UNIVERSITAT DE BARCELONA

Computing with Spin-Wave Solitons

(Collective Excitations in STO)

Ferran Macià

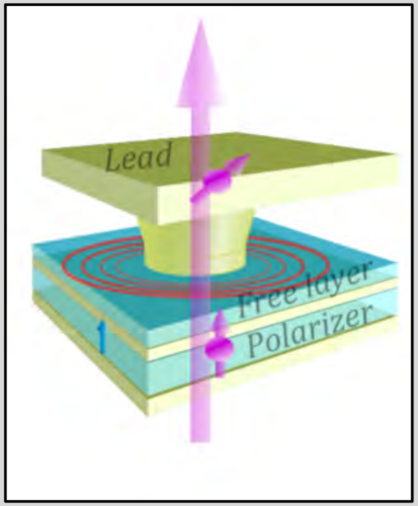
Universitat de Barcelona & ICMAB

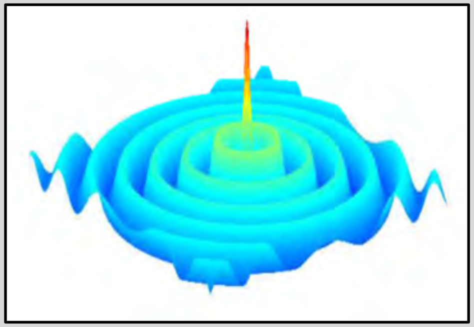
October 2018

ICMAB

INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Outline:
Collective Excitations of Magnetization in STO



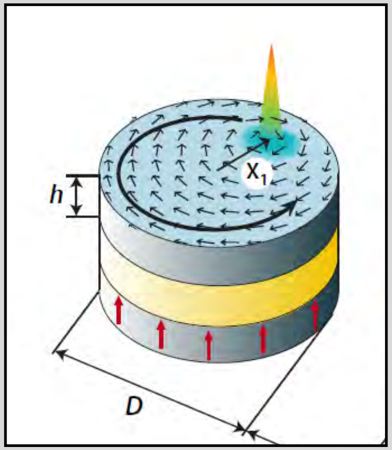


Spin-Waves

Tsoi et al '98
Demidov et al '10
Madami et al '11

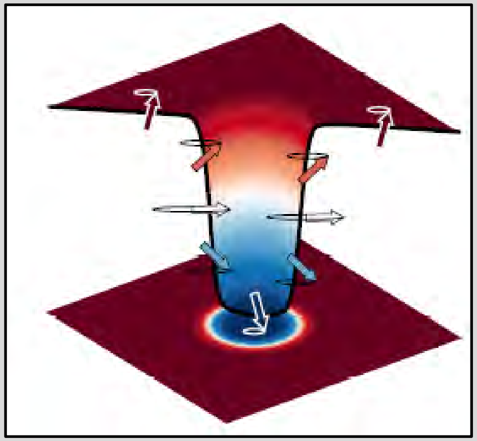
Vortices

Pufall et al '07
Belanovsky et al '12



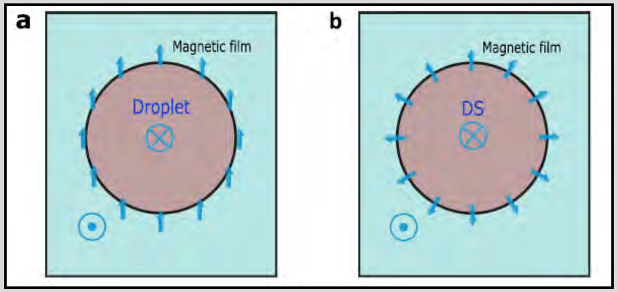
Droplets Solitons

Mohseni et al '13

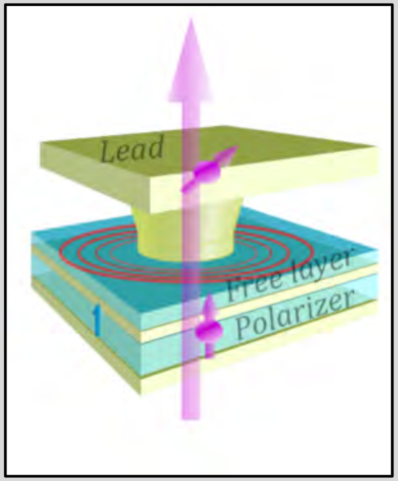


Dynamical Skyrmions

Zhou '15



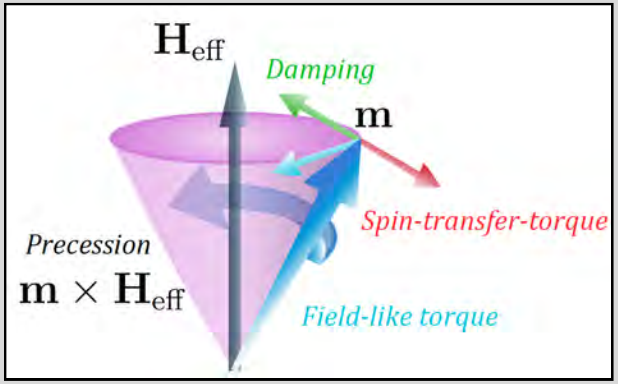
Spin-Torque Oscillators: Macroscopic Modelling



