S12



Simulation - SW DR across periodic stripes

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HYPERCHAOS IN A MAGNETIC NANODISK DRIVEN BY FERROMAGNETIC RESONANCE

AMEL KOLLI[1], HUGO MERBOUCHE[1], SALVATORE PERNA[2], CLAUDIO SERPICO[2], DAMIEN RONTANI[3] & GRÉGOIRE DE LOUBENS

1 - SPEC, CEA, CNRS, UNIVERSITÉ PARIS-SACLAY, GIF-SUR-YVETTE FRANCE 2 - DIETI, UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II, NAPOLI, ITALY
3 - CHAIR IN PHOTONICS, LMOPS EA 4423 LABORATORY, CENTRALESUPÉLEC, UNIVERSITÉ DE LORRAINE, METZ FRANCE

CAREER PATH

SCIENCE COMMUNICATION INTERNSHIP
Design of innovative physics education tools through the **Smartphone Physics Challenge project**, based on systematic measurement and optimization of smartphone sensor technologies.
Supervisors: Julien Bobroff & Frédéric Bouquet

2020

BACHELOR OF SCIENCE
General Physics, advanced mathematics track

2021

DEEPTECH INTERNSHIP
Benchmarking and marketing of **critical heat flux meters** and **temperature probes** intended for industrial and laboratory use in harsh conditions.
Supervisor: Nicolas Lecompte

2022

INTERNATIONAL 1ST YEAR MASTER PROGRAM
Fundamental physics track

BACHELOR STUDENT @ PARIS-SACLAY UNIVERSITY
MASTER 1 STUDENT @ PARIS-SACLAY UNIVERSITY
MASTER 2 STUDENT @ PARIS-SACLAY UNIVERSITY
PHD @ SPEC CEA PARIS-SACLAY

QUANTUM TRANSPORT INTERNSHIP
Anyonic statistics, Majorana fermions and shot noise anlysis. Quasiparticles collisions in the **fractional quantum Hall effect regime**.
Supervisors: Olivier Maillet & Frédéric Pierre

2023

INTERNATIONAL 2ND YEAR MASTER PROGRAM
Quantum, Light, Materials & Nano Sciences, condensed matter track

2024

NANOMAGNETISM INTERNSHIP
Micromagnetic simulations & **multifrequency spectroscopy** of ultra-low damping magnetic nanostructures in the nonlinear regime to perform **neuromorphic computing** tasks.
Supervisor: Grégoire de Loubens

2025

PhD PROGRAM
Exploitation of the **nonlinear properties of spin-waves** in **spintronic devices** for true random number generation and data encryption.
Supervisor: Grégoire de Loubens

SPINCOM

MOTIVATIONS

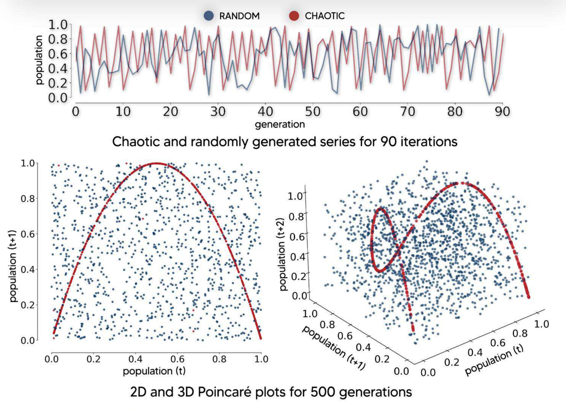
THIS WORK WAS SUPPORTED BY A GOVERNMENT GRANT MANAGED BY THE ANR AS PART OF THE FRANCE 2030 INVESTMENT PLAN FROM PEPR SPIN ANR-22-EXSP 0005 SPINCOM

EXPLOITING THE NONLINEAR DYNAMICS OF MAGNETIC SPIN TORQUE NANO-OSCILLATORS FOR INFORMATION PROCESSING

THESIS

CHAOS THEORY

DETERMINISM CREATES PATTERNS, RANDOMNESS YIELDS A POINT CLOUD



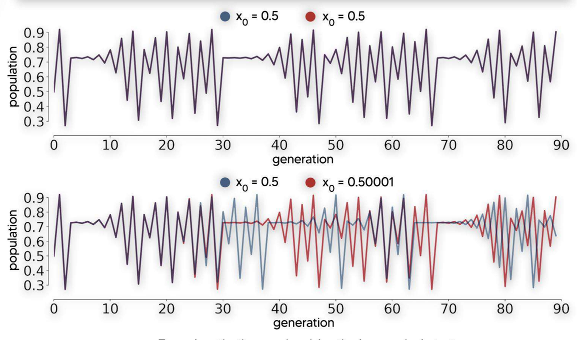
Chaotic and randomly generated series for 90 iterations

2D and 3D Poincaré plots for 500 generations

the chaotic system is constrained by its strange attractor

DETERMINISM

THE TINIEST INITIAL CHANGES QUICKLY GROW INTO MAJOR DISCREPANCIES



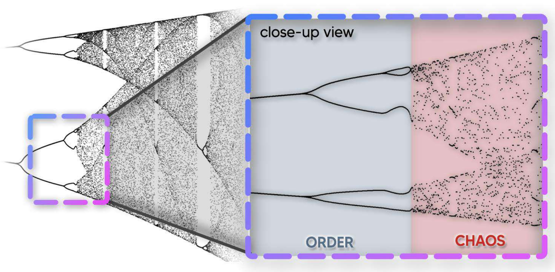
Two chaotic time series: identical vs. varied starts

the butterfly effect in action: time series that start out identical can quickly diverge

SENSITIVITY TO INITIAL CONDITION

INTRICATE PATTERNS EXHIBIT SELF-SIMILARITY ACROSS DIFFERENT SCALES

the **logistic model** is a well-known example of a chaotic system. With the system's equation and control parameter, it shows how growth slows near carrying capacity, revealing a **transition from stable to chaotic dynamics**



Bifurcation diagram of the logistic model

fractals emerge, with smaller sections reflecting the structure of the whole

FRACTAL STRUCTURE

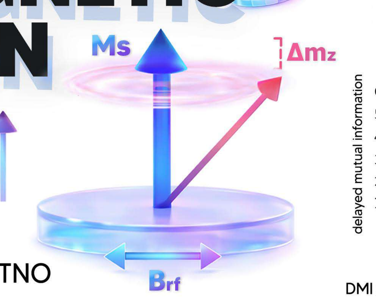
MICROMAGNETIC SIMULATION

K_u 980 kJ/m³ ANISOTROPY CONSTANT (ANISOTROPY FIELD $\mu_0 H_{K_U}$ = 1.568 T)

α 10^{-2} DAMPING PARAMETER

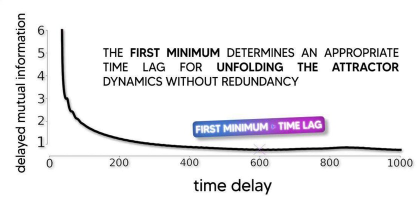
M_s 1250 kA/m SATURATION MAGNETIZATION (MAGNETIZING FIELD $\mu_0 M_s$ = 1.571 T)

A 12 pJ/m EXCHANGE CONSTANT



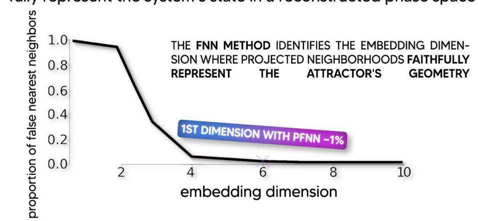
CoFeB magnetic free layer of the STNO

TIME DELAY determines **how much we shift the time series** copies apart to resolve different state variables



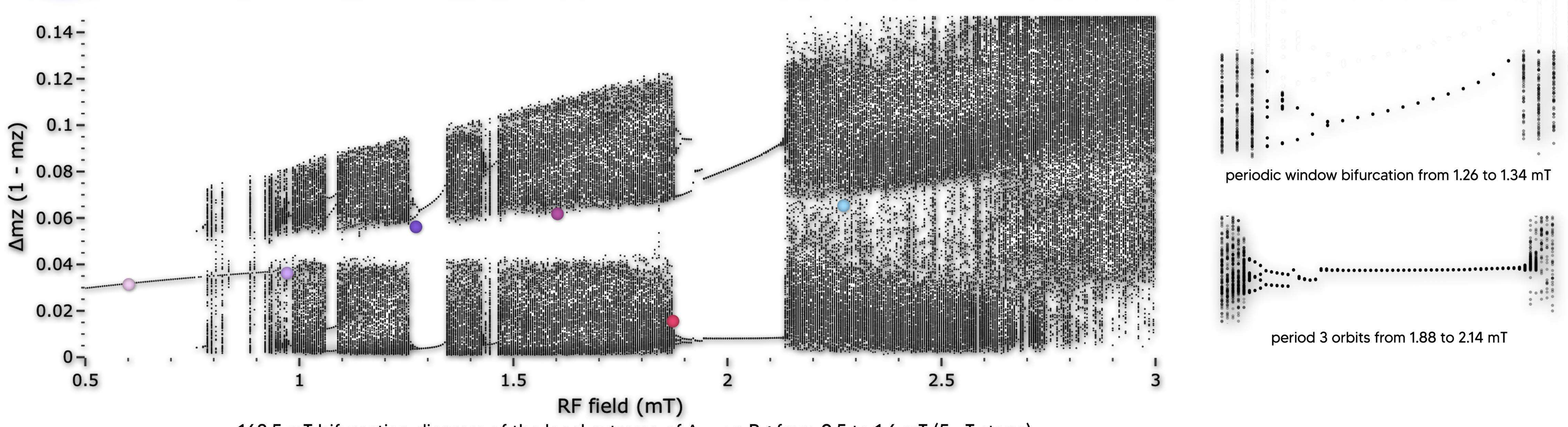
DMI as function of time-lag computed on 10,000 samples

EMBEDDING DIMENSION determines **how many of these timeshifted copies** we need to fully represent the system's state in a reconstructed phase space

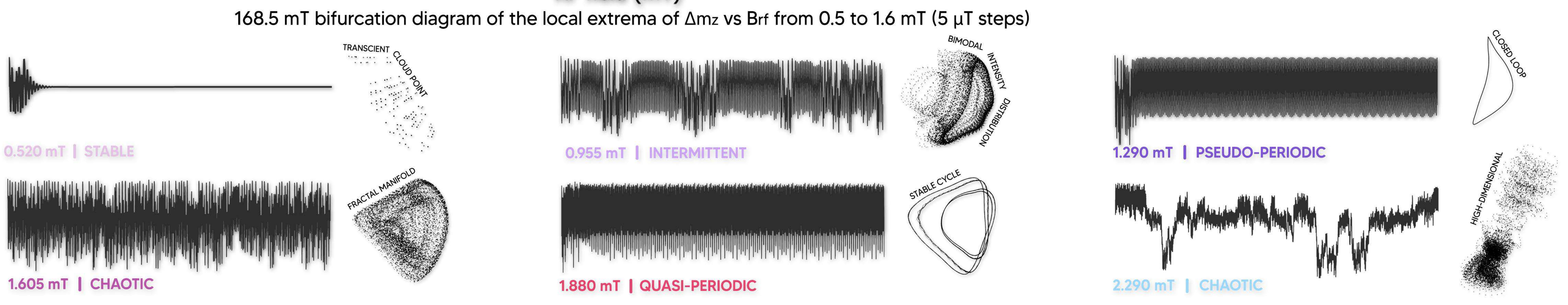


Proportion of false neighbors computed on 10,000 samples

TIME SERIES & PHASE SPACE EMBEDDING



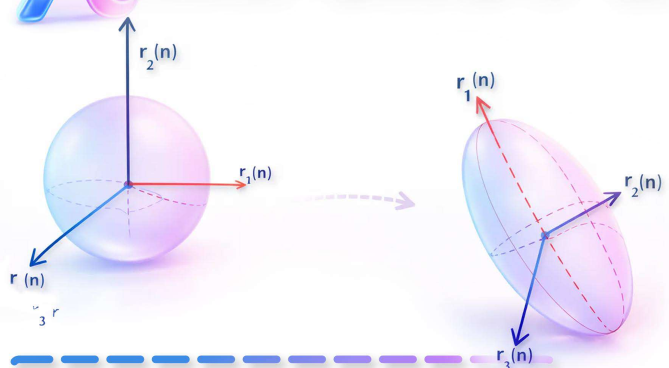
168.5 mT bifurcation diagram of the local extrema of Δmz vs Brf from 0.5 to 1.6 mT (5 µT steps)



Time-resolved evolution of the averaged longitudinal magnetization component mz over 2000 nanoseconds and their reconstructed attractor in the phase space

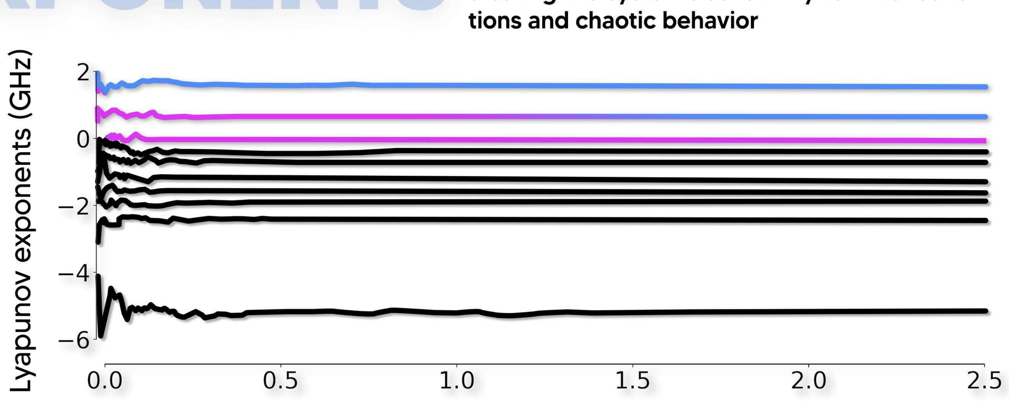
LYAPUNOV EXPONENTS

measures the rate at which nearby trajectories in a dynamical system diverge or converge, indicating the system's sensitivity to initial conditions and chaotic behavior



$$\lambda_k = \lim_{n\to\infty} \frac{1}{n} \ln \left[r_k^{(n)} \right]$$

$r_k^{(n)}$ the magnitude of the half-principal axis of the ellipsoid in the k-th direction of the phase space



Lyapunov spectrum over time (LSOT) with 20,000 samples

$\lambda_1 > 0$ sensitivity to initial conditions, the system chaotic

$\lambda_1 = 0$ the system is oscillating periodically

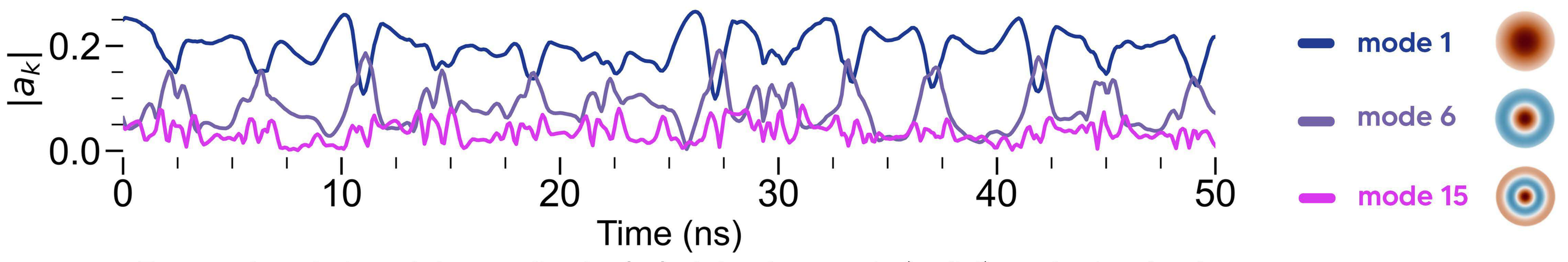
$\lambda_1 < 0$ the system is converging to a steady state

PEPR SPIN WEBSITE

MAIN RESULTS

MULTIMODE ACTIVATION

Using a mode projection technique, the generated complexity is related to the number of quantized spin-wave modes participating in the dynamics



Temporal evolution of the amplitudes $|a_k|$ of the three main (radial) modes involved

VARIATION COEFFICIENT

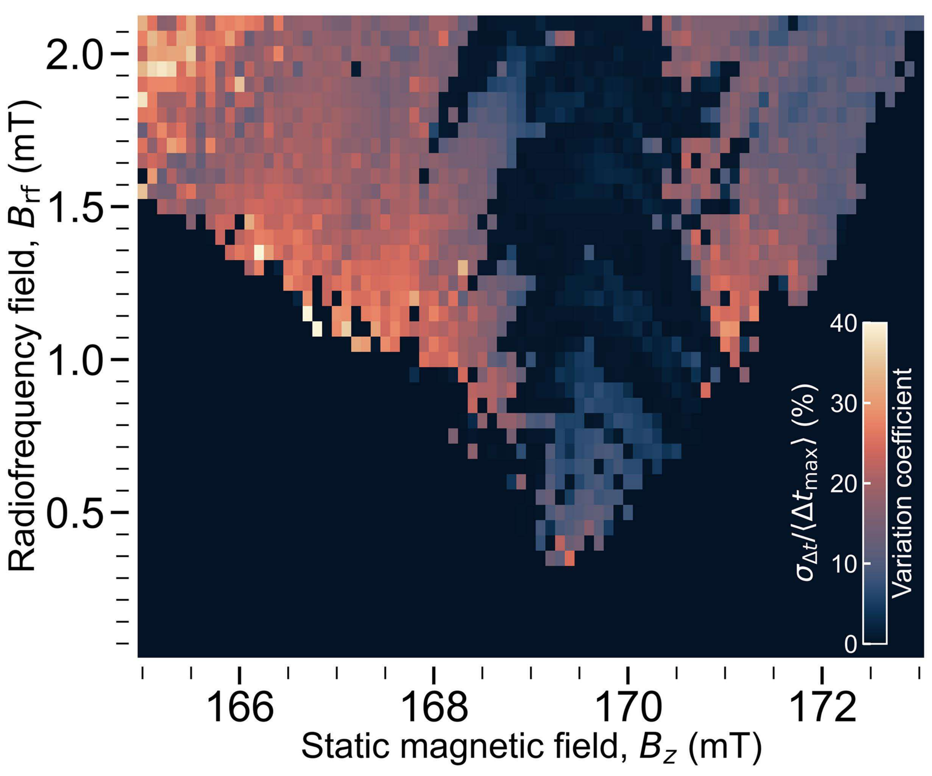
$$c_v = \sigma_{\Delta t} / \langle \Delta t \rangle$$

Extraction of the peak-to-peak time intervals Δt of Δm_z, and computing of the variation coefficient c_v where $\sigma_{\Delta t}$ and <Δt> are the standard deviation and mean of the peak-to-peak intervals.

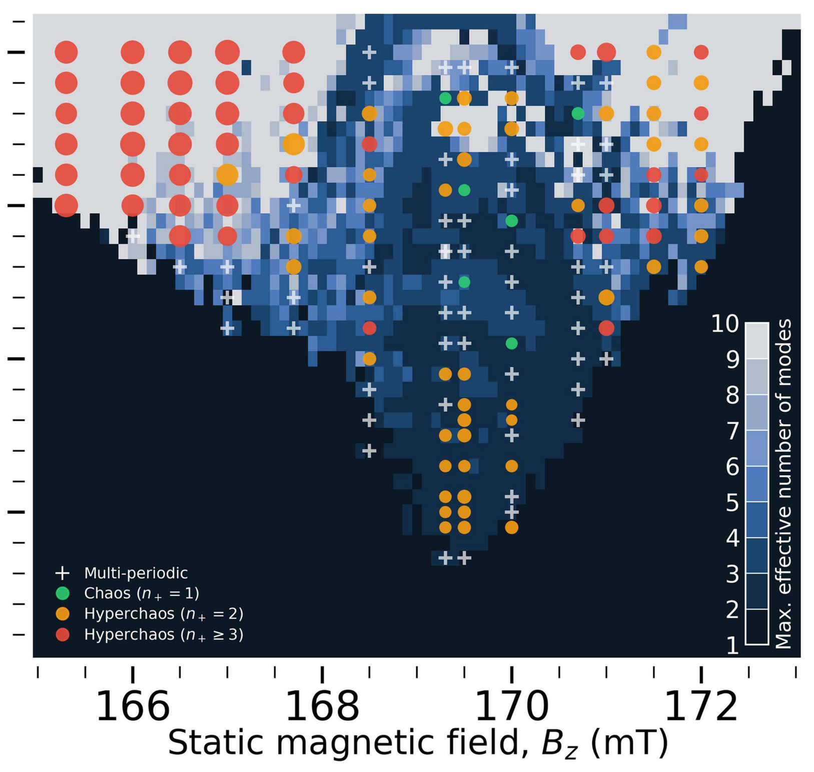
SHANNON PARTICIPATION NUMBER

$$P_s = \exp\left(-\sum_k p_k \ln p_k\right), \quad p_k = \frac{|a_k|^2}{\sum_k |a_k|^2}$$

Classification map of the chaotic dynamics in the (Bz, Brf) plane: multi-periodic (crosses), chaos with n+ = 1, hyperchaos with n+ = 2 and n+ = 3. Marker size is proportional to max. The background color scale shows the effective number of modes.



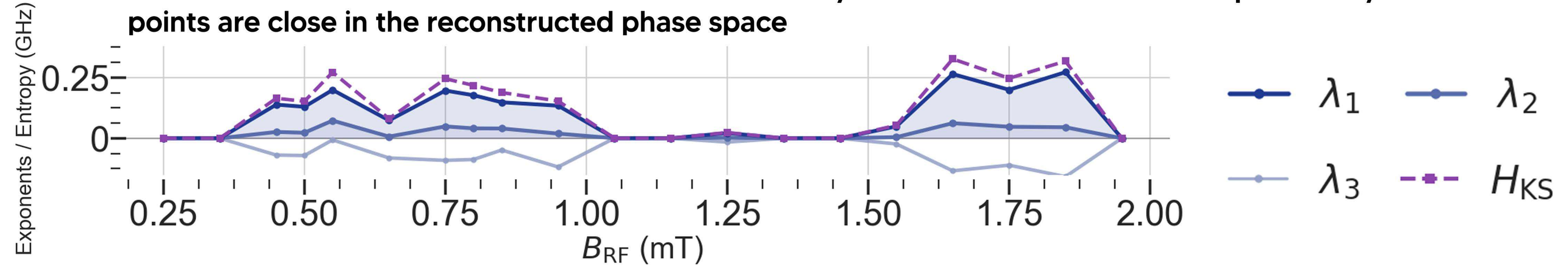
Coefficient of variation of the peak-to-peak intervals



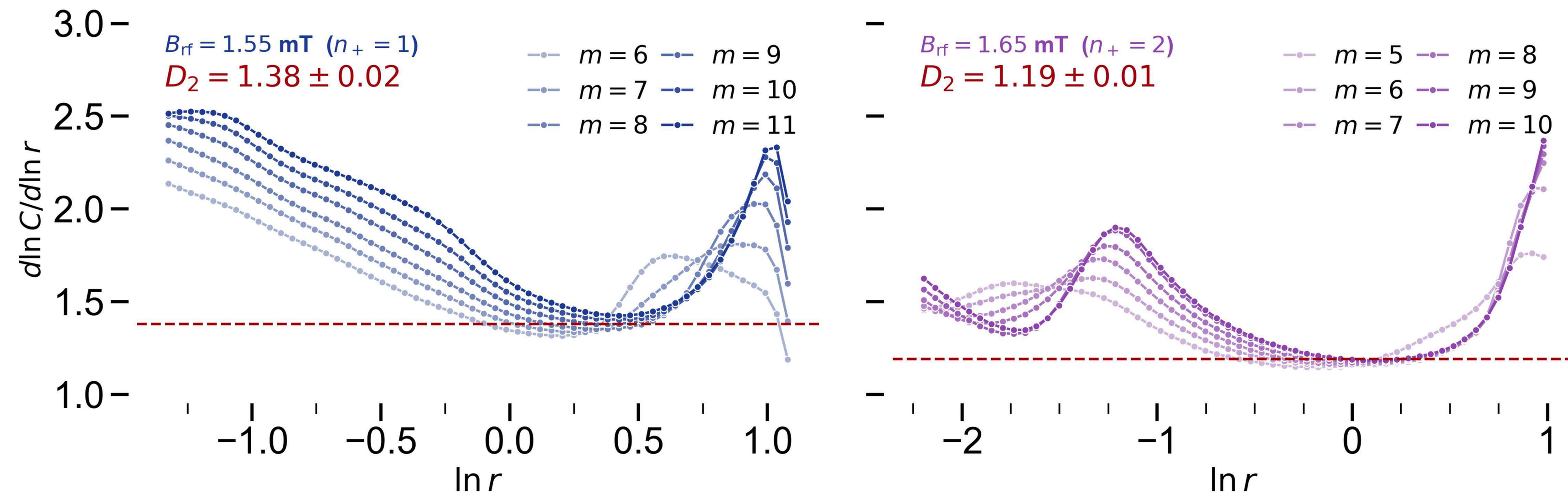
Maximum effective number of the spin-wave modes participating in the dynamics

KOLMOGOROV-SINAI ENTROPY & FRACTAL DIMENSION

the correlation dimension measures the fractal density of an attractor based on the probability that two points are close in the reconstructed phase space



Lyapunov spectrum and Kolmogorov-Sinai entropy as a function of Brf at fixed Bz = 169.5 mT



Grassberger-Procaccia local-slope diagnostic for the two operating points. Each curve corresponds to one embedding dimension from m_{FNN} to m_{FNN+5}

1.38 correlation dimension < **3.44** information dimension

✅ theoretical relation satisfied

KAPLAN-YORKE DIMENSION

the Kaplan-Yorke dimension estimates the fractal dimension (information dimension) of a dynamical system using the number of expanding directions, derived from the Lyapunov exponent spectrum

SPINTRONICS INNOVATIONS FOR A FRUGAL, AGILE, AND SUSTAINABLE DIGITAL FUTURE

Magnetic Textures as Information Bits: Creation and Control

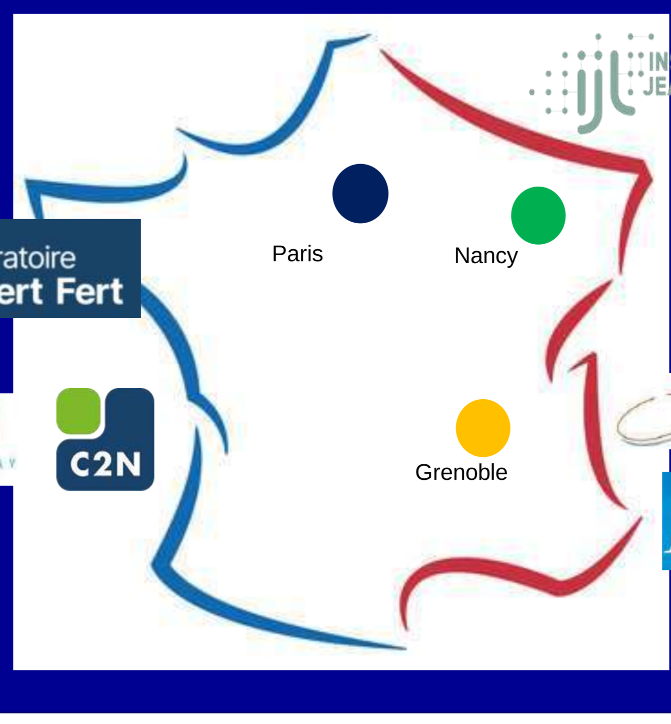
Nicolas Reyren, CHIREX (lab. coordinator), nicolas.reyren@cnrs-thales.fr

Vincent Cros, Co-director of the Exploratory PEPR SPIN, vincent.cros@cnrs-thales.fr

William Bouckaert [1*], J. Chiliquinga[1], Y. Sassi [1], S. Pizzini [2], D. Sanz-Hernández [1], S. Krishnia [1], N. Reyren [1], and V. Cros [1]

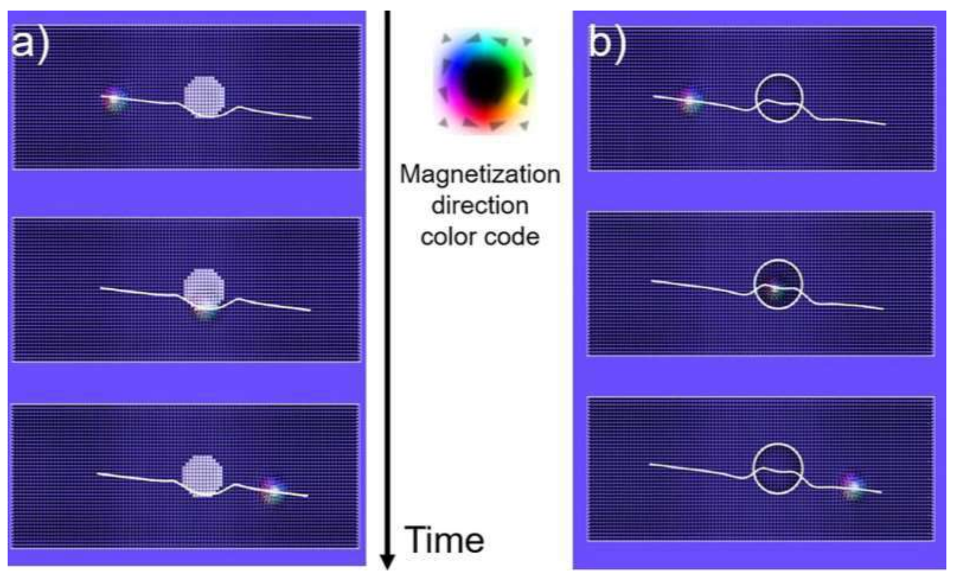
[1]Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, Palaiseau, France

[2]Institut Néel, CNRS and Université Grenoble Alpes, Grenoble, France

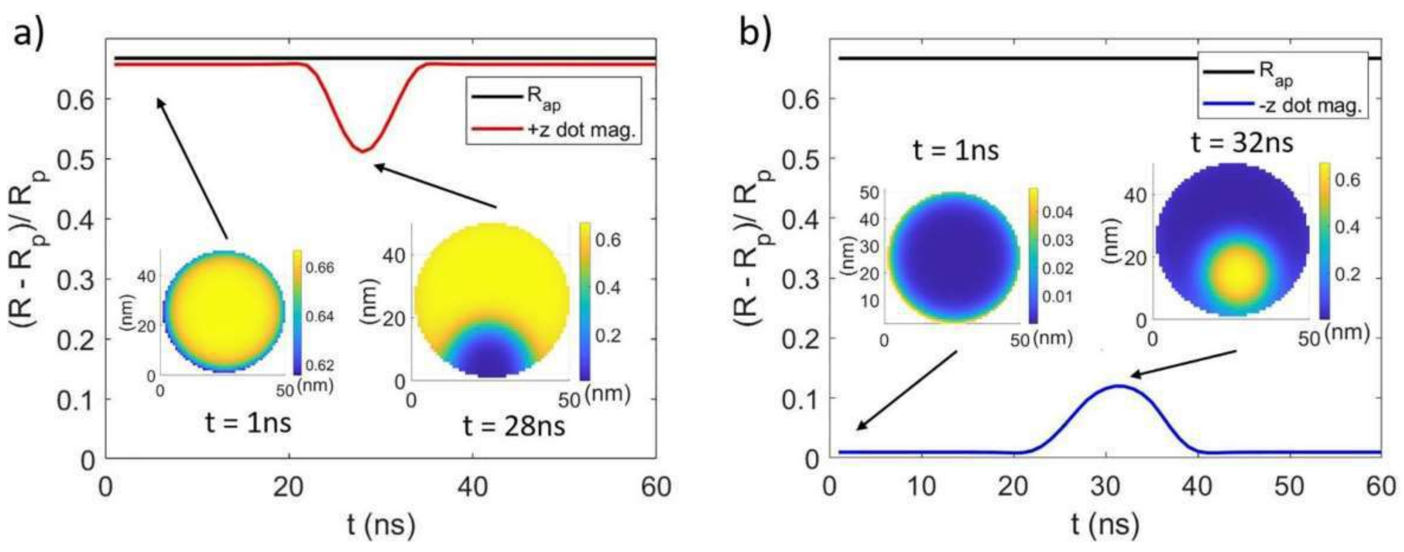


Career path

BSc and MSc in Physics from EPFL (Switzerland).

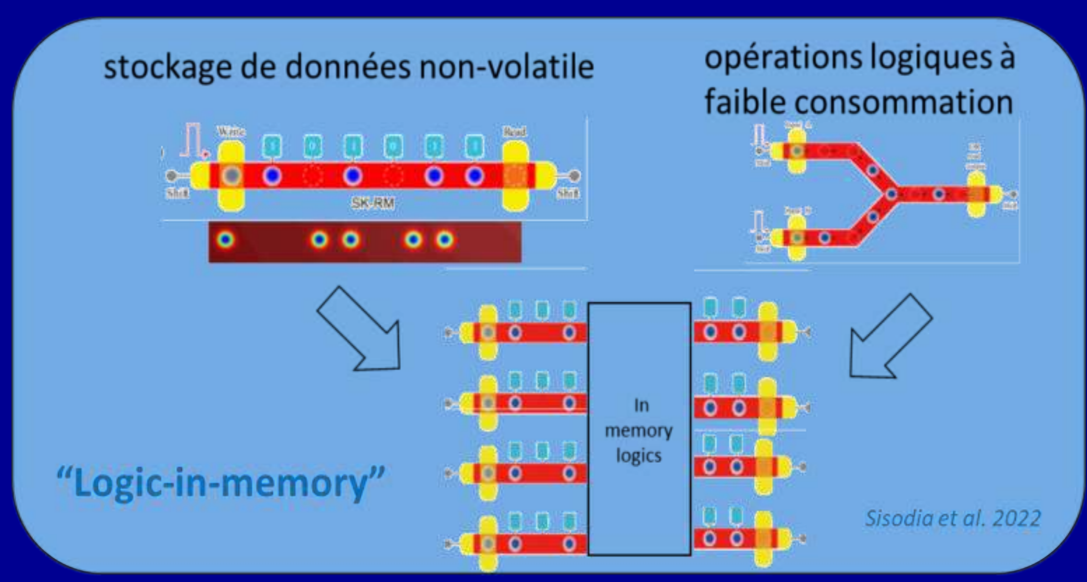


Completed a Master's thesis at Carnegie Mellon University (USA) under the supervision of Prof. Sara Majetich, focusing on *tunnel magnetoresistance detection of skyrmions*.



PEPR-Spin CHIREX

The goal of the CHIREX Targeted Project is to develop a new generation of spintronic components based on the manipulation and interconversion of topological spin textures such as skyrmions and chiral domain walls.



Objective: Develop methods to nucleate, manipulate, and read topological spin textures (such as skyrmions) for low-energy logic and storage devices.

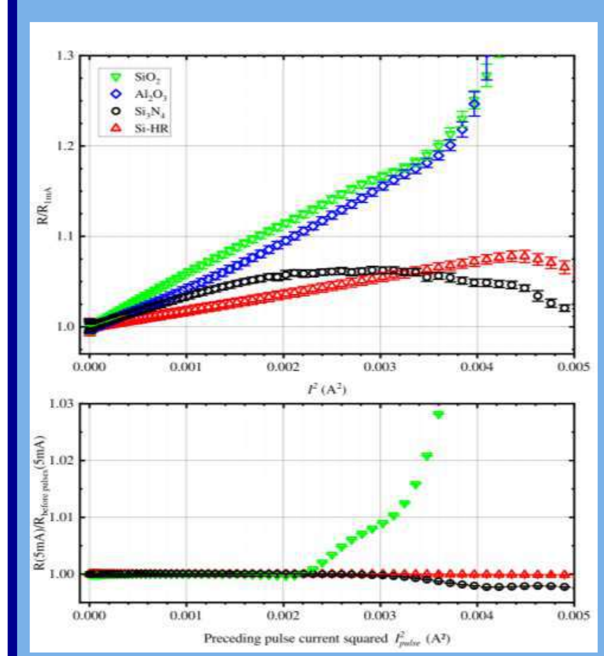
Solutions to be implemented:

1. Nanometer-scale material engineering
2. Ultrafast writing
3. Control of electric polarization for low-power consumption
4. Topological coding
5. Bio-inspired architecture
6. Development of magnetic tunnel junctions

Substrate optimization, role of the field-like torque, and topography-induced nucleation

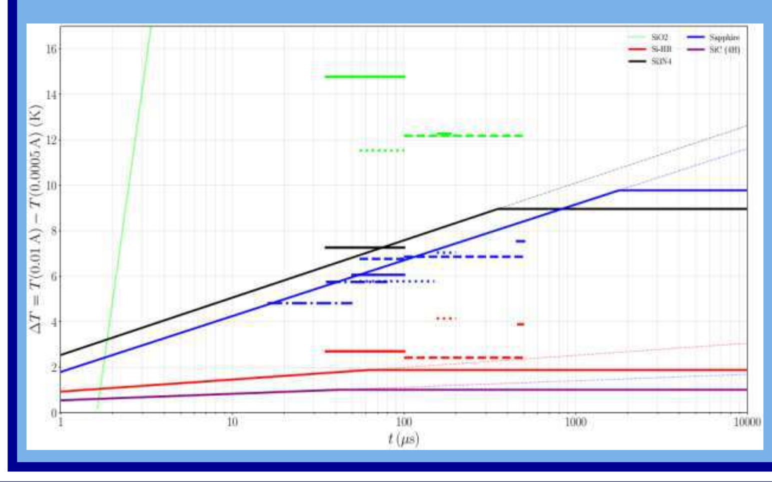
Substrate optimization:

- $R(T)$, $R(I)$, and $H_k(T)$ measurements were used to compare **heat dissipation** and magnetic properties in tracks grown on SiO_2, Si_3N_4, sapphire, and high-resistivity Si.



Samples:
Si/SiO2|| Ta5|Pt8|(Co1.25|Al3|Pt3)$_{10}$
Si-HR|| Al2O3(3)|Ta5|Pt8|(Co1.25|Al3|Pt3)$_{10}$
Sapphire|| Ta5|Pt8|(Co1.25|Al3|Pt3)$_{10}$
Si3N4|| Ta5|Pt8|(Co1.3|Al3|Pt3)$_{10}$

Extended current window: More efficient heat evacuation delays **track degradation** and **unwanted extended nucleation**, enabling higher-current pulses for **faster skyrmion motion.**

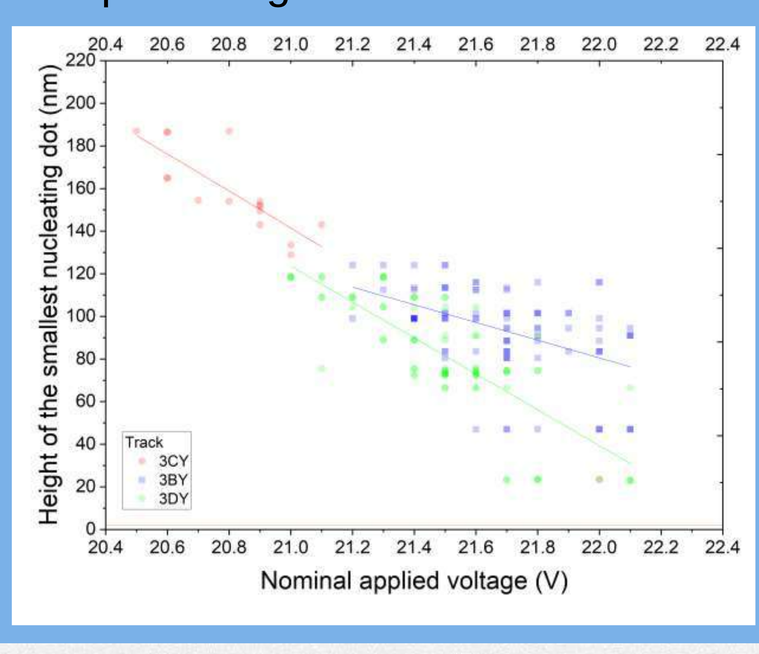


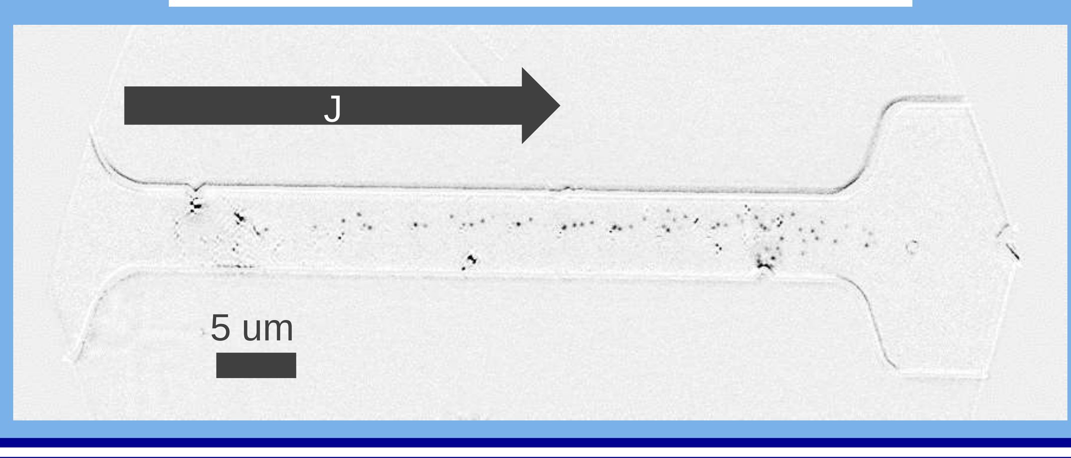
$$\Delta T(t) = \frac{P}{2\pi K l} \ln\left(\frac{16\alpha_{th} t}{\omega_G^2}\right)$$

Analytical estimate of track heating adapted from Curiale et al., Appl. Phys. Lett. 97, 243505 (2010).

Nucleation on topographical defects: **FEBID pillars** grown on top of the substrate before the multilayer deposition, and **FIB-etched holes** through the multilayer act as local nucleation sites for domains and skyrmions.

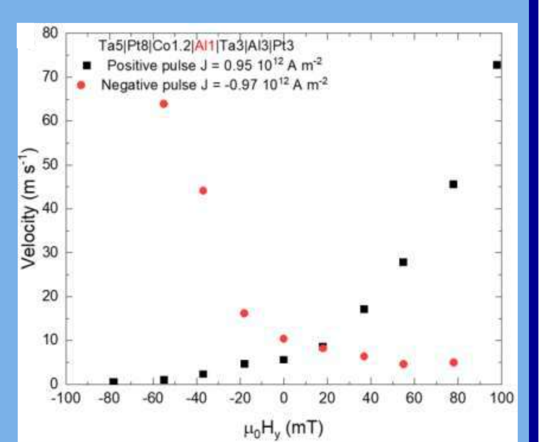
- **Tunable nucleation threshold**: The nucleation current can be modulated by the defect geometry, in particular the FEBID pillar height or the FIB hole diameter.