Spin dynamics (LLG+S)

$$\frac{\partial \mathbf{M}}{\partial \tau} = -|\gamma|\mu_0 \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} - \alpha \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\mathrm{eff}}) + \beta(\mathbf{x}) \mathbf{M} \times (\mathbf{M} \times \mathbf{m}_{\mathrm{f}}),$$

STOs are Gigahertz oscillators.



$$\mathbf{H}_{\mathrm{eff}}(\mathbf{H}_0, \mathbf{H}_{\mathrm{D}}, \nabla^2 \mathbf{M})$$

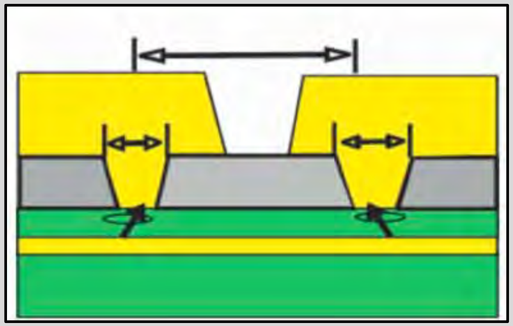
$\longrightarrow$ Applied field
$\longrightarrow$ Demagnetizing field (**M**)
$\longrightarrow$ Exchange field (**M**)

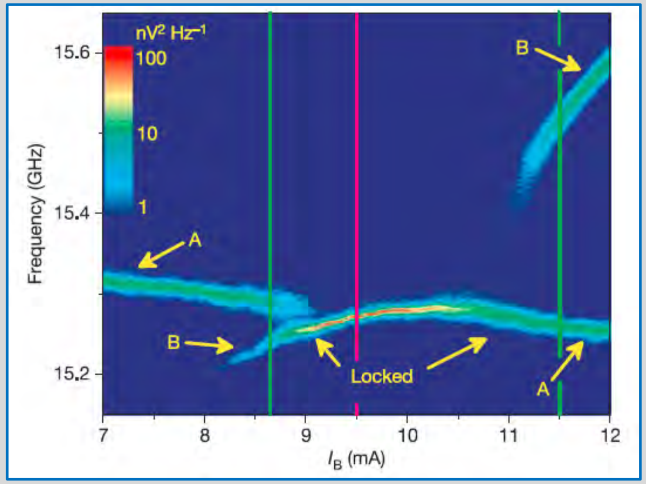
UNIVERSITAT DE BARCELONA

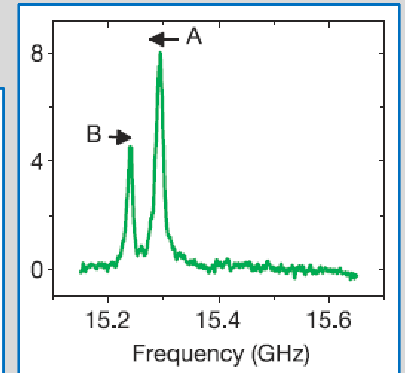
Spin-Torque Oscillators: Key experiments

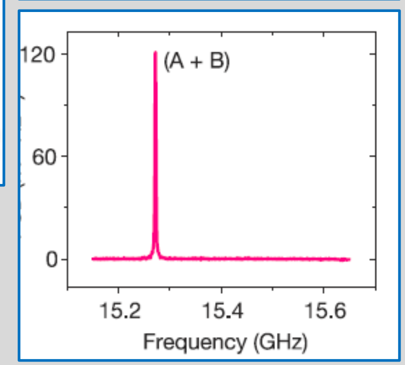
- Spin-wave Synchronization

Kaka et al Nature 437, 389-392 (2005)
Mancoff et al. Nature (2005)



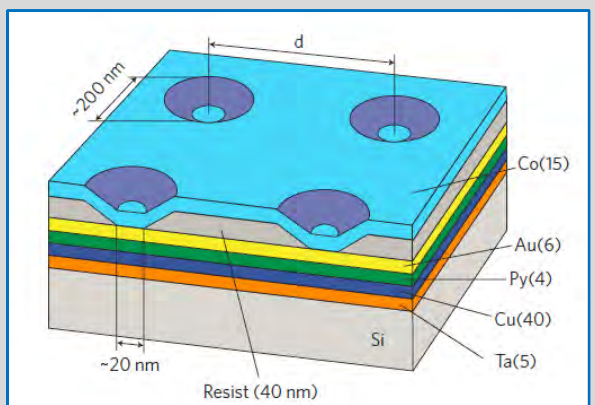






- Vortex Synchronization

Ruotolo et al. Nature Nanotech. ***4****, 528 (2009)*



ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Bio-inspired computing: Towards a new paradigm of non-digital applications

Brain

Neurons
Micrometer scale
Kilohertz

The brain is slower and has fewer units than a computer

HOWEVER, a computer can't do most of the our day-by-day activities

What makes the brain powerful?

DELAYS

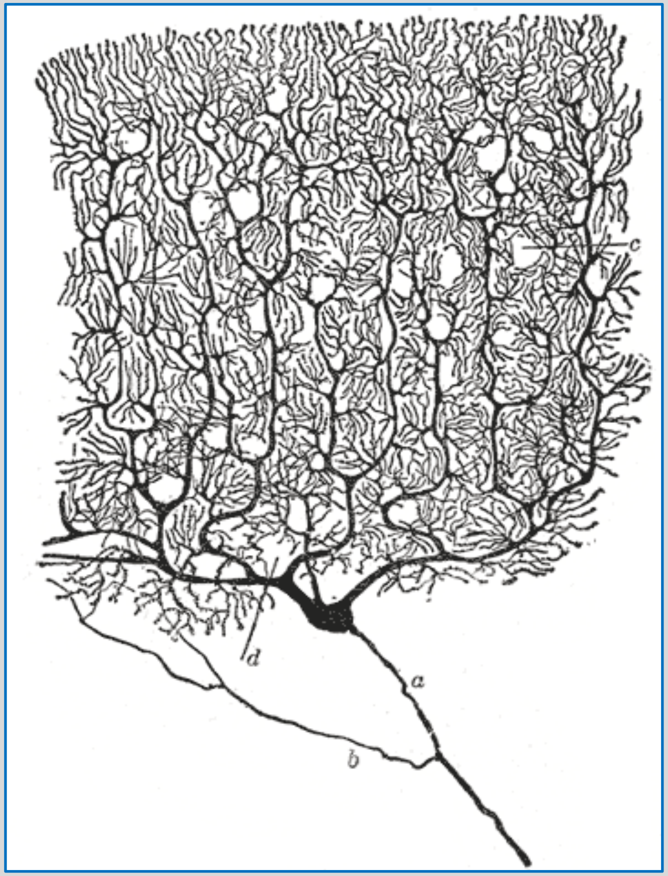
CONNECTIONS

SYNCHRONIZATION

Transistors fire together:
Common clock

Bio-inspired computing: Towards a new paradigm of non-digital applications

A famous bio-inspired computing scheme are the artificial neural networks



The key ingredients brain inspired computing

- Neurons (as signal emitters)
- Neurons (as signal detectors)
- Synapses (as functional connections)

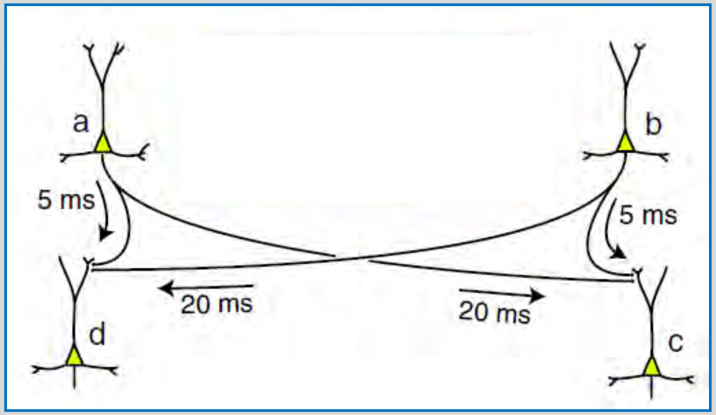
STO may provide

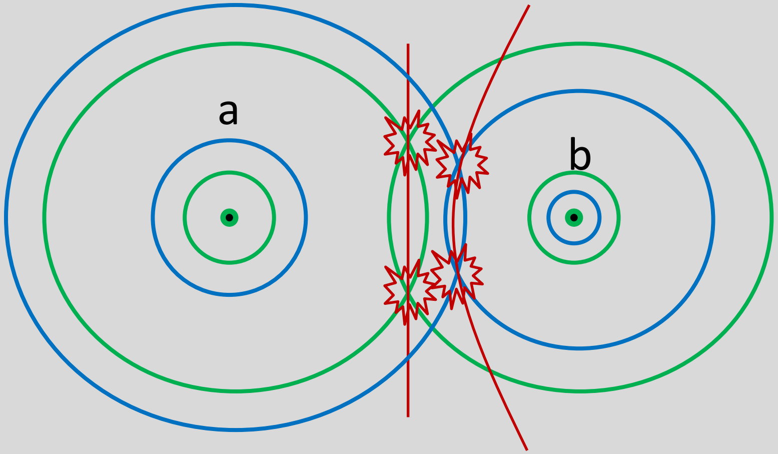
- Microwave oscillators (1-100 GHz)
- Spin-wave emmiters
- Microwave and spin-wave detectors
- Memristors (memory resistor)

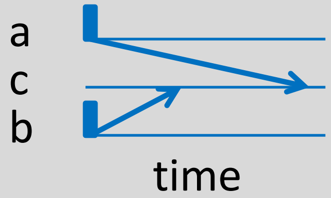
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