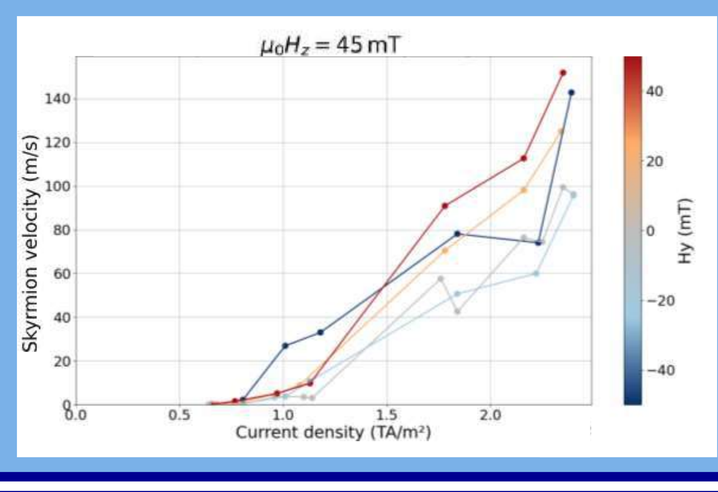




Role of field-like torque in skyrmion motion: Comparison of skyrmion and domain wall (DW) motion using current pulses and in-plane magnetic fields to **explore field-like torque** effects.

- Skyrmion velocity is **less affected** by the magnetic field than the DW motion.
- External magnetic fields significantly impacted the **nucleation current,** the **number of skyrmions** nucleated per pulse, and the skyrmion velocity.
- For domain-wall motion, the **damping-like torque** induces a processional tilt of the in-plane spins perpendicular to the current, which reduces the DW velocity; this effect can be compensated by the field-like torque or by an external H_y field.





Program Description:
The Priority Research Program for SPIN (PEPR) is an exploratory program within the framework of the France 2030 investment plan.
It aims to develop a new generation of components for a more frugal, agile, and sustainable digital world. With a funding of 38 million euros over eight years, the SPIN Research Program is intended to contribute to accompanying a new cycle of innovation in spintronics.

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Non-volatile control of three-dimensional magnetic texture dynamics

Coordinator:Stéfania Pizzini,chercheuse CNRS à l'Institut Néel

Xinyuan Yang[1], B. Paikaray[2], H. Singh[2], A. Durnez[1], J. Grollier[2], V. Cros[2], N. Reyren[2], and L. Herrera Diez[1]

[1]Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 91120 Palaiseau, France

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

Career Path

2016-2020: Bachelor- Beihang University

2020-2023: Master- University of Tokyo

Since 2024: PhD candidate- Université Paris Saclay

CHIREX

The aim of the CHIREX Target Project is to develop a new generation of spintronic components based on the manipulation and interconversion of topological spin textures such as skyrmions and chiral domain walls.

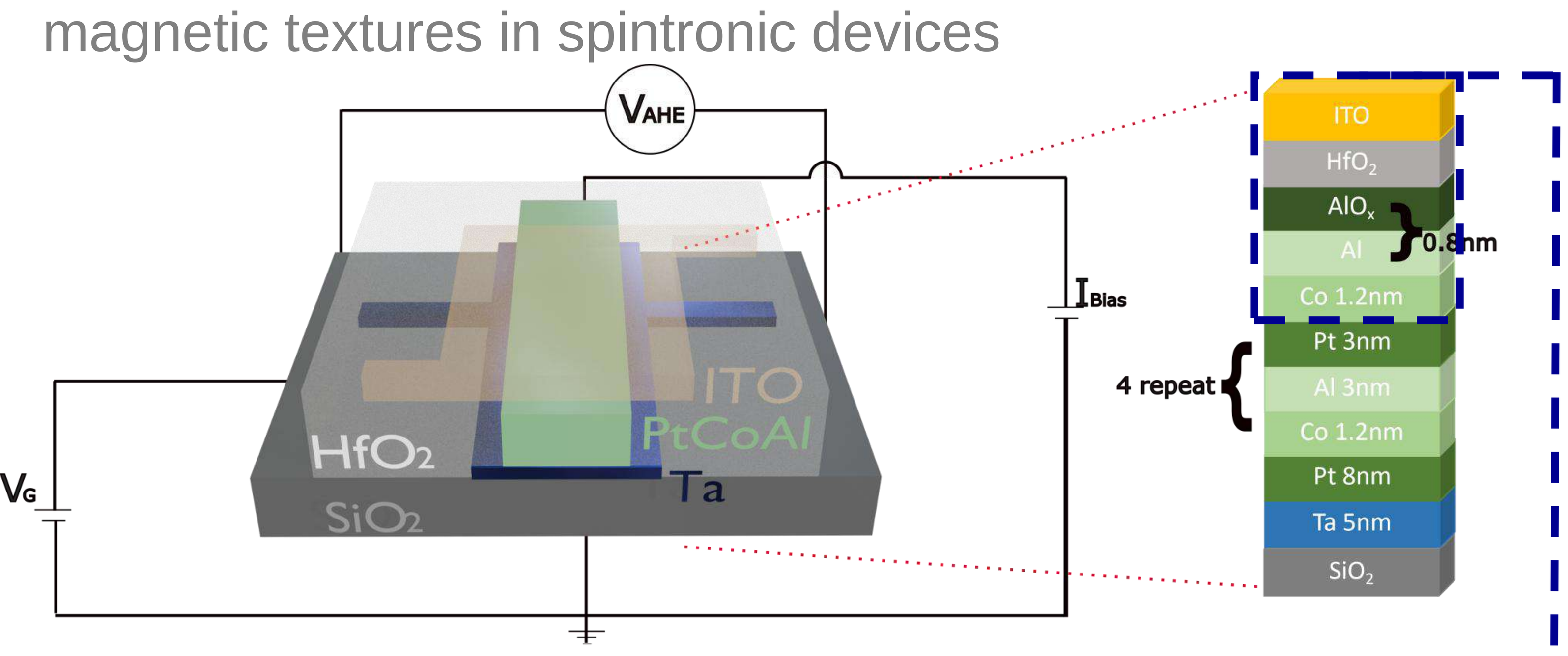
Magneto-ionic control of chiral magnetic structures

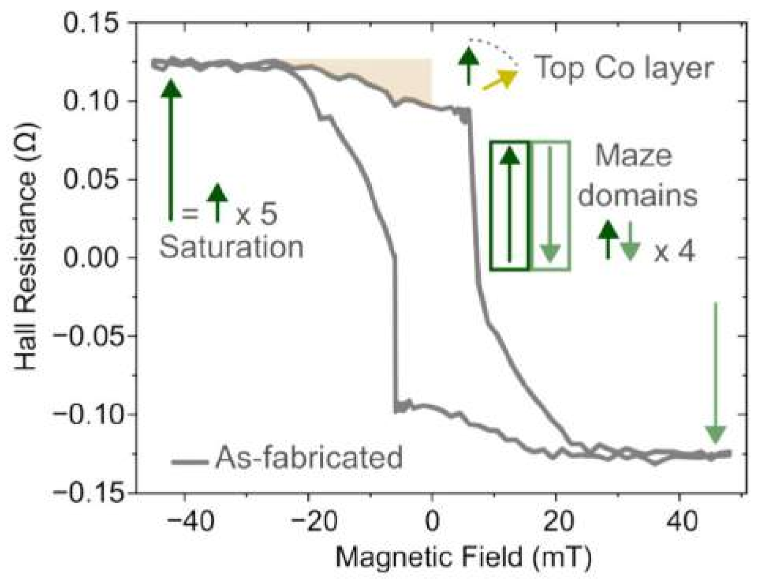
3D magnetic structures:

a new playground for spintronics device design

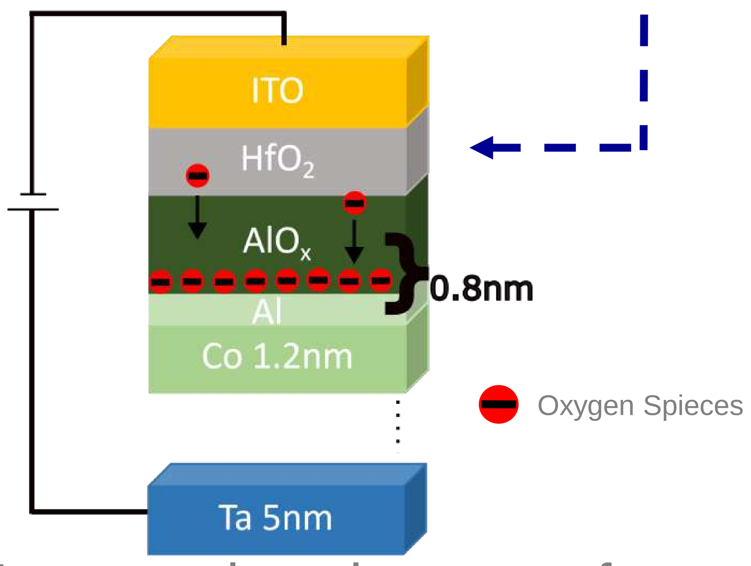
A.Fernandez-Pacheco. et al. *Nat Commun* **8**, 15756 (2017)

Magnetic multilayers: a platform for exploring 3D chiral magnetic textures in spintronic devices

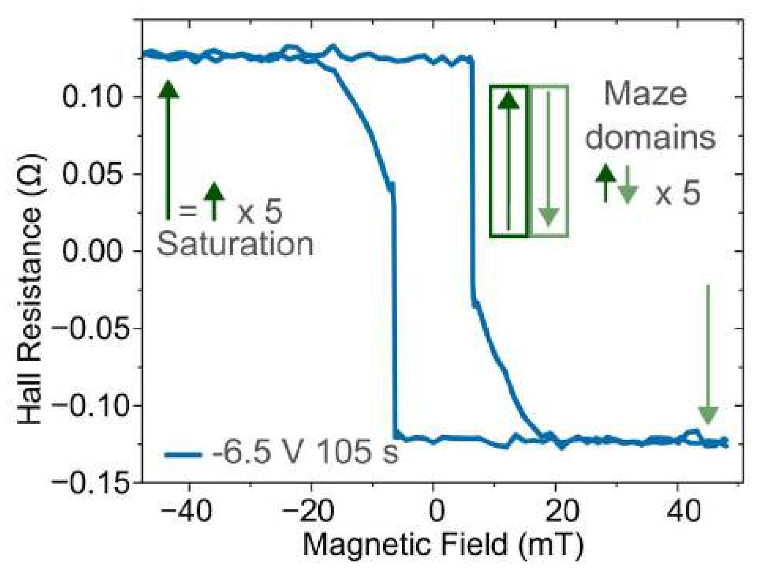




As fabricated state: top Co layer shows weaker anisotropy than the rest of the multilayer and switches independently.



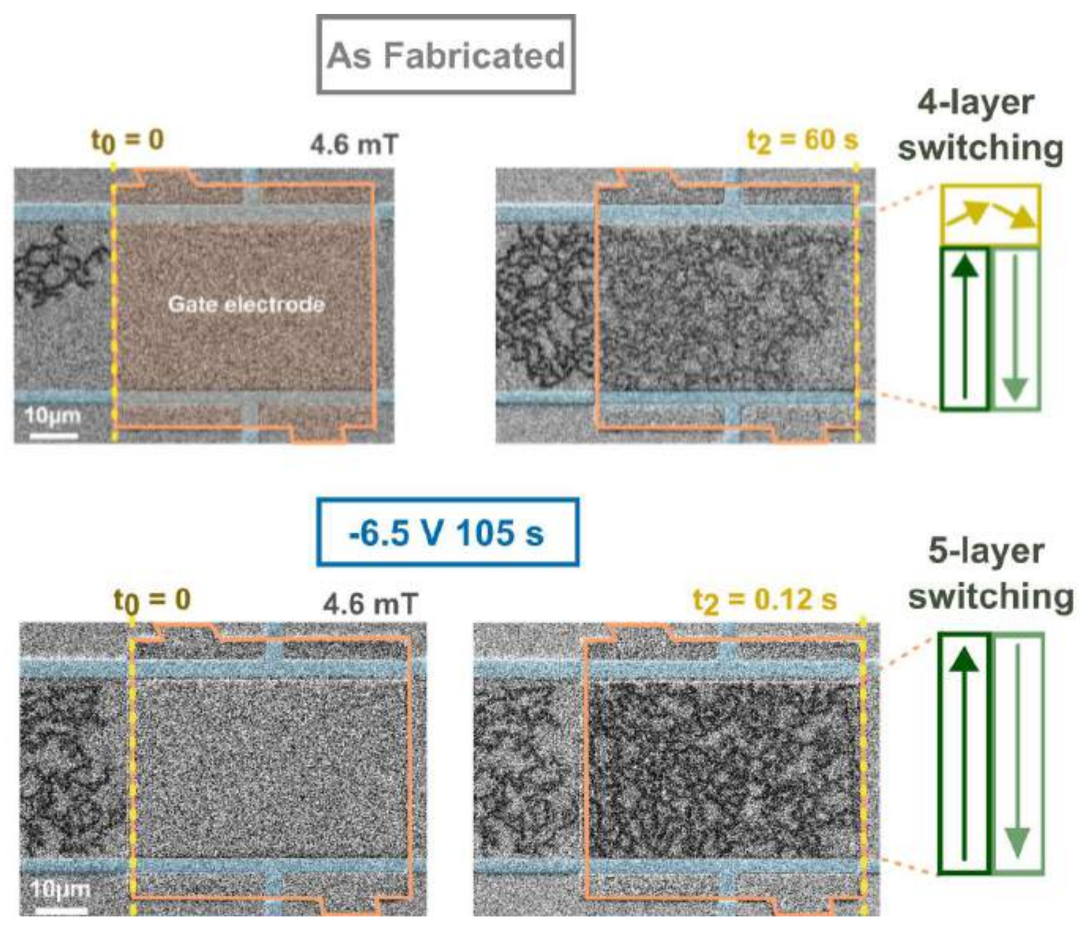
Magneto-ionic gating

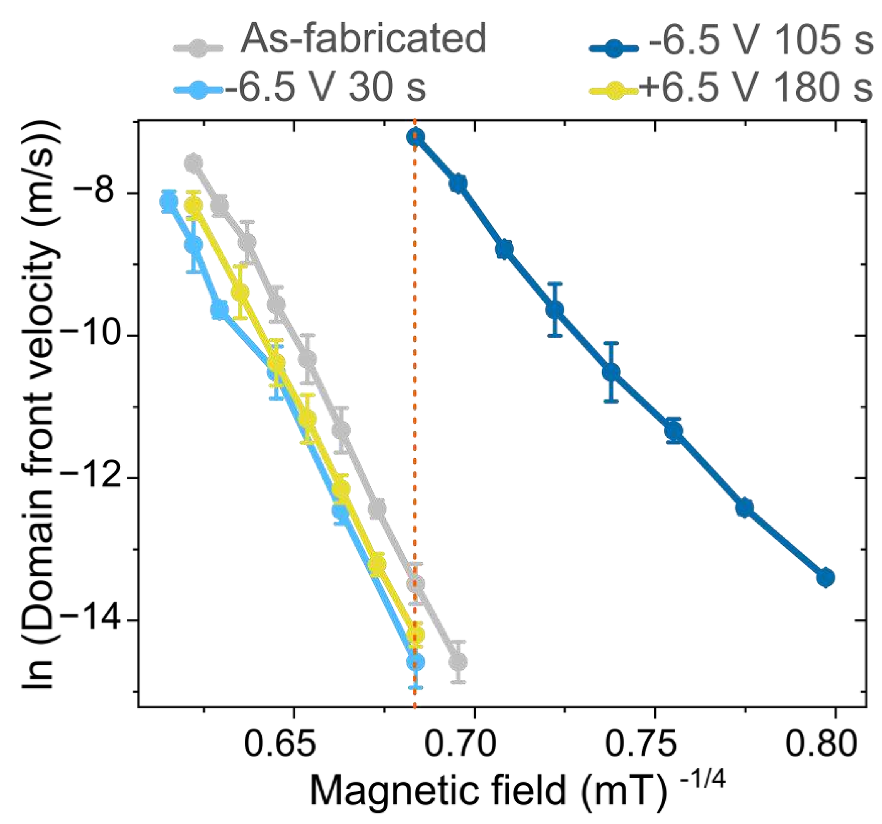


- Increase in anisotropy of the top layer
- Collective switching of all layers.
- Non-volatile and reversible effect

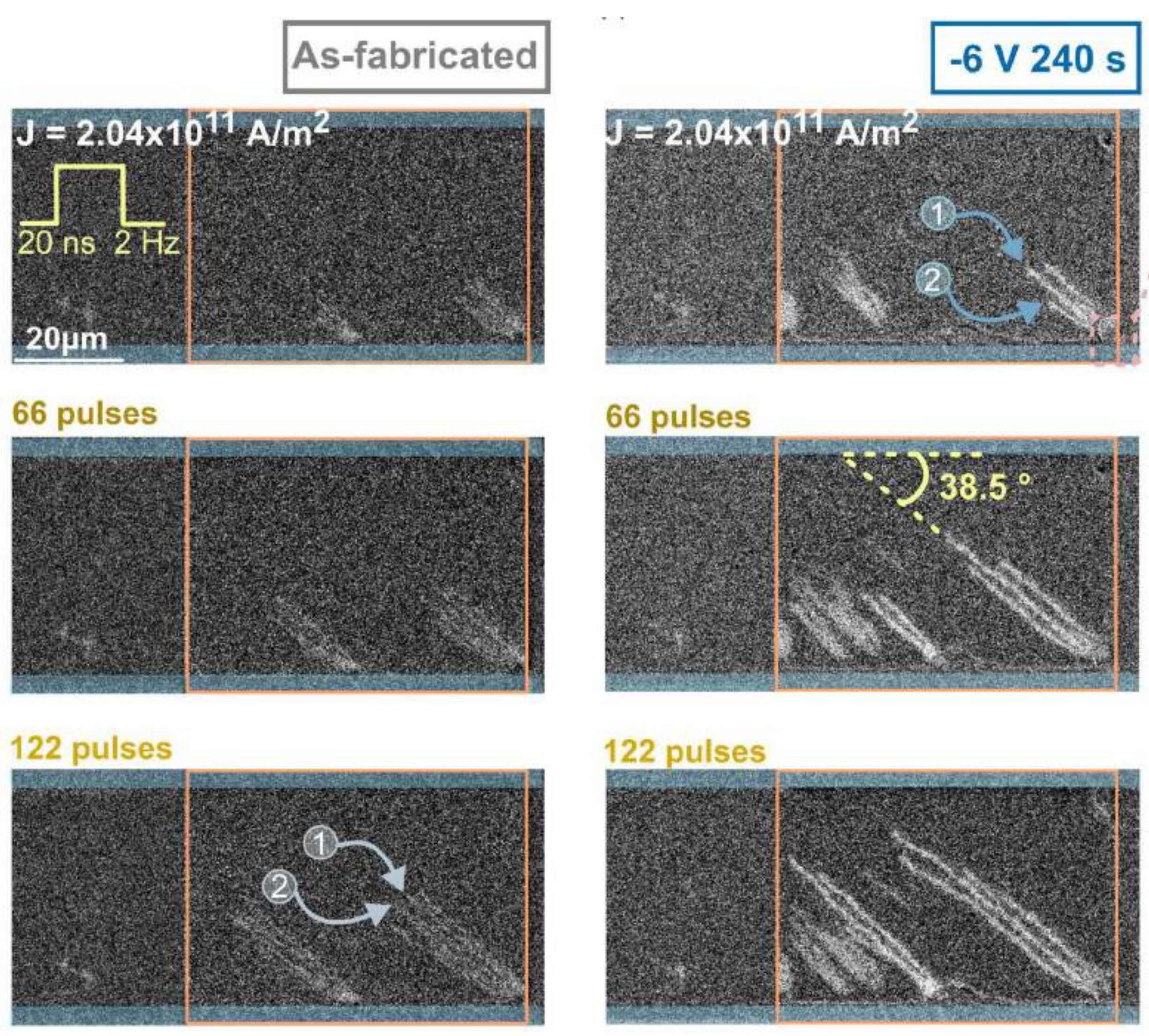
Chiral domain walls and half-skyrmions motion after magneto-ionic gating

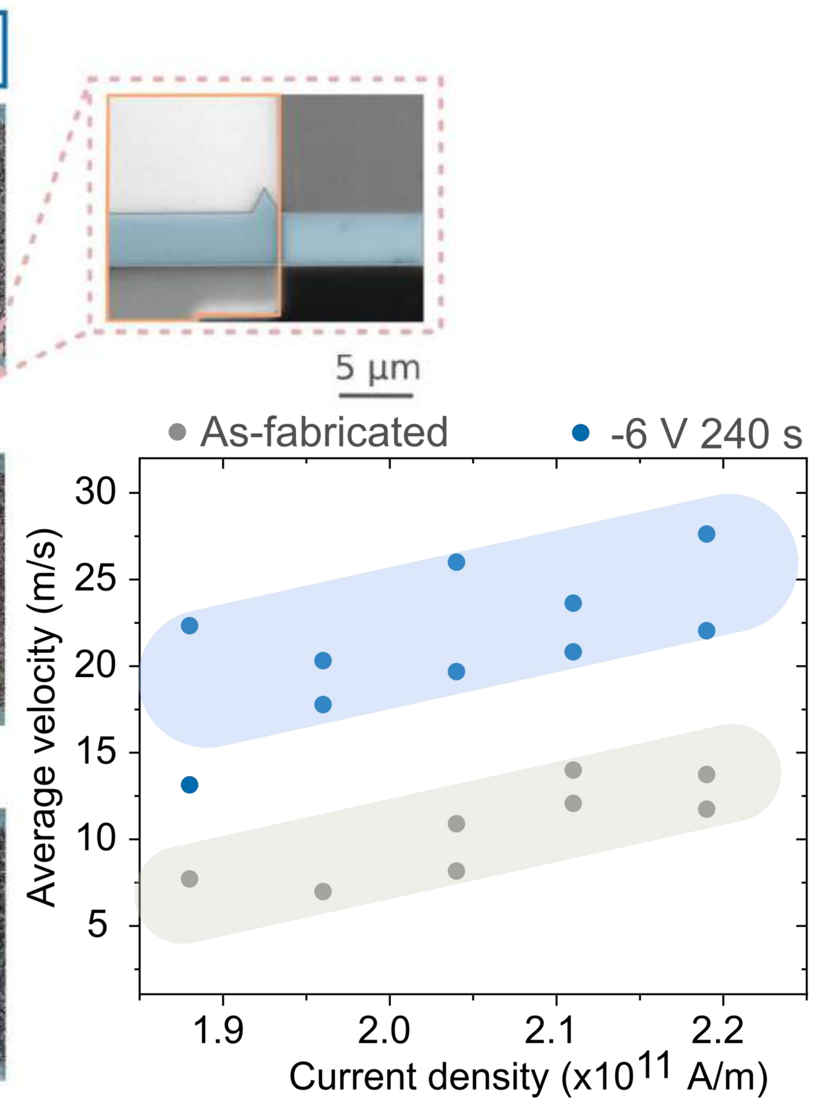
Increasing the magnetic anisotropy of the upmost Co layer induces a significant enhancement of domain wall velocity under external magntic field