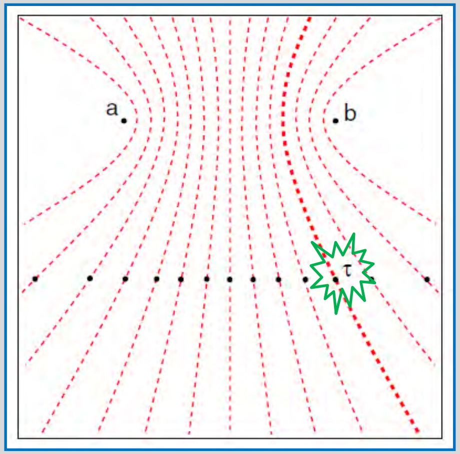
UNIVERSITAT DE BARCELONA

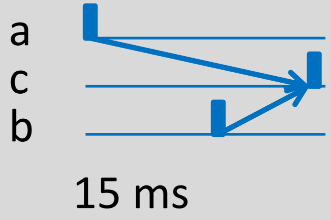
Spin-wave patterns and computation











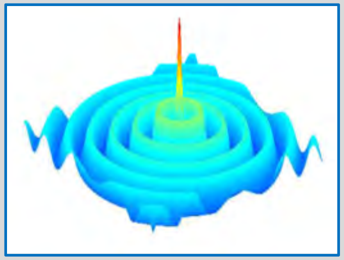
Proposal for spin wave computing

Macià et al., Nanotechnology 22, 95301 (2011)
Macià et al., Nanotechnology 25, 045303 (2014)
Patent: US9739851B2: Aggregated spin-torque nano-oscillators (2017)

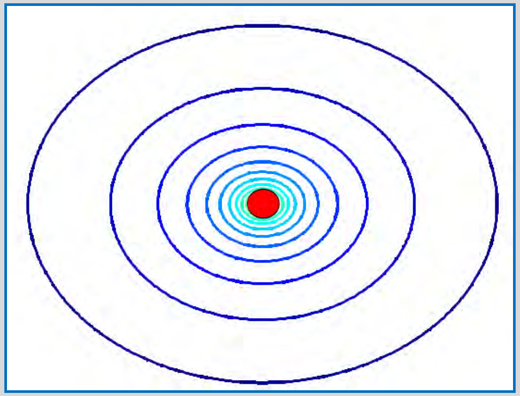
Computations using a polychronous wave propagation system
Patent number: 9582695 (2017)

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

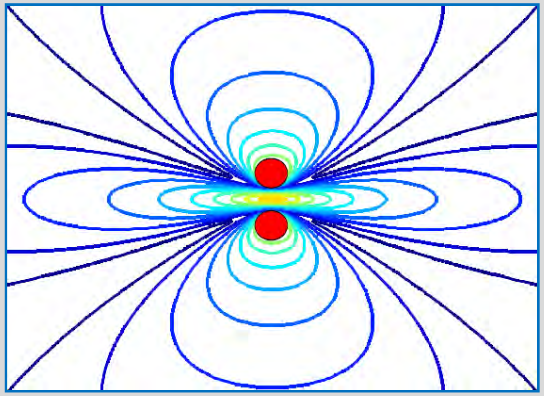
Spin-wave patterns and computation



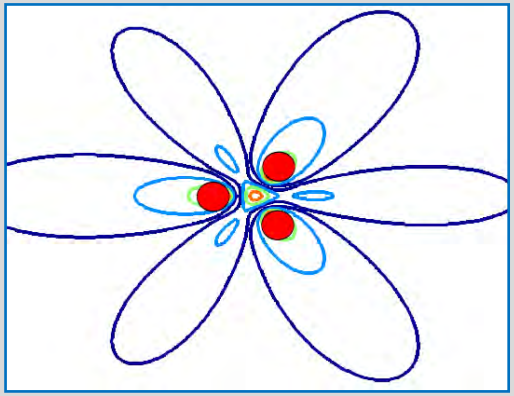
Single STO



Double STO



Triple STO



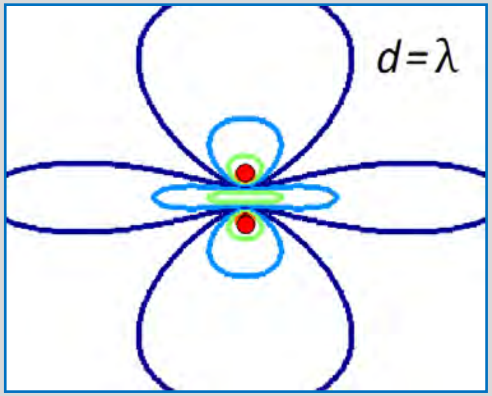
Simulation results for point contacts of 40 nm in diameter, and separation between contacts of 100 nm ~ λ.

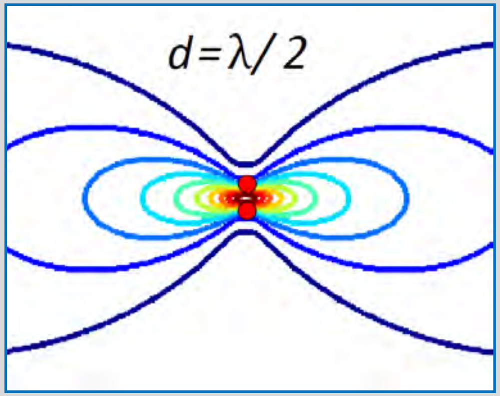
Spin waves interfere and enhance activity in certain locations

Macià et al., Nanotechnology 22, 95301 (2011)
Macià et al., Nanotechnology 25, 045303 (2014)
Patent: US9739851B2: Aggregated spin-torque nano-oscillators (2017)

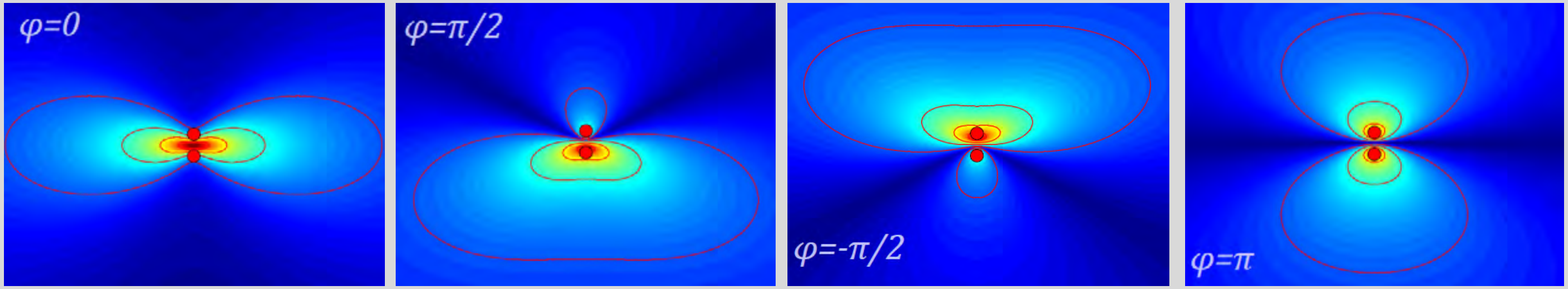
Spin-wave patterns and computation

What do radiation patterns depend on?





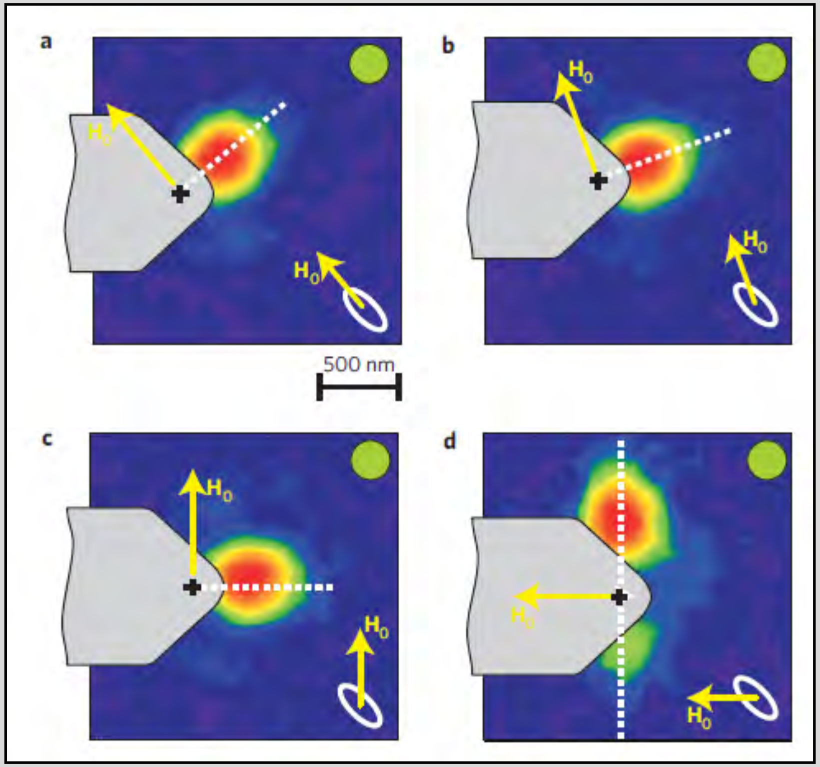
Can we actively control the radiation direction of an array of STOs?