Current-driven motion of half-skyrmions (finger-like structures) also shows an enhancement after magneto-ionic gating





Magneto-ionic gating is an effective strategy to reversibly reconfigure the 3D spin structure of magnetic textures in multilayers, offering exciting perspectives for controlling their dynamics

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Xinyuan.yang@universite-paris-saclay.fr
Centre de nanosciences et de nanotechnologies

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FRANCE 2030 PROGRAMME DE RECHERCHE SPINTRONIQUE

anr cnrs cea

Study of oxide thin films for THz applications by TEM

Niels Keller, coordinator of ANR MOXSPIN project, IPR, CNRS, niels.keller@cnrs.fr

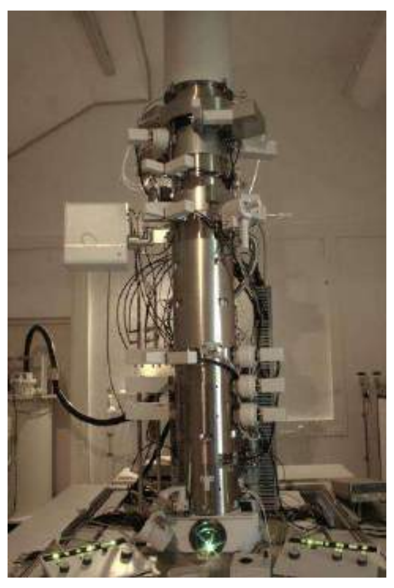
PhD supervisors: Bénédicte Warot-Fonrose and Christophe Gatel, Centre d'élaboration de matériaux et d'études structurales (CEMES), CNRS

Partner laboratories: Institut de Physique de Rennes (IPR), Institut des Molécules et Matériaux du Mans (IMMM), Institut d'Électronique, de Microélectronique et de Nanotechnologie (IEMN), Institut de physique et chimie des matériaux de Strasbourg (IPCMS)

Sarah Clément: from space industry to PhD

INSA Toulouse, Physics department
Telespazio France (space operations) – working for European Union space program agency, 2 years

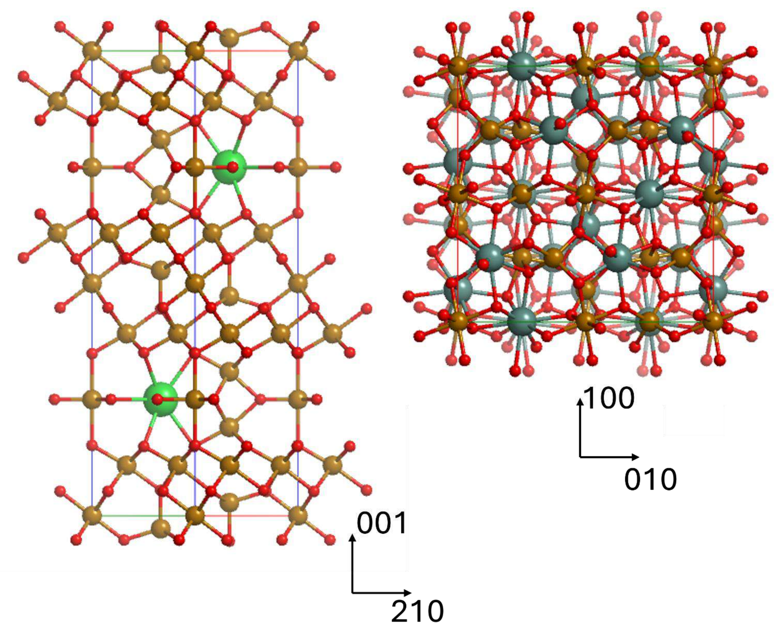
TELESPAZIO a LEONARDO and THALES company
EUSPA European Union Agency for the Space Programme

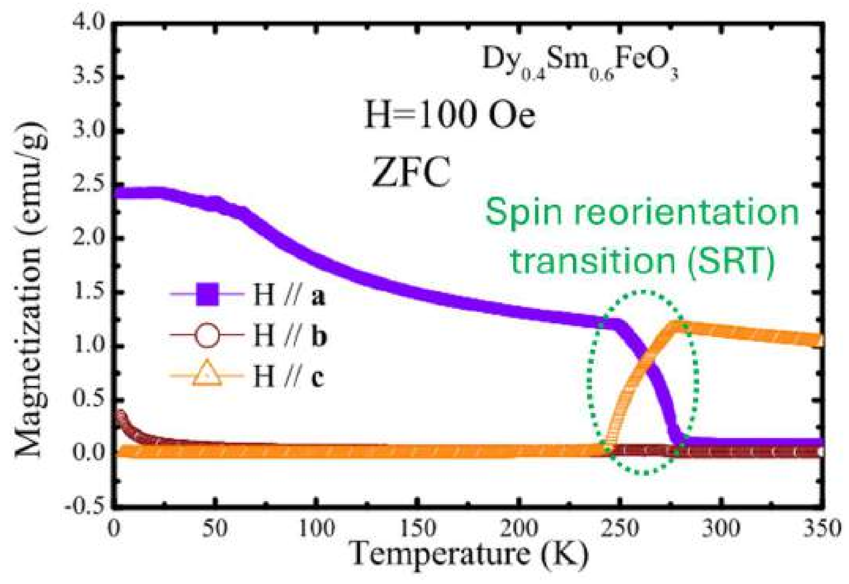


Curious about many things, I wanted to discover how the industry works. Realizing that scientific aspects interest me the most at the moment I started a PhD in order to be able to reach R&D engineer positions.

ANR MOXSPIN

Development of new magnetic oxides for ultrafast spin-based information technologies

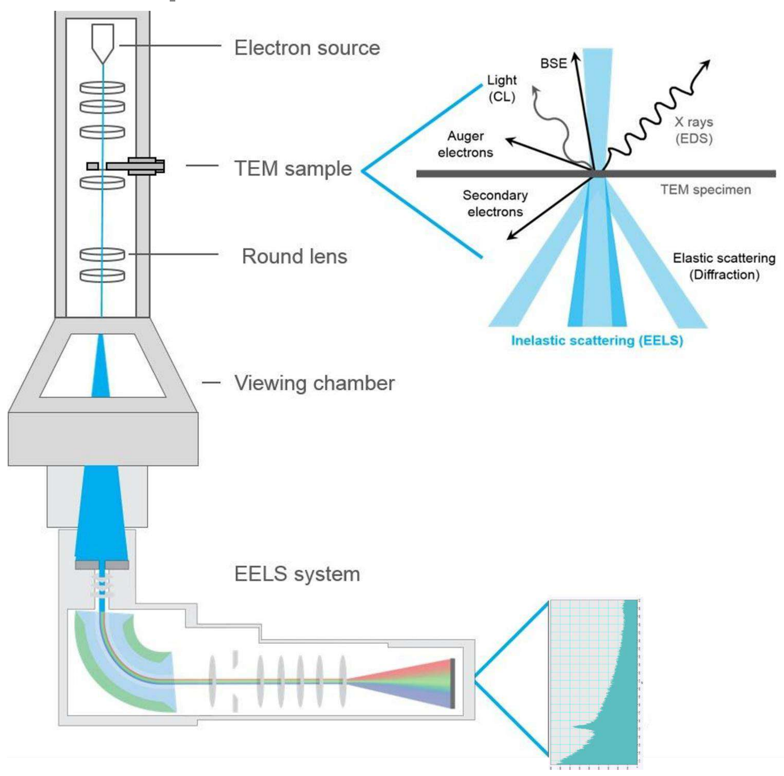




One of the objectives: tailoring the chemical composition and structure of magnetic thin films in order to obtain a material whose **dynamic response in the THz range can be controlled** by either applying magnetic field or by thermal variation.

Local structural and chemical material properties

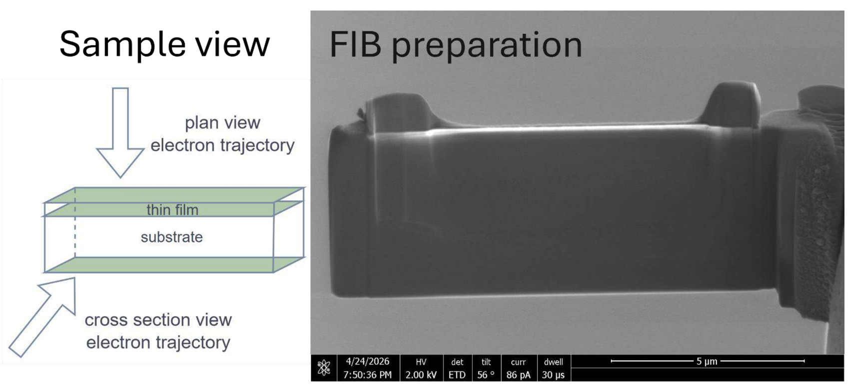
Atomic-level study of structure and chemical composition

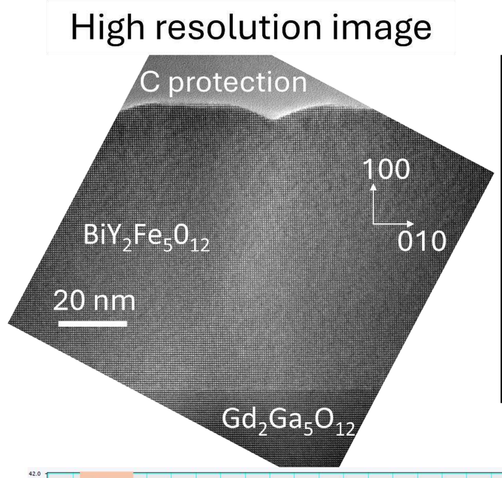


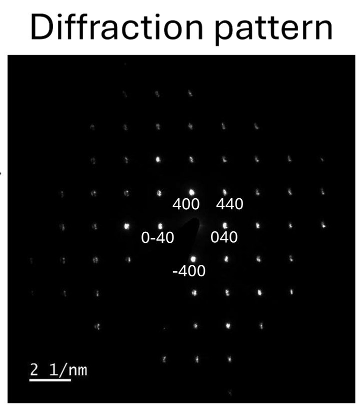
High resolution images
→ strain and defects

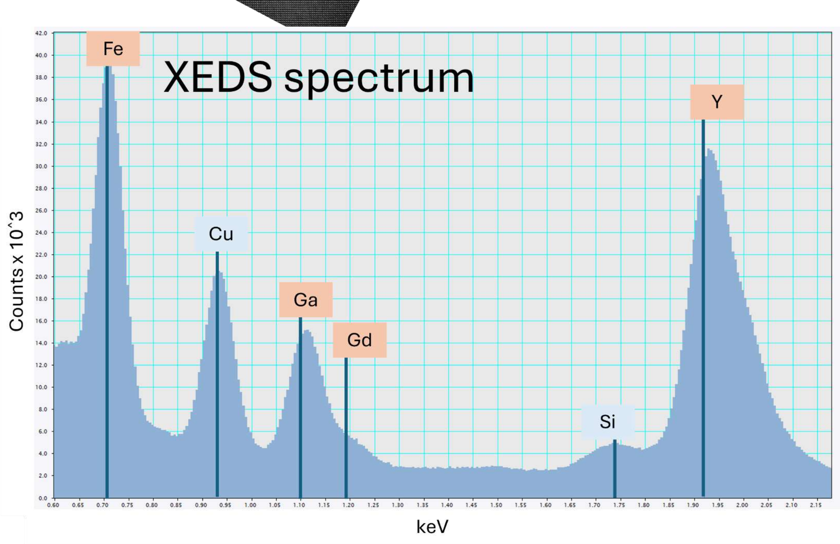
XEDS and EELS
→ chemical composition and diffusion

Understanding the link between oxide growth, its structure and its magnetic properties





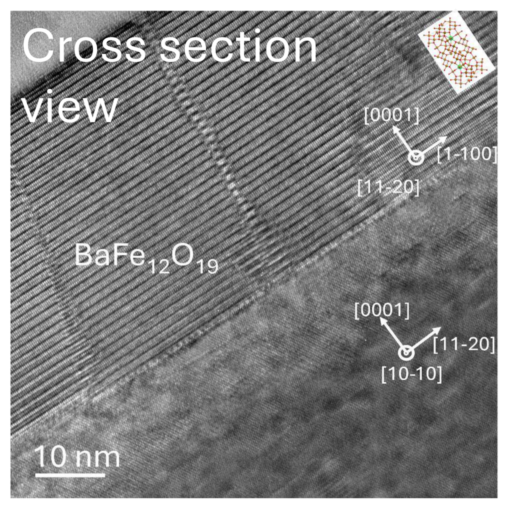


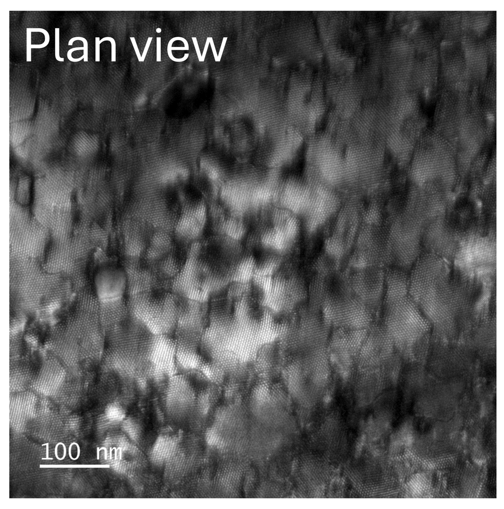


Thin films grown by pulsed laser deposition by IPCMS and IPR partner:

1. M-type **hexaferrite** $BaFe_{12}O_{19}$ and $SrFe_{12}O_{19}$
2. rare-earth (R) **orthoferrite** $RFeO_3$

High resolution TEM images show whether the film is monocrystalline or it contains grains which alter the propagation of a spin wave across the film.





XEDS and EELS detect the elements present in the sample and give access to the distribution of the elements across the thin film which helps to understand the magnetic properties of the sample.

Scan to discover the website

Contact : sarah.clement@cemes.fr

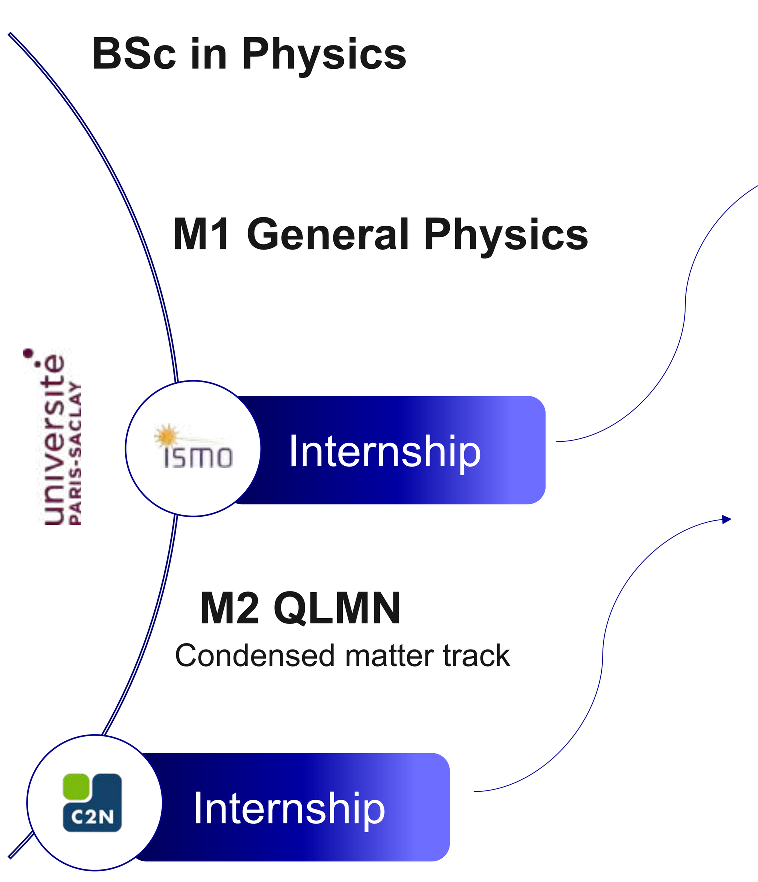
This work has benefited from public funding managed by the French National Research Agency under the France 2030 program, with the reference 'ANR-24-EXSP-0007'

Interactions between Skyrmions and Surface Acoustic Waves

Johan Sebastian RAMIREZ AMADO, PhD Student
Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 91120, Palaiseau, France

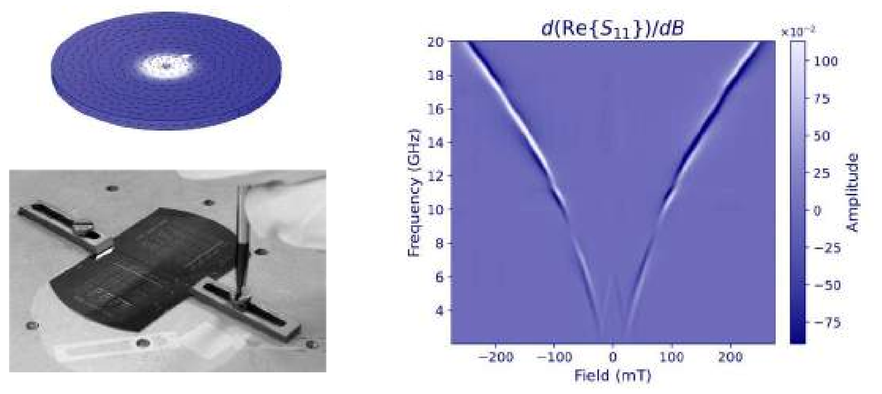
Titiksha Srivastava (C2N), Thibaut Devolder (C2N), Alexandre Hamadeh (C2N), Roy Chowdhury Mouli (SPINTEC), Stephane Auffret (SPINTEC), Bea Helene (Project Manager. SPINTEC - IUF)

Scientific background



Experimental and theoretical introduction to the electronic structure of solids
ARPES and IR spectroscopy of quantum materials.

Magnetoelastic coupling for HF phononic spintronics devices.
Numerical modeling, nanofabrication, and experimental characterization (FMR - BLS).



ACOUSKYR project

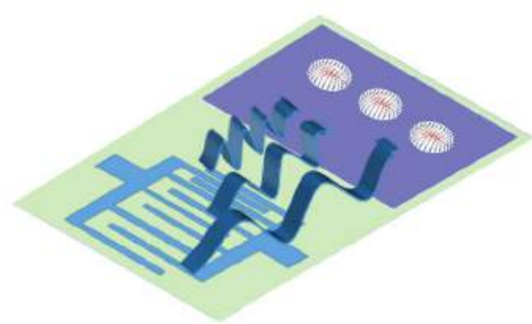
Acoustic control and detection of **skyr**mions and skyrmion lattices, toward memory and neuromorphic computing applications.

Challenges

- Develop models and optimize the geometry and type of SAWs for efficient magnetoelastic coupling and better control of skyrmions.
- Optimize skyrmion-hosting materials and piezoelectric substrate orientation for efficient SAW-driven skyrmion nucleation and motion.
- Manipulate the skyrmions and arrange them into lattices using SAWs.
- Explore the coupling between the resonant modes of skyrmions and SAWs in skyrmion lattices and use it to detect these skyrmion lattices.

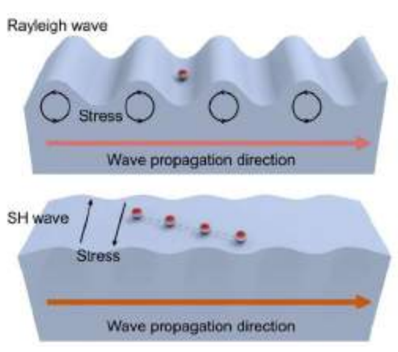
Personal involvement in the project

My work includes IDT fabrication, SAW-driven skyrmion manipulation and ordering, and the measurement of collective skyrmion modes.



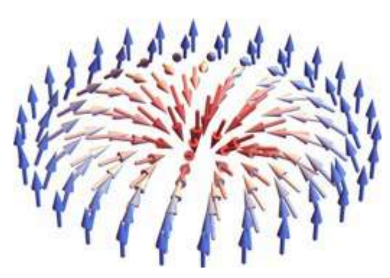
PhD Project
Interactions between SAWs and magnetic textures

Surface Acoustic Waves (SAWs) are elastic waves propagating along the surface of a substrate, generated by interdigital transducers (IDTs). They travel over centimeter-scale distances with low attenuation and tunable frequency.



YANG YANG et al.

Skyrmions are topologically protected nanoscale spin textures stabilized by the Dzyaloshinskii-Moriya interaction (DMI), which gives them a well defined chirality and a particle like stability.

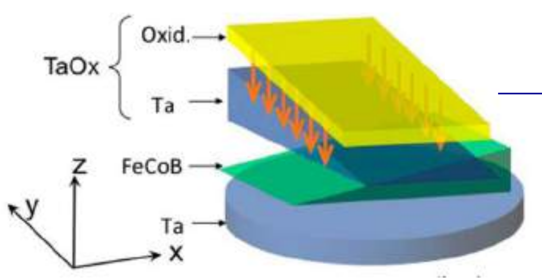


Néel skyrmion ZHANG et al.