Macià et al., Nanotechnology 22, 95301 (2011)
Macià et al., Nanotechnology 25, 045303 (2014)
Patent: US9739851B2: Aggregated spin-torque nano-oscillators (2017)

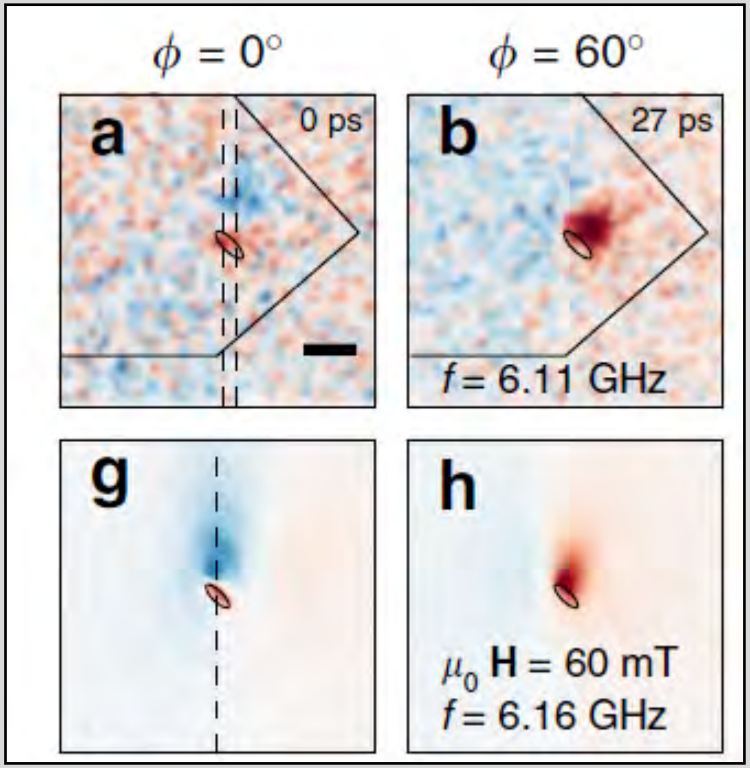
Imaging Spin Waves from ST0

Micro Brillouin Light Scattering



Demidov et al. Nat. Matet. ***9****, 984 (2010)*

Scanning X-ray Microscopy

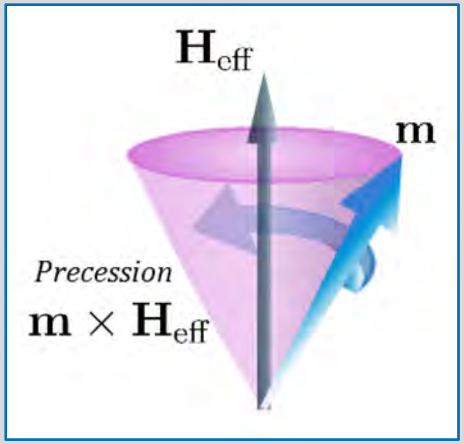


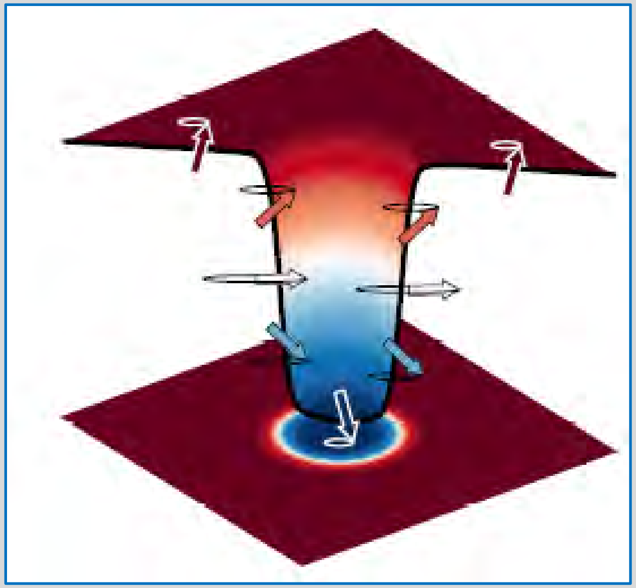
Bonetti et al. Nat. Commun. ***6****, 8889 (2015)*

Magnetic Droplet Solitons

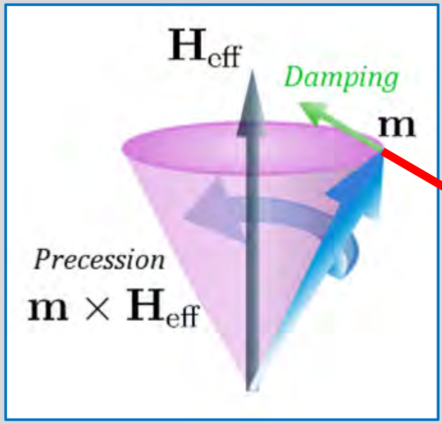
- Excitation states of a ferromagnet without dissipation [Ivanov et al. 1976; 1977].
- LLG equation in a uniaxial magnet takes a set of solutions consisting of reversed dynamically precessing spins known as magnon drops

$$\frac{\partial \mathrm{M}}{\partial \tau} = -|\gamma|\mu_0 \mathrm{M} \times \mathrm{H}_{\mathrm{eff}} - \alpha \mathrm{M} \times (\mathrm{M} \times \mathrm{H}_{\mathrm{eff}})$$