SAWs and skyrmions can interact through magnetoelastic coupling, where SAW-induced lattice distortions modify the local magnetic parameters.

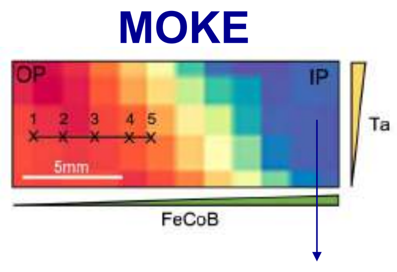
First Steps Toward Acoustic Skyrmion Control

We present two complementary experimental contributions: the characterization of skyrmion properties in a $Ta/FeCoB/TaO_x$ stack on Si/SiO_2, and the development of chirped IDTs for broadband SAW generation on $LiNbO_3$.



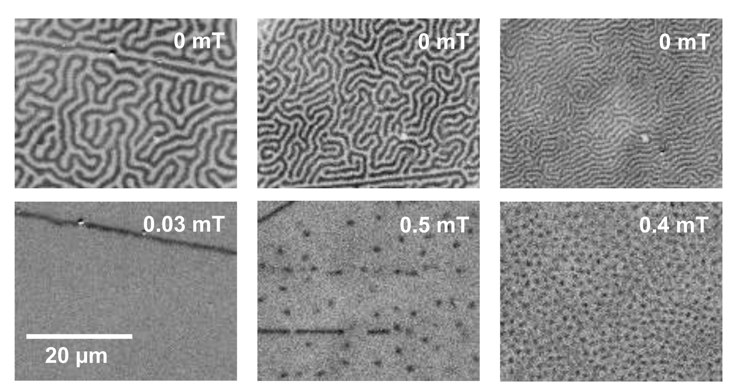
TITIKSHA SRIVASTAVA et al.

MOKE

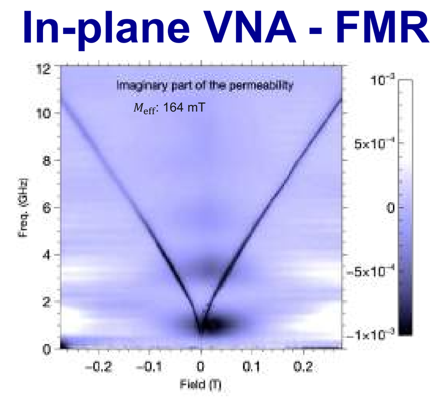


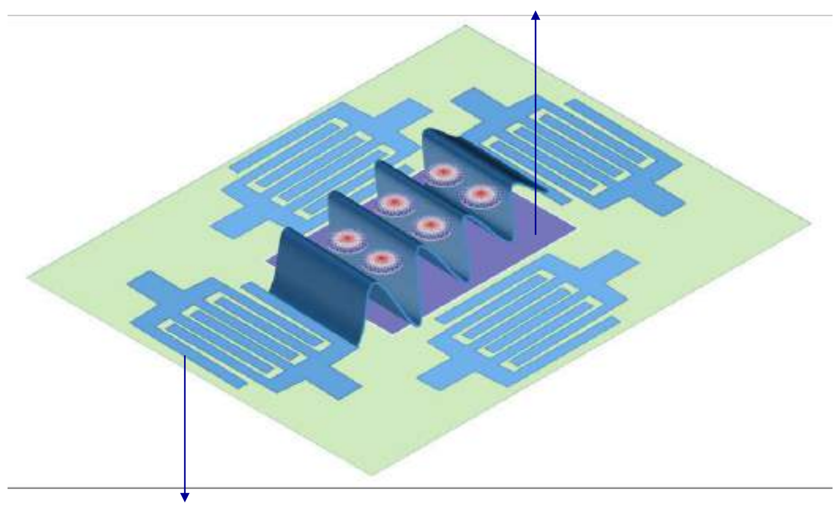
PMOKE measurements

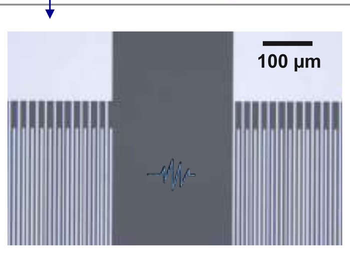
Region	1	2 - 4	4 - 5
Skyrmion Nature	free	Isolated	Lattice like
Skyrmion Size	n/a	1.5 – 1 µm	1 – 0.7 µm
Stability field range	-1 mT … 1 mT	-1 mT … 1 mT	-1 mT … 1 mT



In-plane VNA - FMR





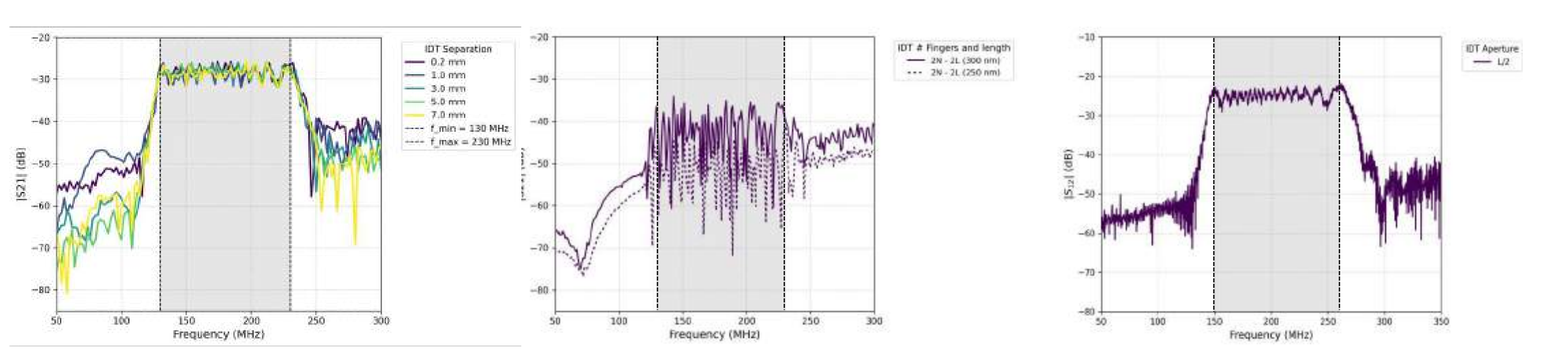


IDT on LNO

Substrate	Crystal Cut	SAW Propagation direction	K^2 (%)	Vφ (m/s)
$LiNbO_3$	Y	Z	4.8	3488
		X	1.5	3740
	128° - Y	X	5.3	3888

D. CIPLYS and R. RIMEIKA

VNA - Transmission measurements



LNO Y – Cut, SAW Propagation along Z – Dir

LNO 128° Y – Cut, SAW Propagation along X – Dir

Scan to discover the website

The Priority Research Program for SPIN (PEPR) is an exploratory program within the framework of the France 2030 investment plan. It aims to develop a new generation of components for a more frugal, agile, and sustainable digital world. With a funding of 38 million euros over eight years, the SPIN Research Program is intended to contribute to accompanying a new cycle of innovation in spintronics.

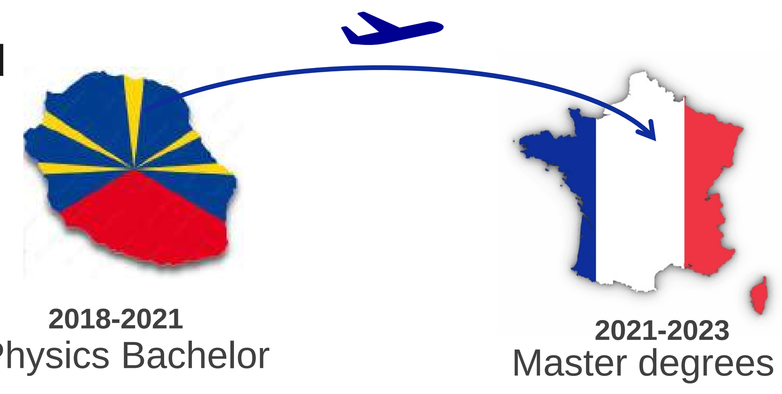
Advanced signal processing using spin waves non-reciprocity

Gaël Yann Thiancourt, Centre de Nanosciences et de Nanotechnologies(C2N), PhD student

Thibaut Devolder (C2N), Matthieu Bailleul (IPCMS), Laura Thevenard (INSP), Anane Abdelmadjid (LAF), Vincent Vlaminck (IMT), Fatih Zighem (LSPM)

From an island to the main land

Originally from Reunion island I went to mainland France to pursue my academic studies for my master. I was able to do internships where I learnt about spintronics, characterization methods and sample growth methods.



M1 Physics and applications

M1 Internship: Coupling between molecules and nanoparticles

Diffuse reflectance spectroscopy, Sum Frequency Generation and scanning electron microscope

M2 Quantum, Light, Materials and Nano Sciences (QLMN)

Centre de Nanosciences et de Nanotechnologies

M2 Internship: Measurement of spin wave dispersion relation of a synthetic antiferromagnet using an electrical method

Basics of spintronics, RF measurements, spin waves measurement technics and spin waves in a synthetic antiferromagnet

SWING: SPIN WAVES FOR ADVANCED SIGNAL PROCESSING

The **SWING** project aims to exploit the complex properties of magnon, to develop new information technologies, using their phase or amplitude for coding. This project will lead to new magnonic components for analog and digital devices.

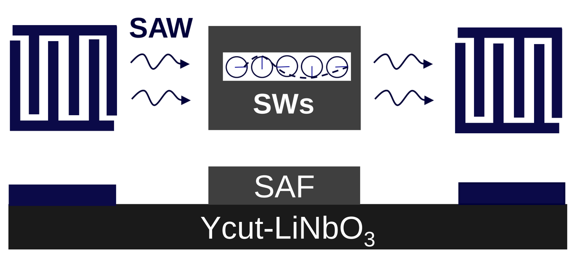
Challenges

The main challenges in the project are:

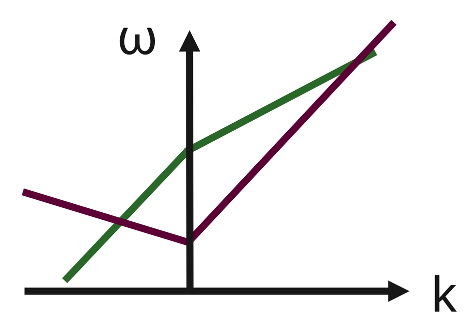
1. Design devices more efficient in energy consumption
2. Develop new ways to manipulate magnon propagation
3. Design new magnonic captors and signal processing item

Methods

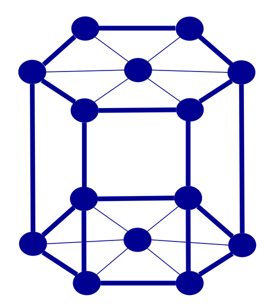
I will focus on the hybrid magnonic system and reciprocal devices. We will also focus on the design of signal processing devices using spin wave properties.



hybrid magnonic systems



Non-reciprocal devices

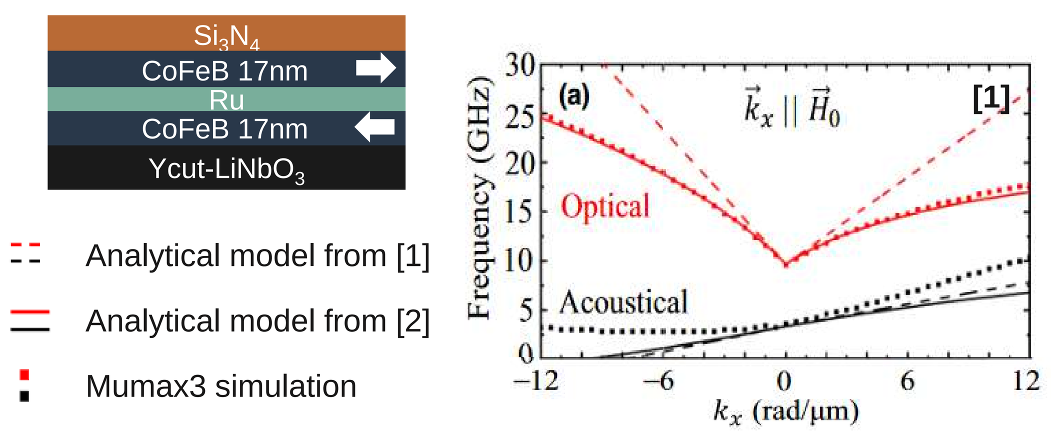


Development of new materials and devices design

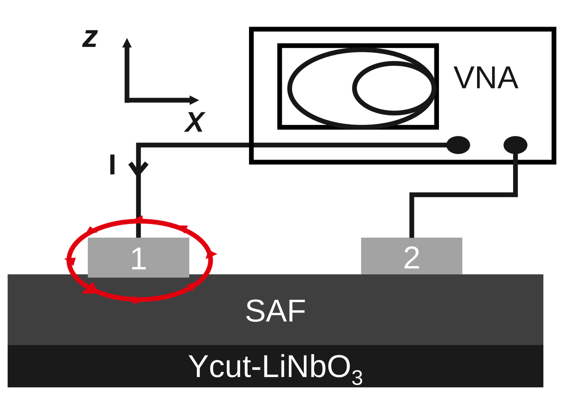
Advanced signal processing using spin waves non-reciprocity

Objectives: develop signal processing item using spin waves and their properties

Non-reciprocal material and spin waves measurement

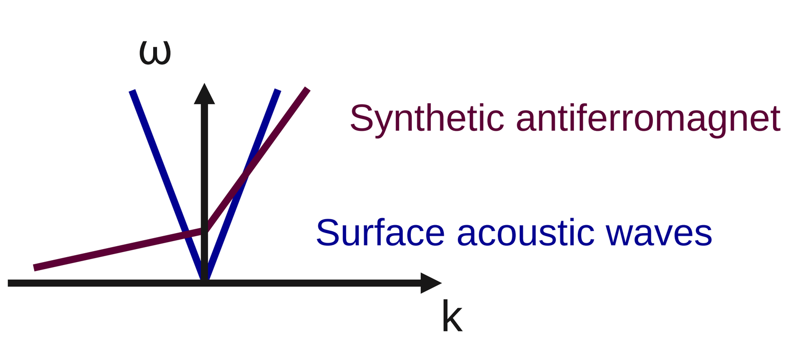


Synthetic antiferromagnet

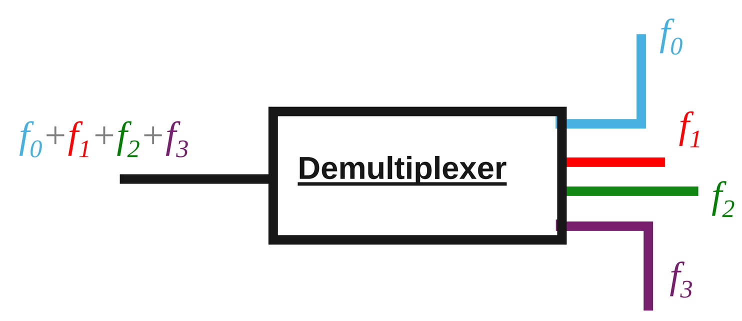


Propagating spin wave spectroscopy (PSWS)

Upcoming works in the thesis



Magneto-elastic coupling for filters



Signal demultiplexing using spin waves

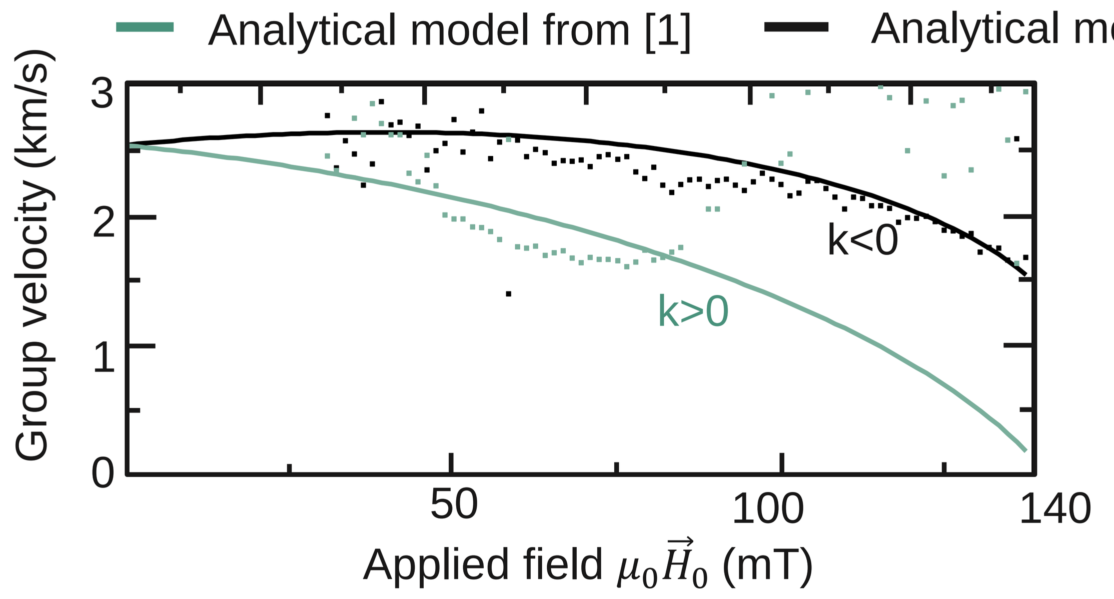
Measurement of spin wave dispersion relations using an electrical method

The dispersion relation of spin waves can vary monotonically about the center of the Brillouin zone which is of interest for applications. Here, through a theoretical model [3], we present a method to analyze spin waves $\omega(k)$.

Group velocities of SAF acoustical spin wave mode in a non-reciprocal propagation

From an analytical model [3] we can derive a formula linking the wavevector with the S parameter obtain by PSWS

$$\mathrm{Arg}\left[\frac{\partial \tilde{S}_{21}^{exp}}{\partial H_0}(\omega)\right] + \frac{\pi}{2} + 2\pi\mathbb{Z} = k\left(r + \frac{w_{ant}^2}{6L_{att}} + \frac{w_{ant}^2}{6r}\right) + O(w_{ant}^4)$$



G.Y. Thiancourt, S.M. Ngom, N. Bardou, and T. Devolder Phys. Rev. Applied **22**, 034040

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References

[1] F. Millo et al. Physical Review Applied 20, 054051 (2023)
[2] M. Ishibashi et al. Science Advances 6, eaaz6931 (2020).
[3] T. Devolder, Physical Review Applied 20, 054057 (2023)

Acknoledgement

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Driving interfacial magnetic interactions in 2D heterostructures by electric fields

Antoine PASCAUD, Laboratoire de Physique des Solides, PhD funded by SpinMat

Advisors : Alexandra Mougin (LPS), Joao Sampaio (LPS), Liza Herrera Diez (C2N)

SpinMat – coordinator: Vincent CROS

My academic path

2020-2022 — Université Paris-Saclay, IUT d'Orsay

2022-2025 — UTT Université de Technologie Troyes

2023 — Politecnico Milano 1863

2025 — KIT Karlsruher Institut für Technologie

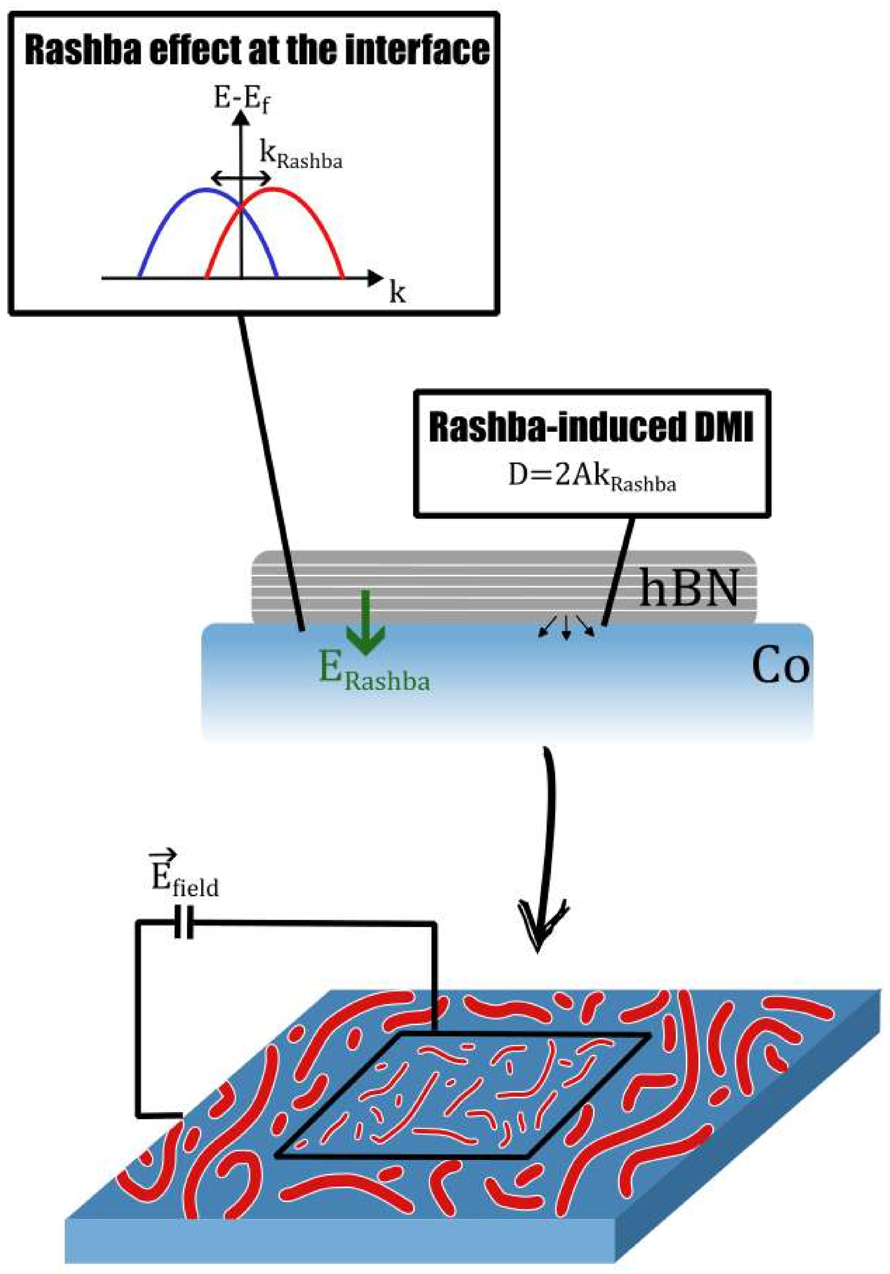
2025-2028 — LPS Orsay

SpinMat

The SPINMAT project aims to create a national "platform" with unique capabilities for the development of new materials for spintronics in the form of a structured national network. The goal is to equip and structure the French community in the field of material growth for spintronics by providing design and production tools for materials that offer new physical properties, new functionalities, and new ways to create, manipulate, and detect spin information.