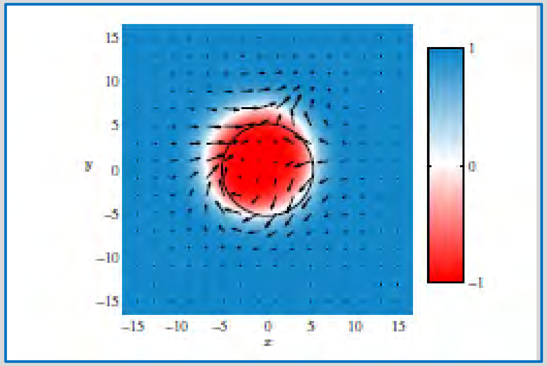
Dissipative Magnetic Droplet Solitons



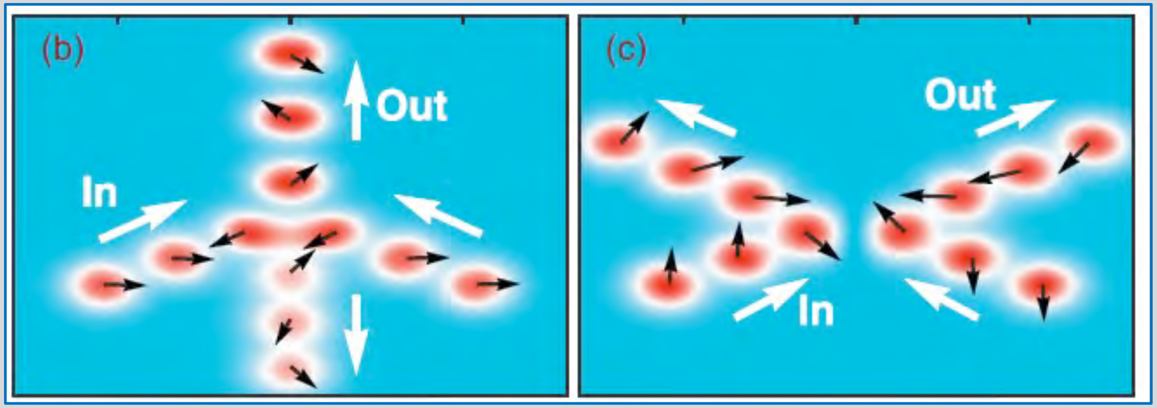
Spin dynamics (LLG)

$$\frac{\partial \mathrm{M}}{\partial \tau} = -|\gamma|\mu_0 \mathrm{M} \times \mathrm{H}_{\text{eff}} - \alpha \mathrm{M} \times (\mathrm{M} \times \mathrm{H}_{\text{eff}}) + \beta(\mathbf{x}) \mathrm{M} \times (\mathrm{M} \times \mathrm{m}_{\mathrm{f}}),$$

In *ferromagnetic* thin films, the *spin-transfer-torque* effect can compensated the damping



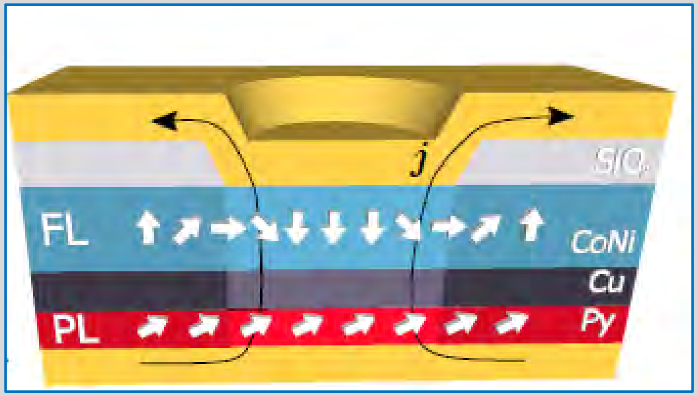
Hoefer et al. Phys. Rev. B ***82****, 054432 (2010)*

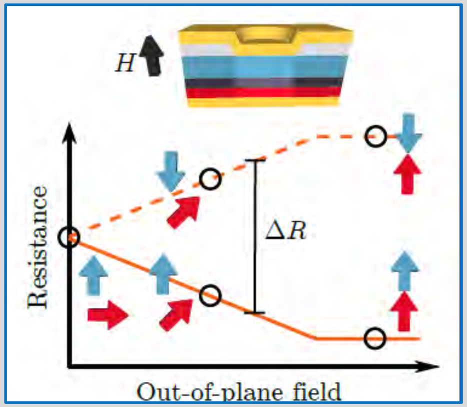


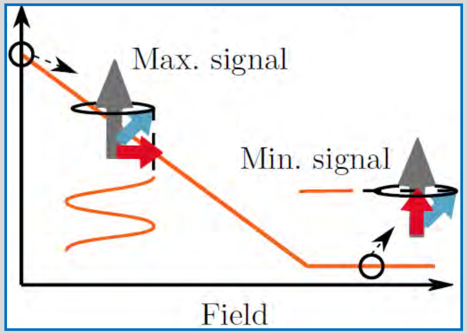
Hoefer et al. Phys. Rev. B 89 (18), 180409 (2014)