My PhD project

Rashba interaction controls the magnetic properties at Co/hBN interface (anisotropy, DMI…)

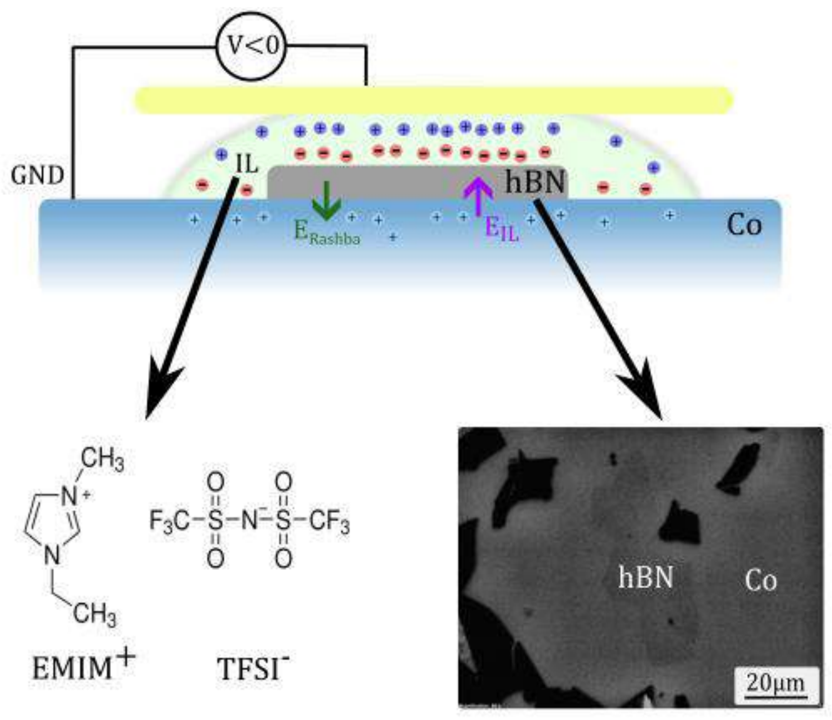


Possibility to tune the Rashba effect with an external electric field

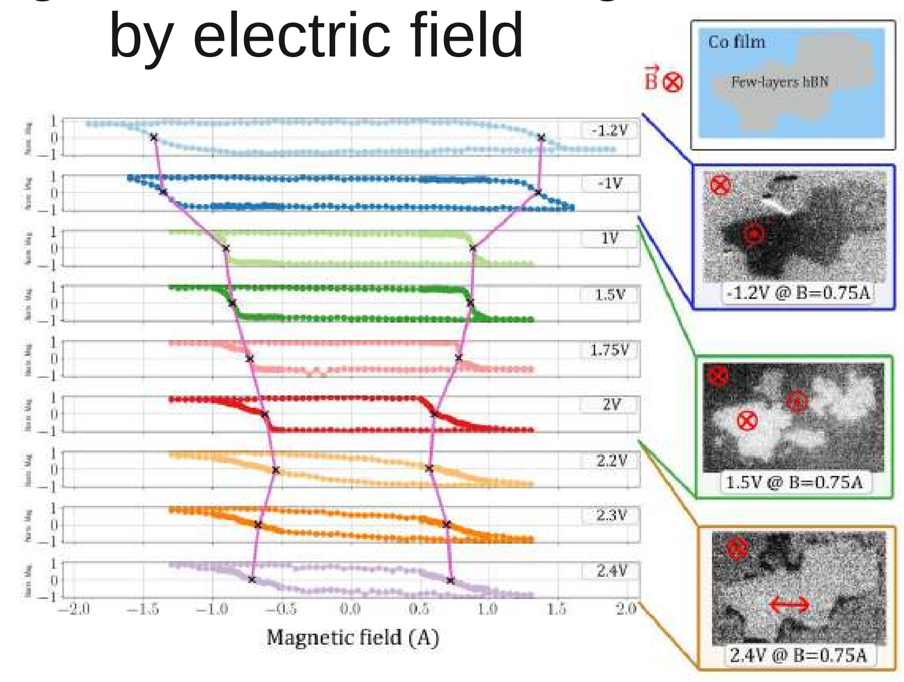
→ Ultra-low power control of magnetic interactions and textures

First results

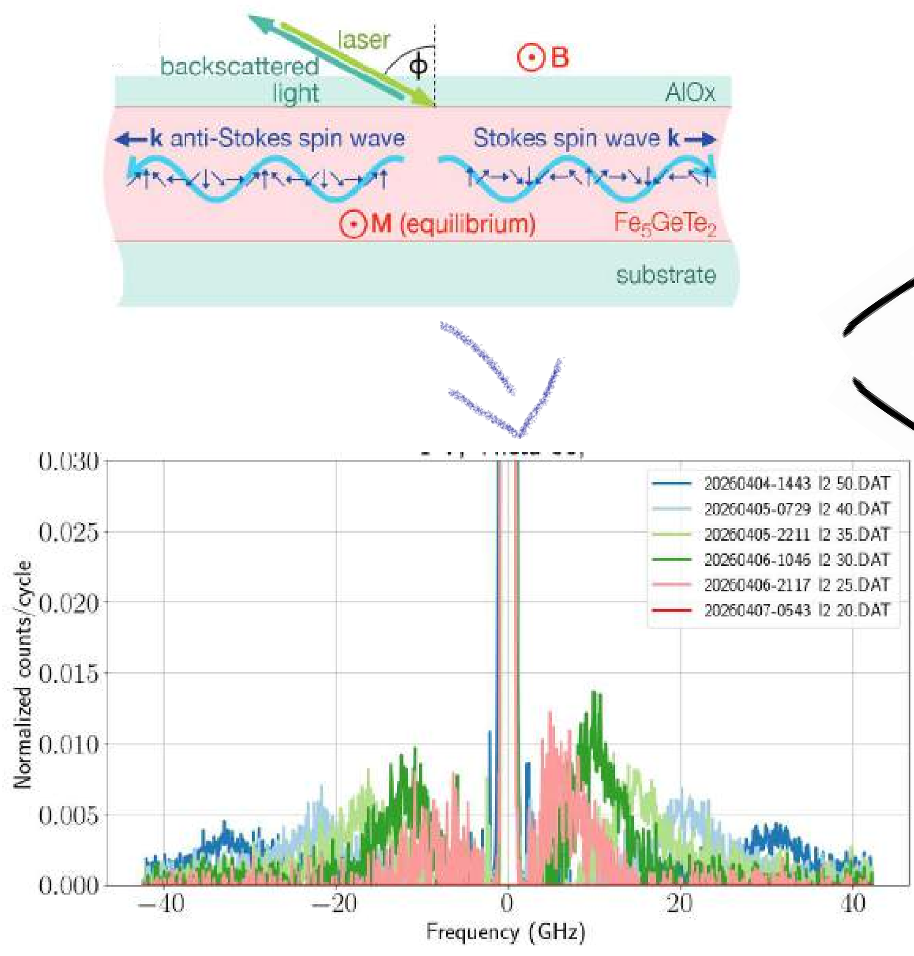
Ionic liquids are a way to apply huge electric fields with low voltages



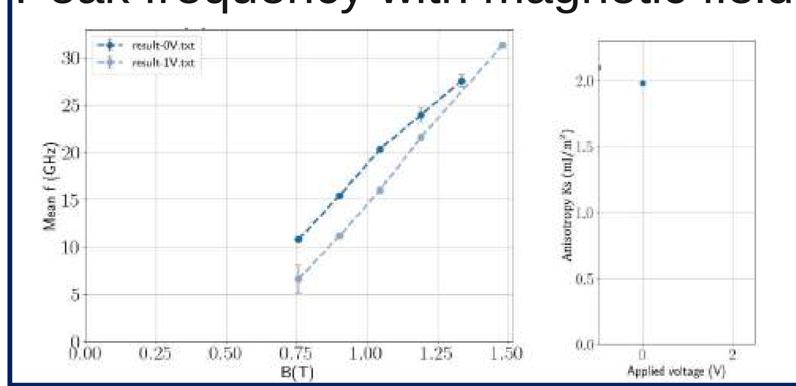
Magnetic reversal changed by electric field



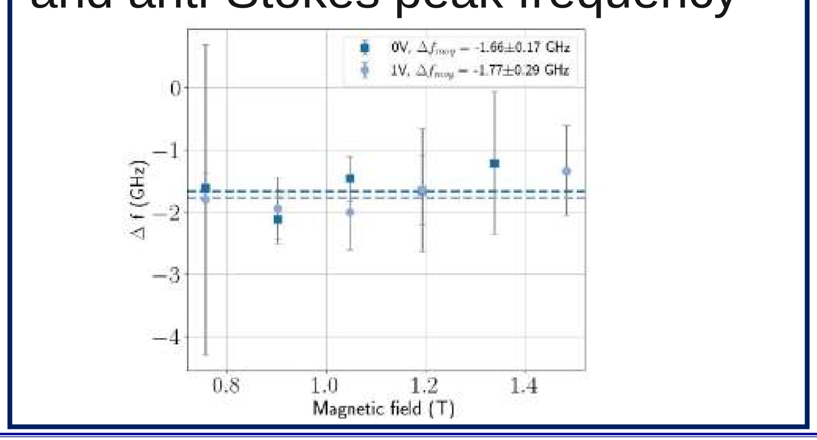
Brillouin Light Scattering (BLS)



Peak frequency with magnetic field



DMI: difference between Stokes and anti-Stokes peak frequency



Clear effect on magnetic anisotropy

No clear conclusion on the effect on DMI

Scan to discover the program !

antoine.pascaud@universite-paris-saclay.fr

Orbital driven angular momentum conversion in CoFe/CuOx probed by THz emission and spin-orbit torque

Anil Anakha, Vomir Mircea, Bailleul Matthieu, Noël Paul

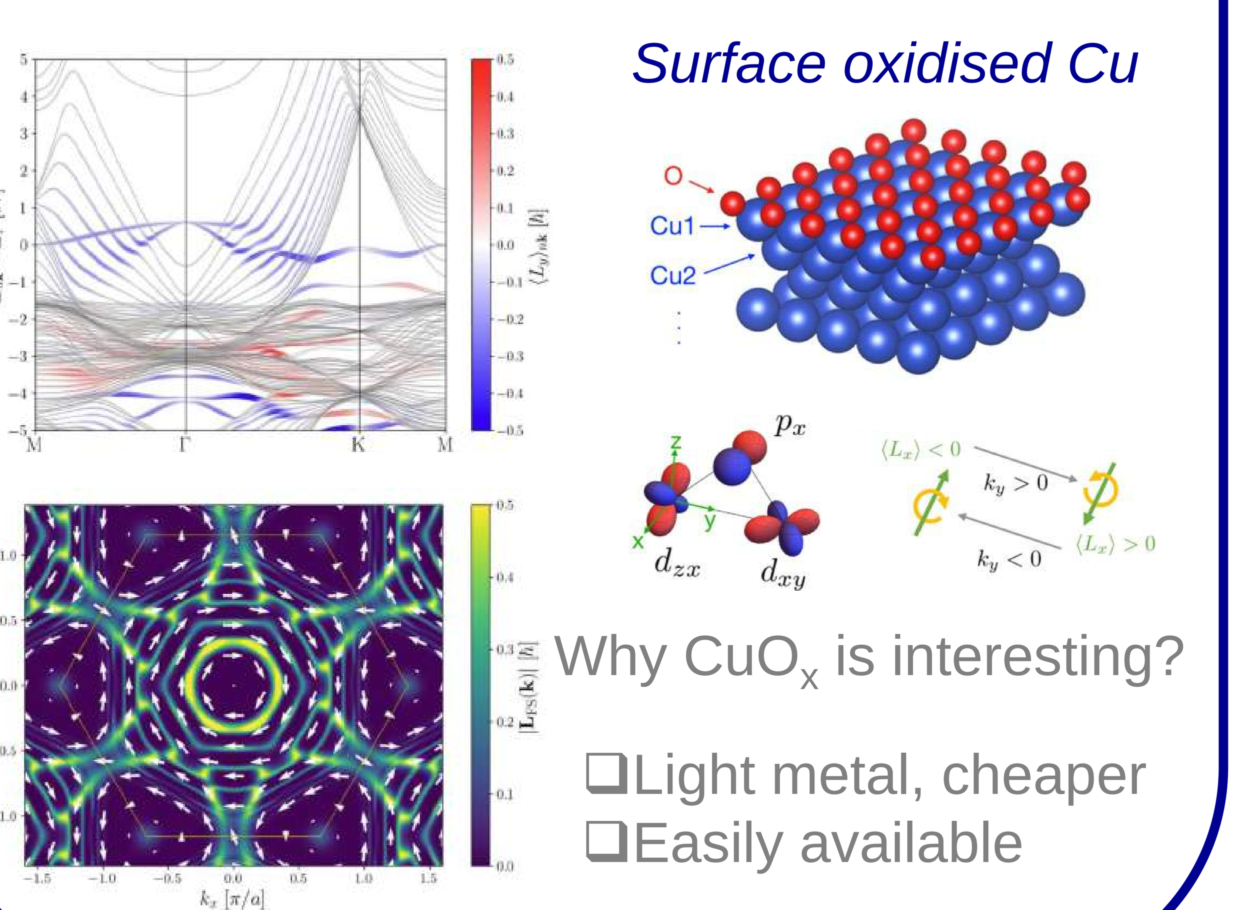
Institut de Physique et Chimie des Matériaux de Strasbourg

Objectives of my PhD

- ❑ Detection of THz waves using spintronic techniques.
- ❑ Fabrication of microstructure devices and antenna integration.
- ❑ **Studying Orbitronics in CuO_x**

1. Introduction

Orbital Hall transport: efficient angular momentum flow without strong spin–orbit coupling- *New possibilities*



Why CuO_x is interesting?

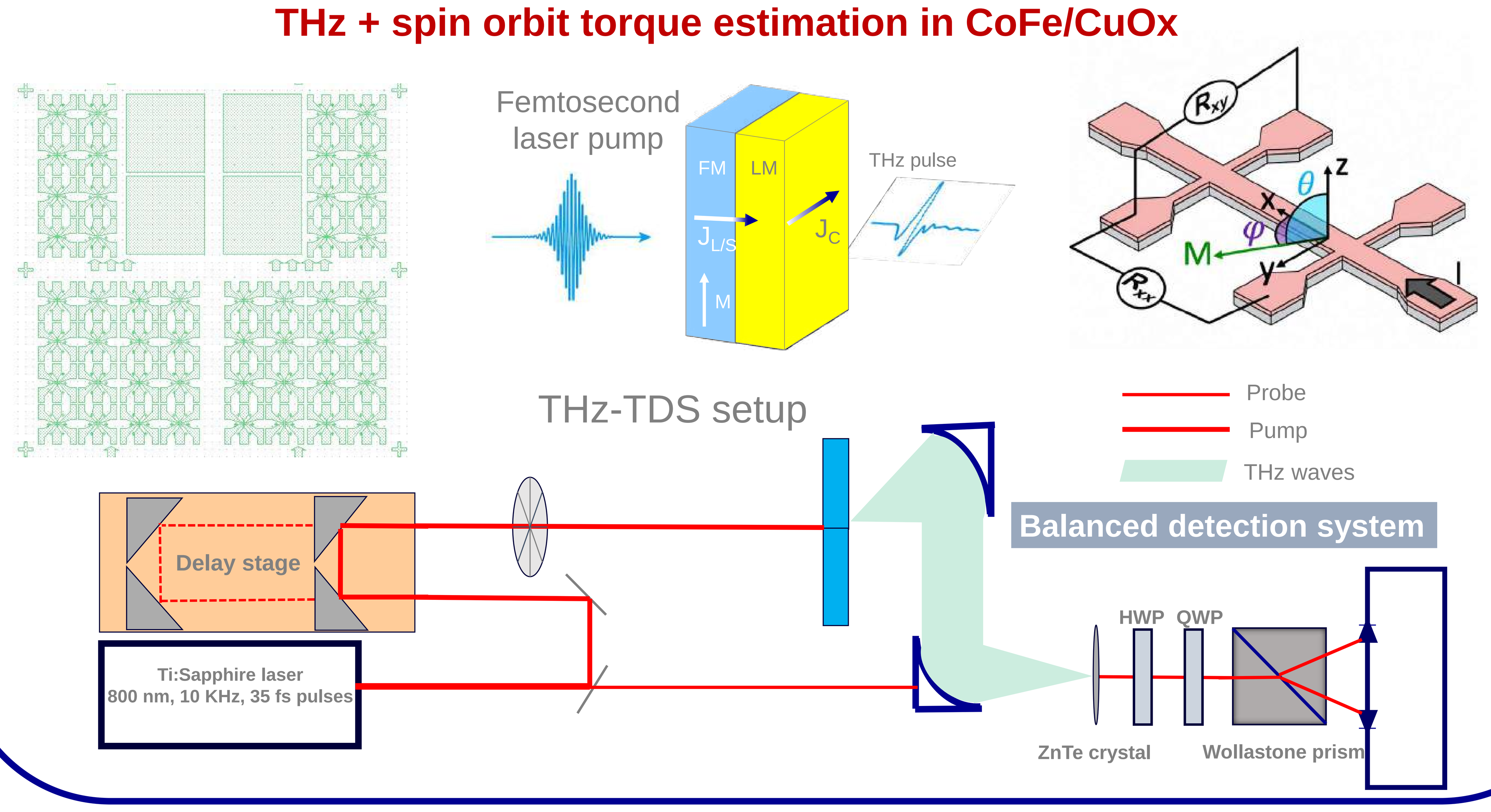
❑Light metal, cheaper
❑Easily available

D. Go et al., *Phys. Rev. Lett.* 103, L121113 (2021)

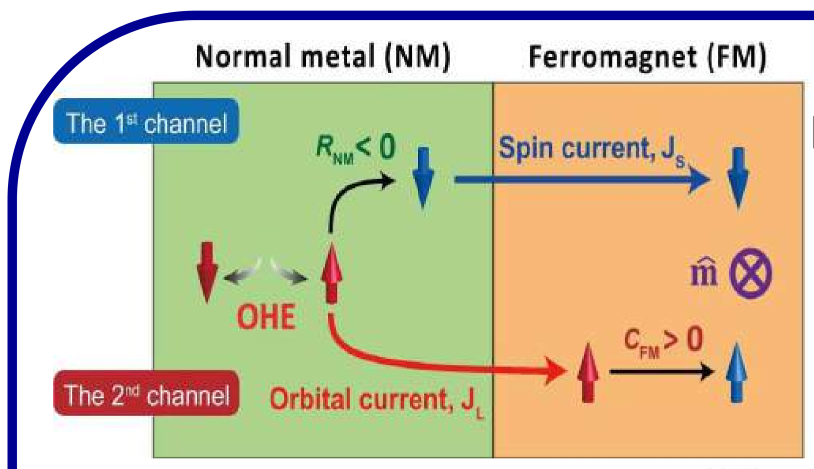
3. Methodology

We will study *CoFe(3 nm)/Pt(5 nm), CoFe(3 nm)/Cu (5 nm), CoFe(3 nm)/Cu(5 nm)/SiN(6 nm)*

THz + spin orbit torque estimation in CoFe/CuOx



2. Motivation



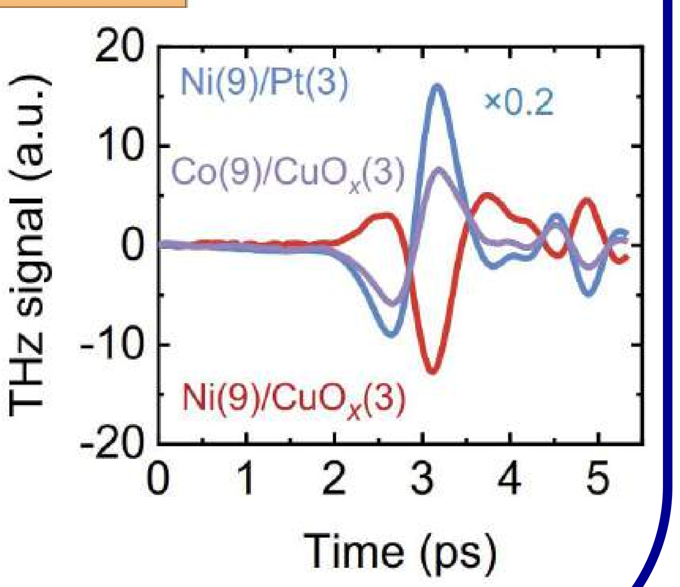
❑ Large torque reported compared with Pt

Lee, D., *et al. Nat Commun* **12**, 6710 (2021)

❑ Weak THz emission compared with Pt

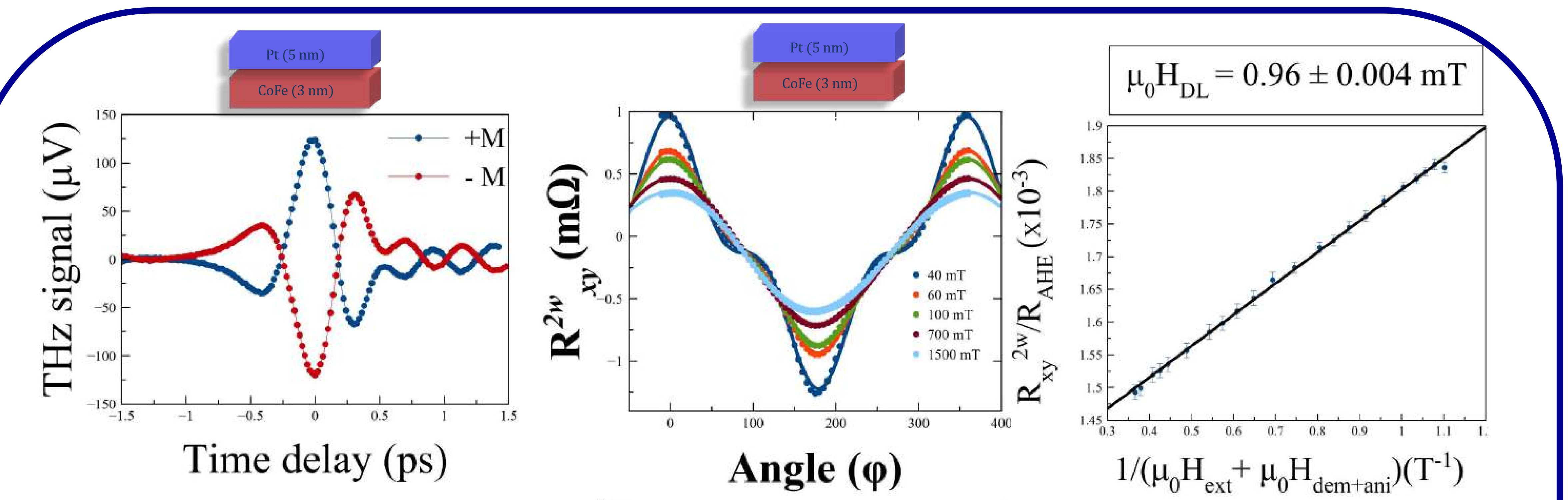
RECIPROCITY?

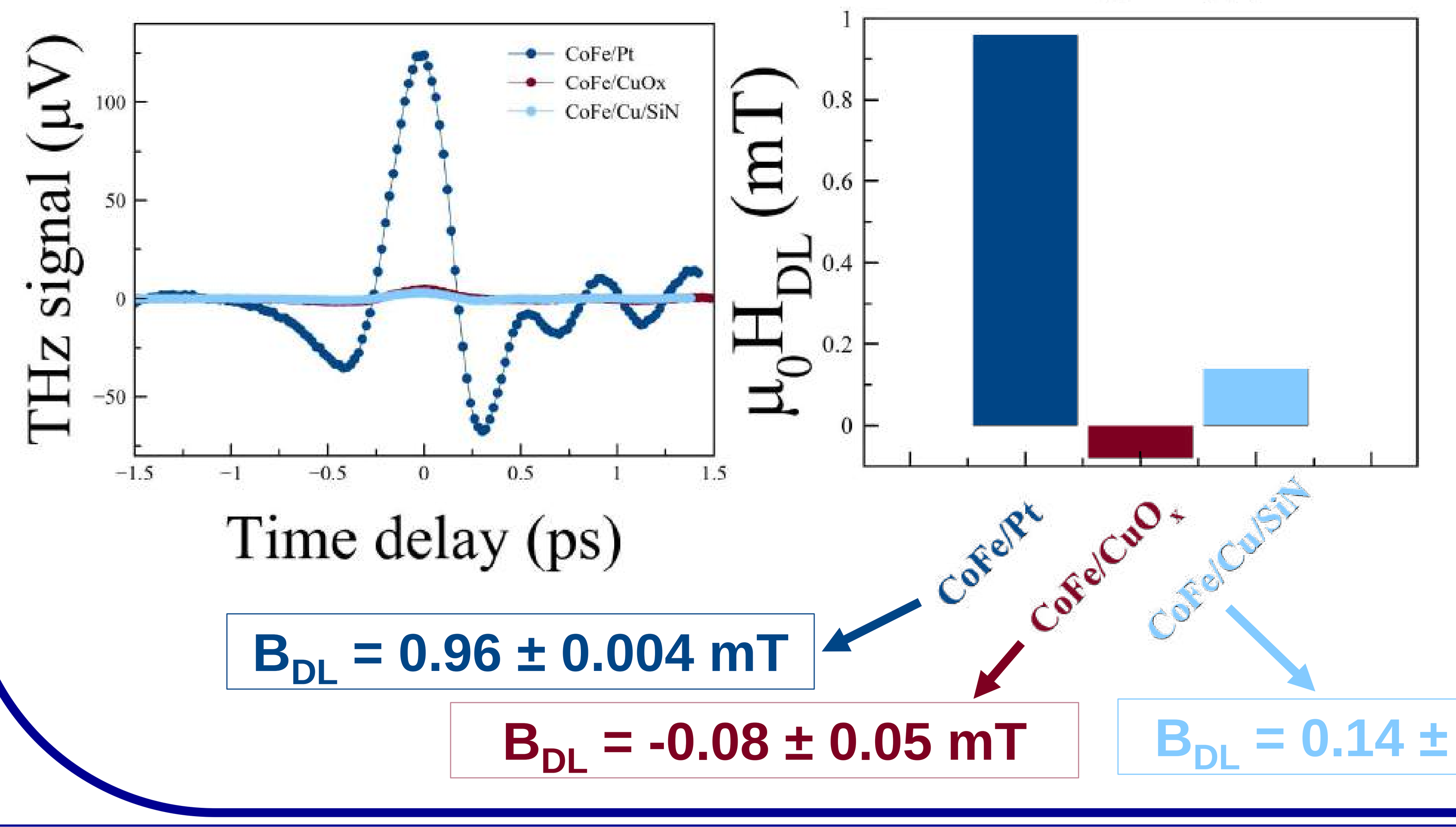
This motivates a direct test of reciprocity



Lee, D., *et al. Phys. Rev. Research* 7, L012042 (2025)

4. Results and discussion

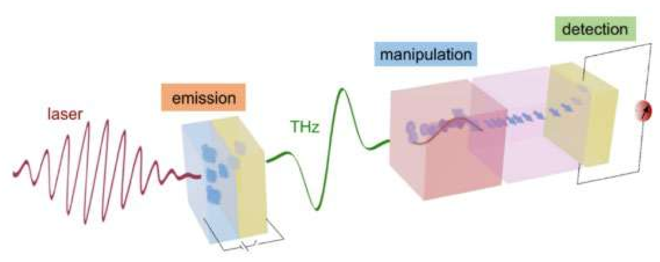




- ❑ THz and transport give the same result – No discrepancy!
- ❑ Systematic study about sensitivity of the sample to oxidation and growth conditions
- ❑ To further understand the orbital conversion in CuOx, we plan to study thickness dependence of FM

5. Acknowledgment

This work is funded by the French national research PEPR SPIN program through project *ANR-22-EXSP-0003 TOAST*



TOAST project

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Ultrafast spin currents and ferroic oxides

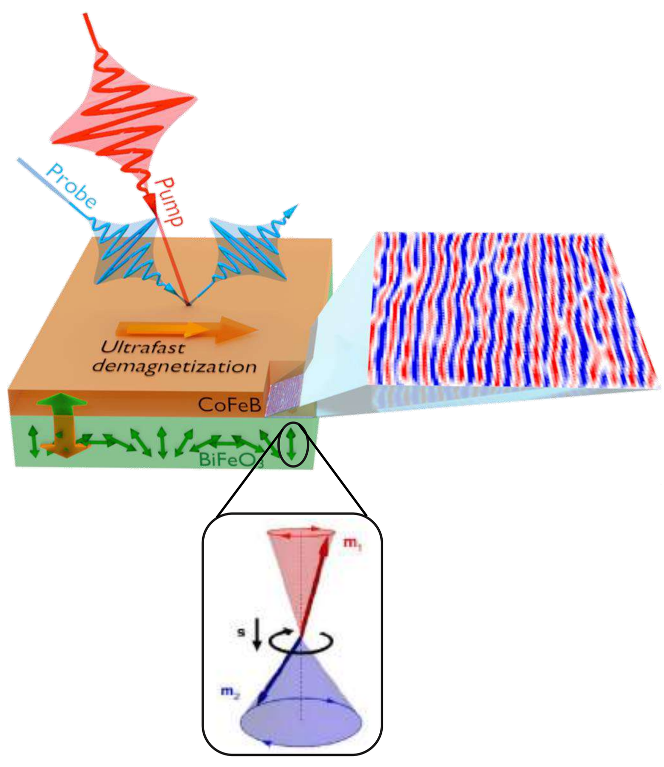
Holger Grisk[1], Sylvain Massabeau[2], Amr Abdelsamie[2], Michel Viret[1], Stephane Fusil[2], Vincent Garcia[2], Romain Lebrun[2], Jean-Yves Chauleau[1]

[1] *SPEC, CEA, CNRS, Universite Paris-Saclay, Gif-sur-Yvette*

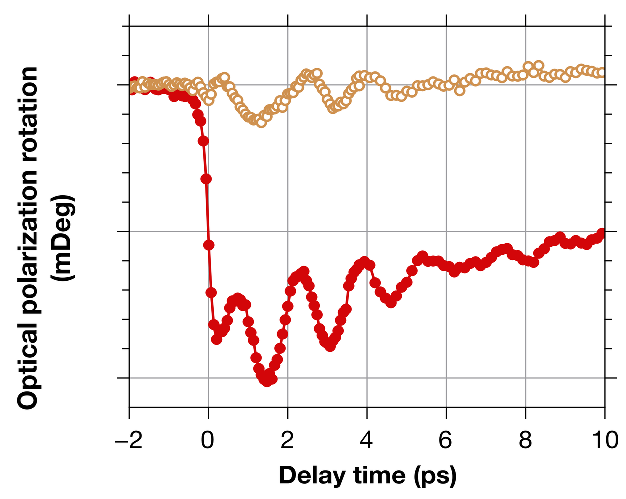
[2] *Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau*

Motivation

Idea: Inject ultrafast spin currents into insulating antiferromagnets and trigger AFM dynamics

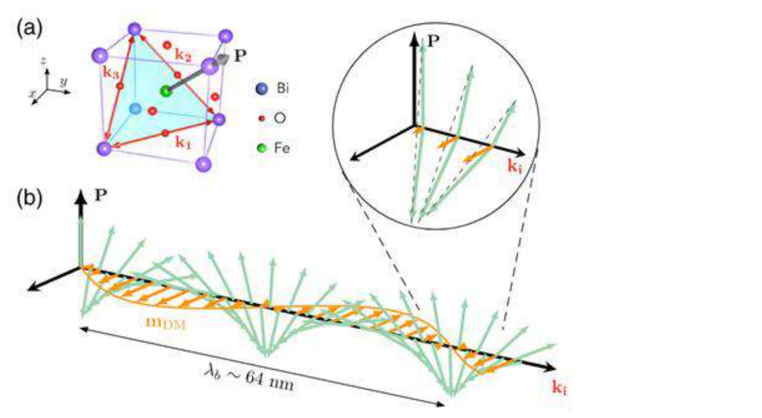


- AF dynamics in THz range triggered by ultrafast spin currents
- investigating: role of strain, spin diffusion length etc.
- different magnetic taxtures of BFO (cycloid, G-type)
- generalize to other FM/AFM structures
  - NiO
  - Hematite etc.



- electromagnon at the frequency of around 0.5 THz triggered by ultrafast spin current injection.

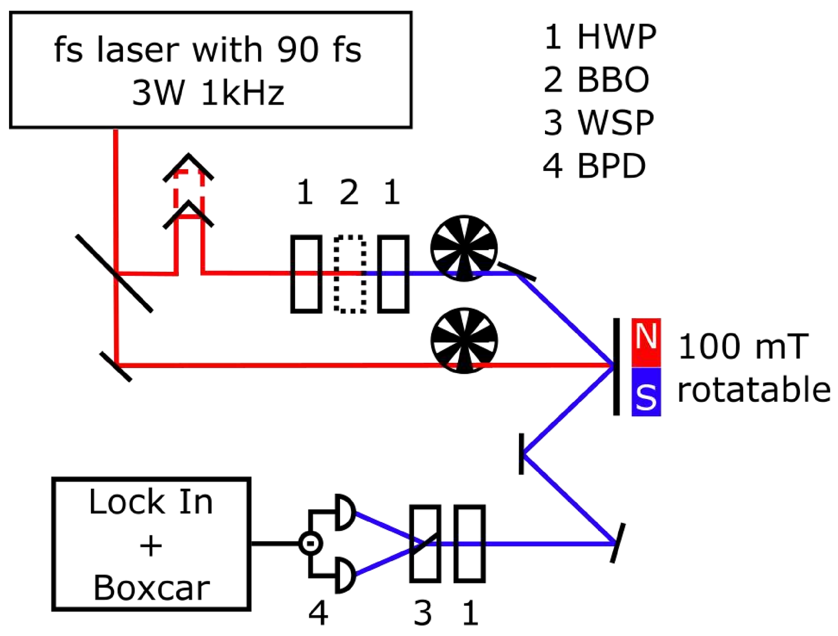
Rene et al., Sci Adv 11 45, eadx1107 (2025)



- Neél_vector and polarization vector coupled
- due to DMI in strained films cycloid formation

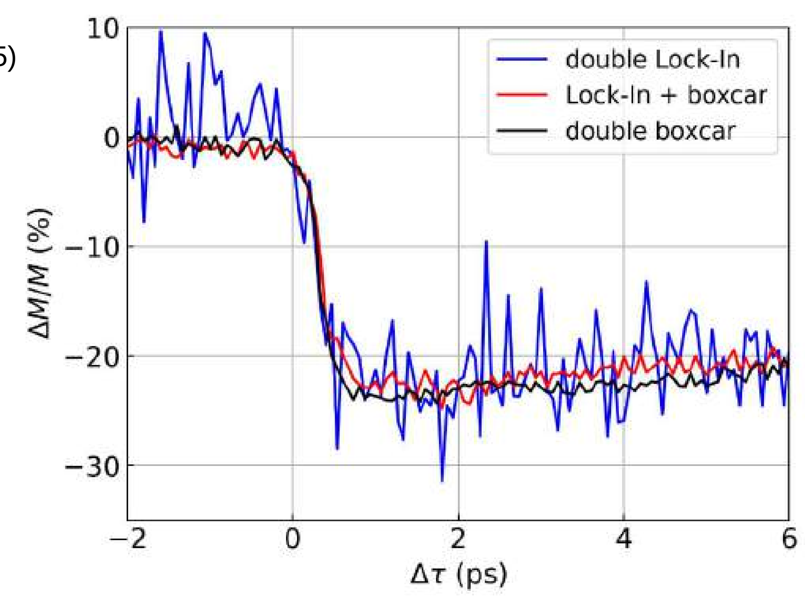
Finco et al. PRL 128 187201 (2022)

Experimental setup

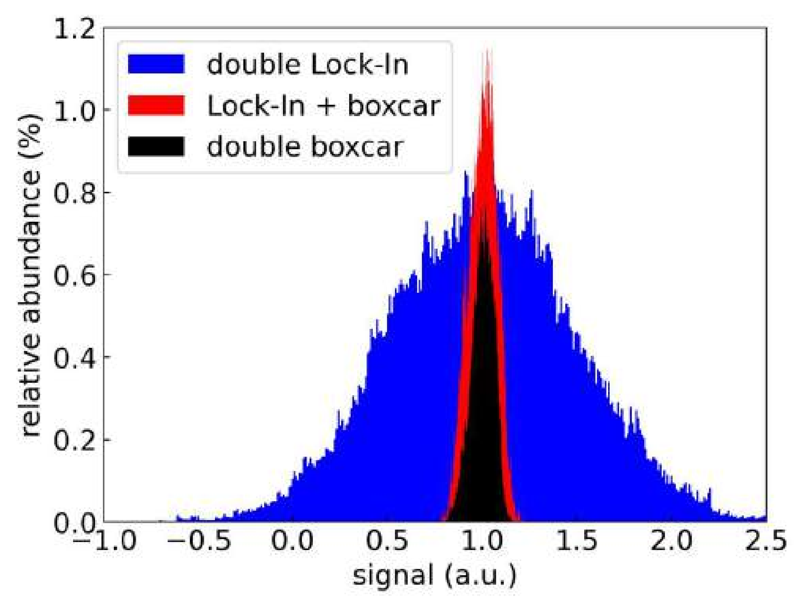


Set up for time resolved MOKE and time resolved birefringence

- **Upgraded with boxcar detection technique**
- Improvement factor of the SNR by a factor of:
  - Lock-In + boxcar: 6.5
  - double boxcar: 8
- leading to a reduction of the measurement time by a factor of 42 or 64 respectively
- disadvantage of the double boxcar detection: no drift correction

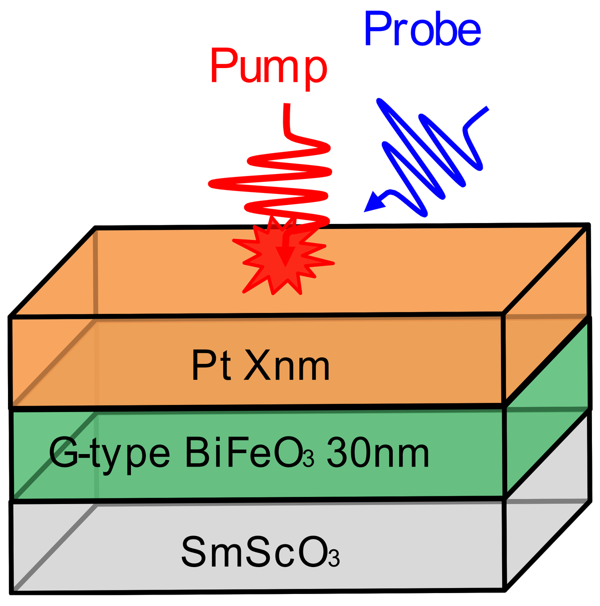


Single pass measurement

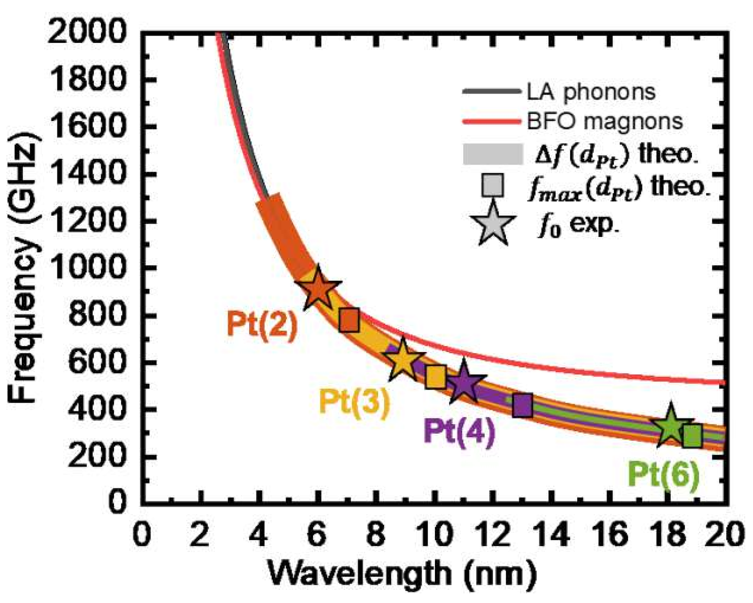


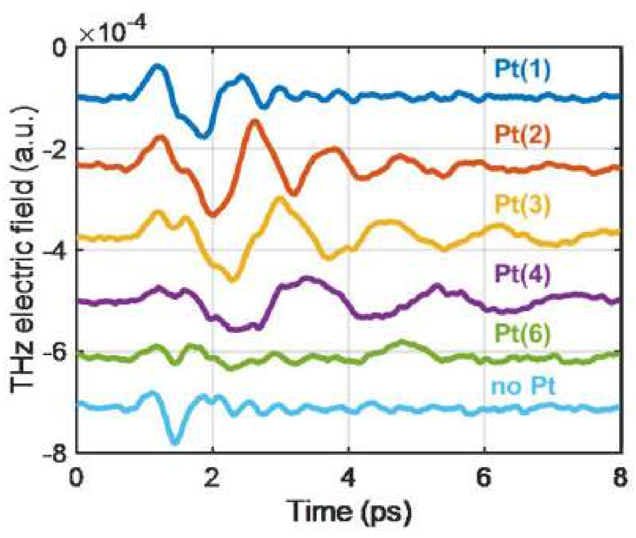
Histogram of the signal at a fixed delay

Results



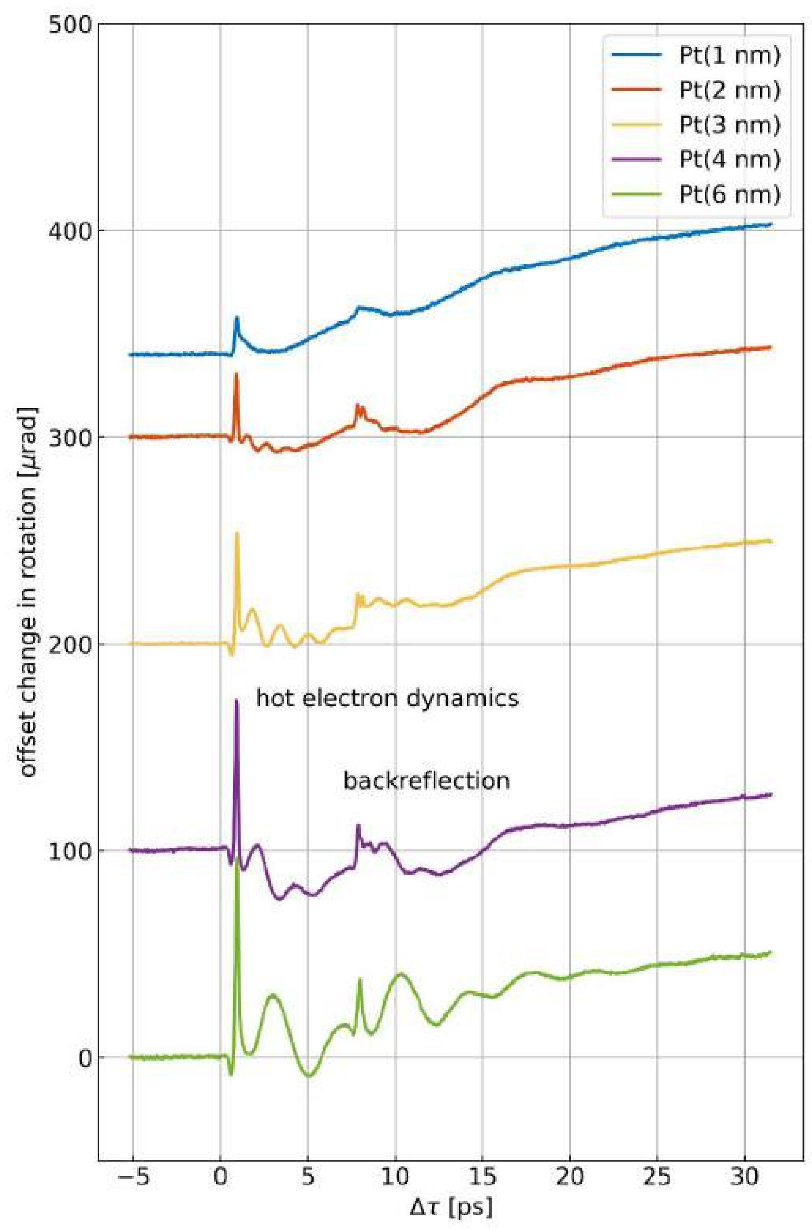
- unveiling the full dynamics of 30 nm G-type $BiFeO_3$
- the role of strain is investigated by replacing the ferromagnetic layer with platinum
- -acting as a strain transducer, to probe the strain isolated from magnetic contributions.



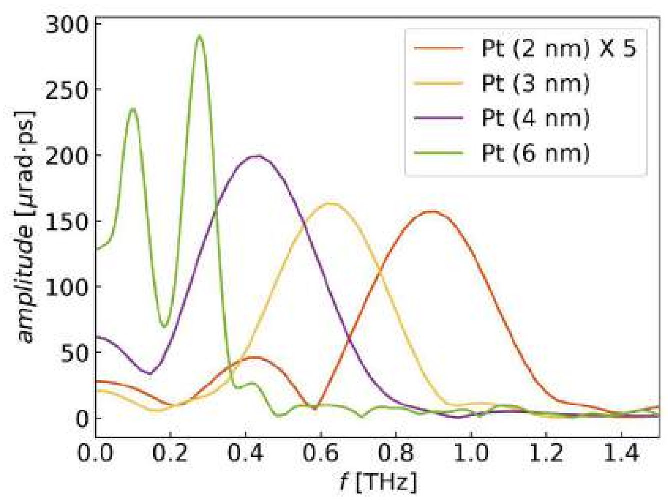


- Right: dispersion relation of the phonons and magnons in $BiFeO_3$
- frequency of the strain transduction of platinum
- Left: THz-TDS at Laboratoire Albert Fert

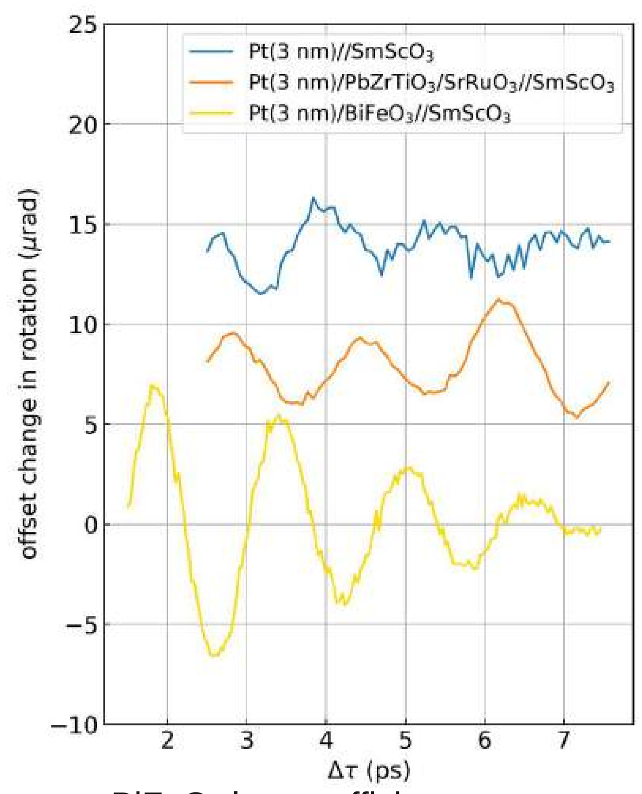
Massabeau et al., arXiv:2511.21596 (2025)



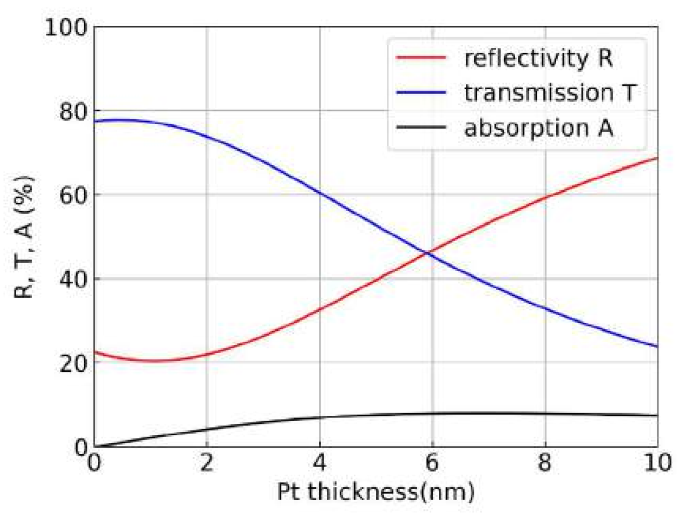
- Strain induced change in birefringence
- Low THz phonon modes with narrow bandwidth are excited
- Ferroelectricity of $BiFeO_3$ plays key role
- In good agreement with THz-TDS

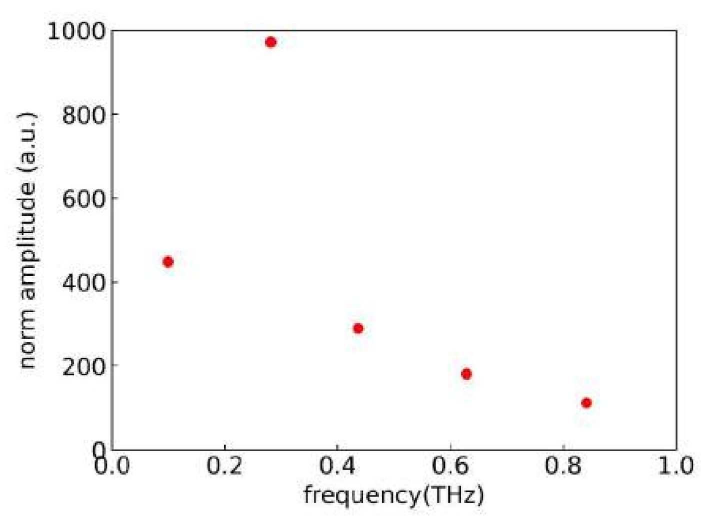


- Filtered spectra to extract the frequency and lifetime of the excitation
- By changing the thickness of the platinum transducer frequency can be tuned



- $BiFeO_3$ larger efficiency as non-multiferroic ferroelectrics





- Right: Absorption (black) of light at λ=800nm for the investigated stack
- Left: Oscillation amplitude normalized to the absorbed light
- Lower frequency modes have higher efficiency

Scan to discover the website

Magnetoresistive detection of spin-waves

Quentin ROSSI, 3rd year PhD student. E-mail: quentin.rossi@ipcms.unistra.fr

Daniel STOEFFLER (IPCMS), Grégoire DE LOUBENS (CEA-SPEC), Hugo MERBOUCHE (CEA-SPEC), Hicham MAJJAD (IPCMS), Yves HENRY (IPCMS), Igor NGOUAGNIA, Aurélie SOLIGNAC (CEA-SPEC) and Matthieu BAILLEUL (IPCMS)

Academic path

2019: Bachelor in Fundamental and Applied Mathematics (Université de Lorraine)

2021: Bachelor in Fundamental and Applied Physics (Université de Lorraine)

2023: Master degree in Condensed Matter and Nanophysics (Université de Strasbourg)

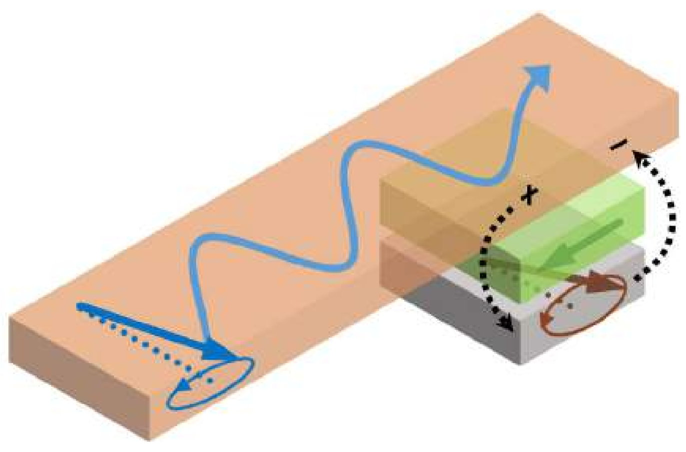
2023: First steps as a PhD student in the PEPR SPIN

SWING Project

The SWING project is part of the magnonics field, which aims to exploit the unique physical properties of spin waves, or magnons, to develop new information technologies, using their phase or amplitude for coding.

My thesis project

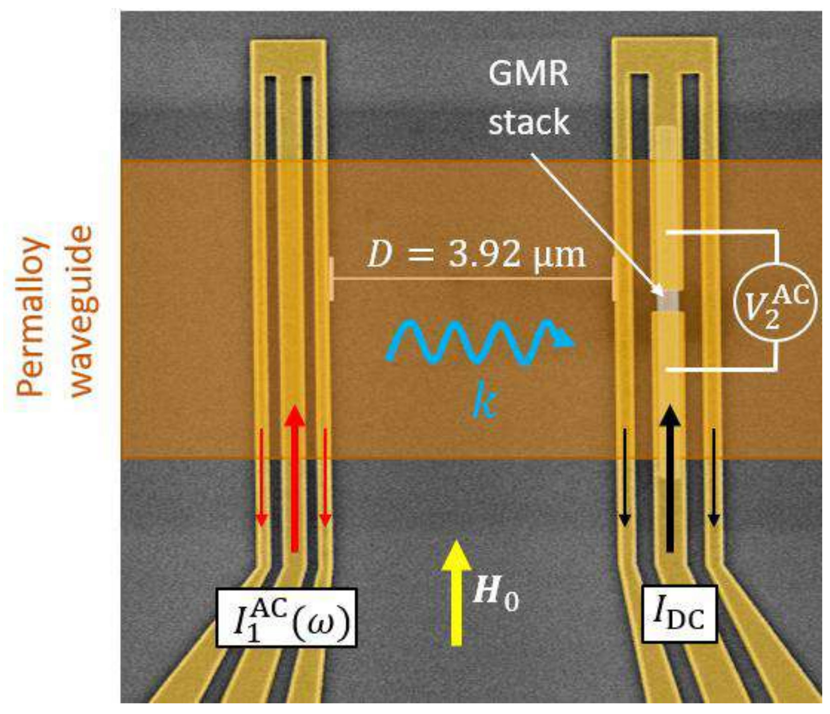
Spin-wave-based data processing architectures have a strong need in high magnetic sensitivity at nanoscale which is not achieved by modern methodologies.



We employ GMR/TMR stacks exhibiting high magnetic field sensitivity. The free layer of the MR sensor is dipole-coupled to the nearby propagating spin-wave, resulting in a measurable resistance oscillation that is electrically read out.

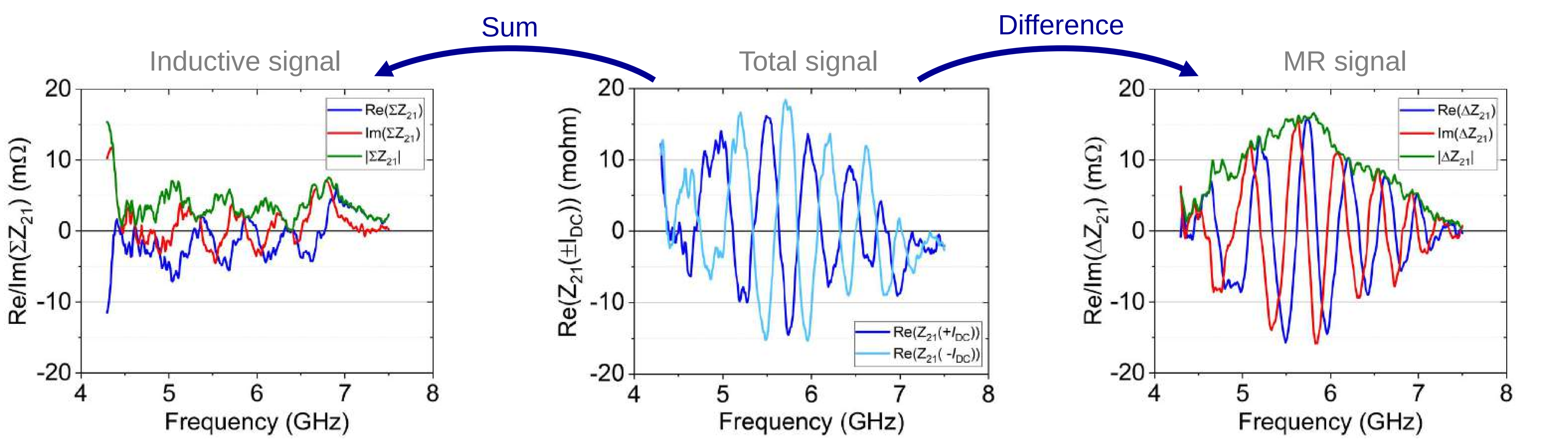
Efficient spin-wave detection at the nanoscale

Rossi et al., Science Advances 11, eadx4126



We have shown that magnetoresistive (MR) detection is approximately fifty times more efficient than inductive detection at the nanoscale.

The favorable scaling law of MR detection makes it a strong candidate for future applications in spin-wave-based data processing architectures.



Study of magphonic crystals

Coordinator of SWING: Matthieu Bailleul

LSPM Partner of SWING : Ulrich LEUGA, Yves ROUSSIGNE and Fatih ZIGHEM

Academic background

2024-now: PhD student in physics

2022-2024: Master SGM in Functional Materials

2021-2022: Master 1 in Materials Science

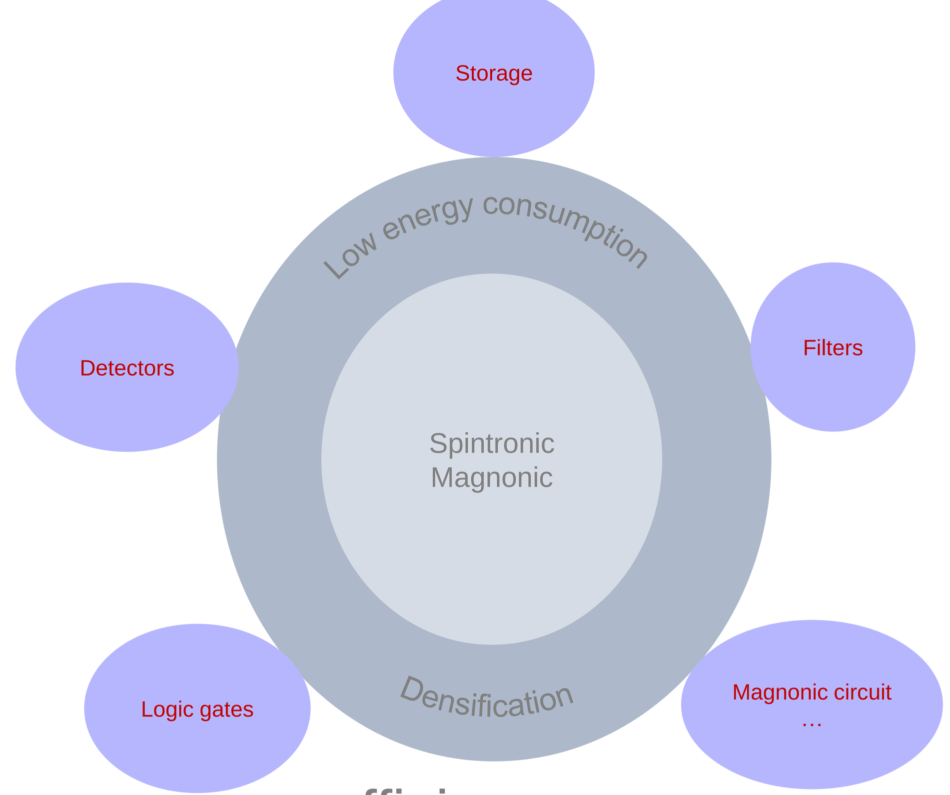
2018-2021: Bachelor's degree in Fundamental Physics

Master 1 Internship : Numerical modelling of micro-galvanic corrosion of magnesium alloys

Master 2 Internship : Study of magnetization dynamics and magnetoelastic coupling in magphonic crystals

SWING project

Spin **W**aves for advanced signal process**ING**



❖Increase energy efficiency

❖Control the properties of SW modes

❖Integration of existing magnonic components

❖(LSPM) generation / regeneration of SW via acoustics

Thesis Project

Magnon-phonon interaction in magnetic films

Generation / Regeneration of SW via acoustics

Magphonic = Magnonic + Phononic

❖Numerical derivation of dispersion law

❖Crystals design (period, materials,…)

❖ Layout of Antenna array

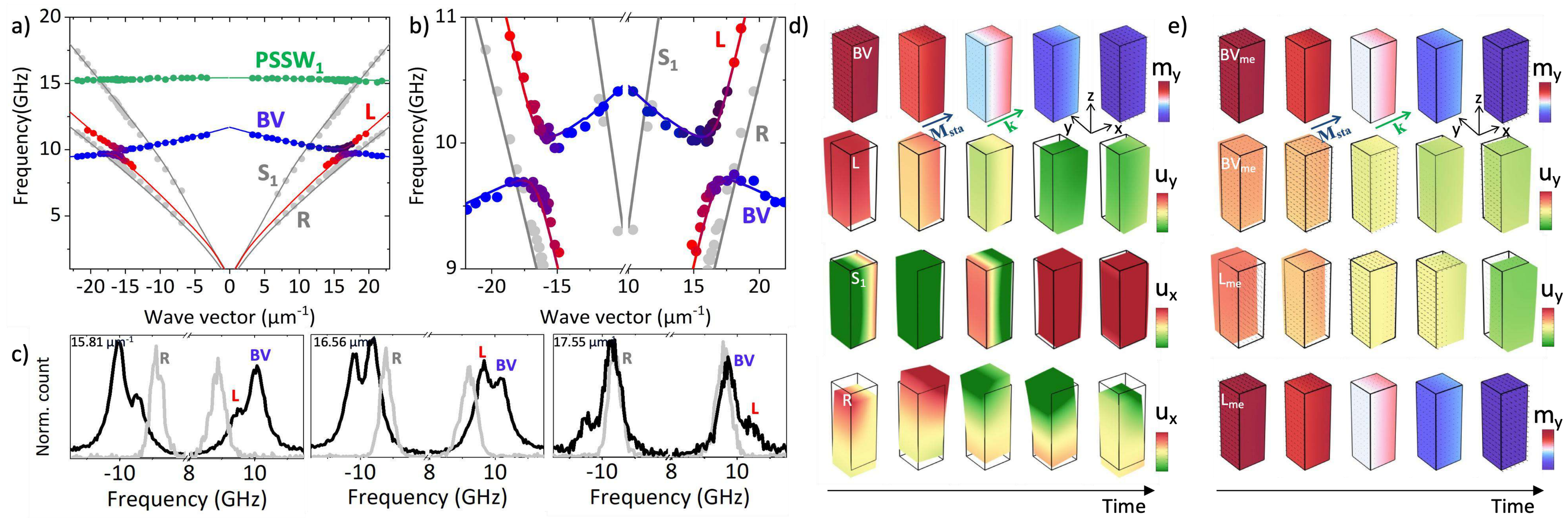
❖Analysis of experimentals results

❖Measure SW attenuation and regeneration : µBLS

❖Detection of SW : BLS

❖Parametric pumping : Antennas

❖Samples fabrication : Clean room USPN



- Magnon–phonon hybridization in nanometric CoFeB films was investigated in the backward-volume geometry using thermally activated Brillouin light scattering (BLS).
- The coupled dispersion was accurately reproduced by micromagnetic-elastodynamic simulations, revealing coherent energy transfer between elastic and magnetic excitations.
- During hybridization, the phonon mode (L) acquires a finite dynamical magnetization component while the spin-wave mode (BV) acquires a finite elastic displacement component.

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