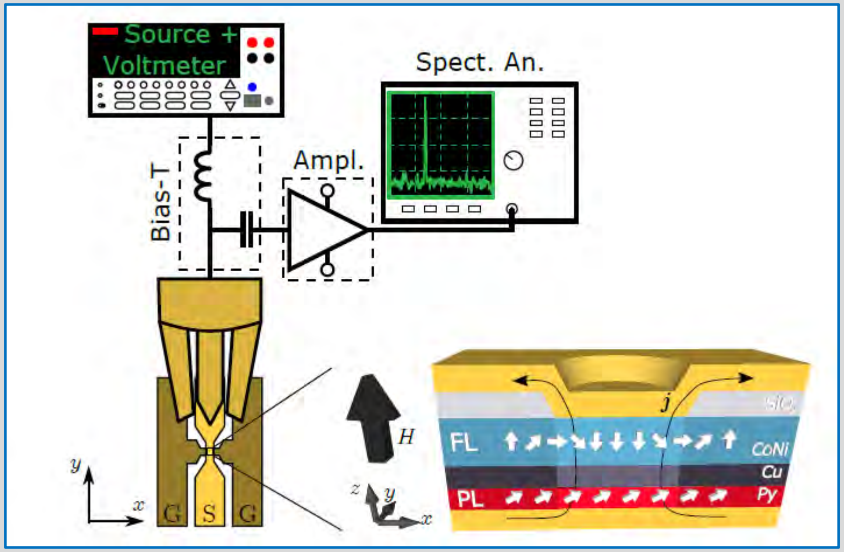
Experimental detection of Magnetic Droplet Solitons

- Out-of-plane free layer CoNi
- In-plane fixed polarizing layer Py
- Contact diameter 80-150 nm





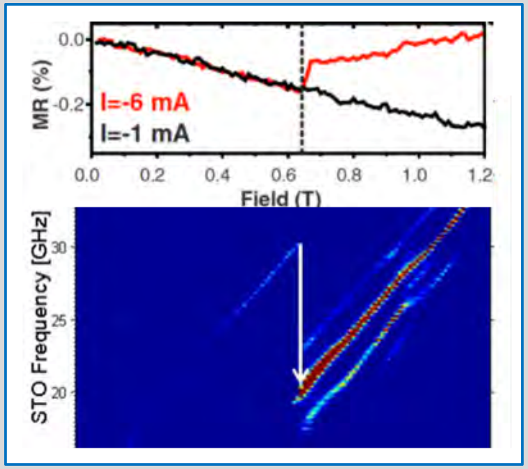




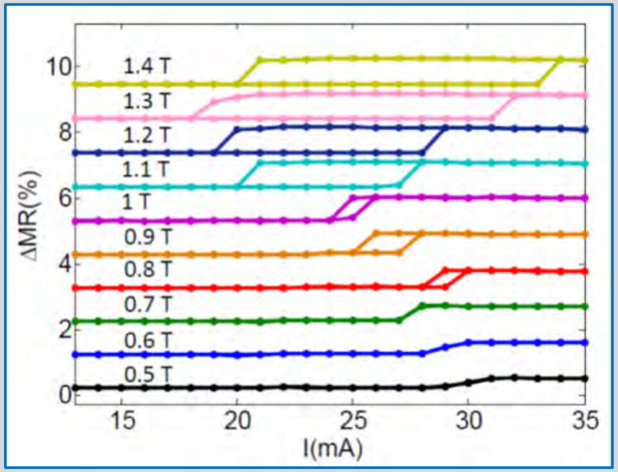
Experimental detection of Magnetic Droplet Solitons

Experimental signatures of droplet nucleation

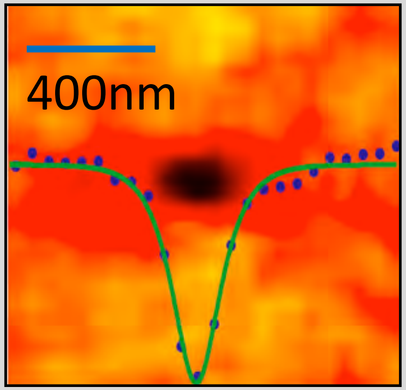
Experimental signatures of droplet Stability



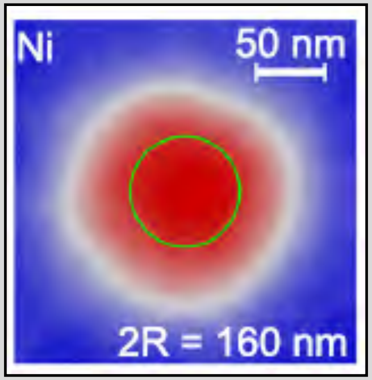
*Mohseni et al. Science **339**, 1295 (2013)*



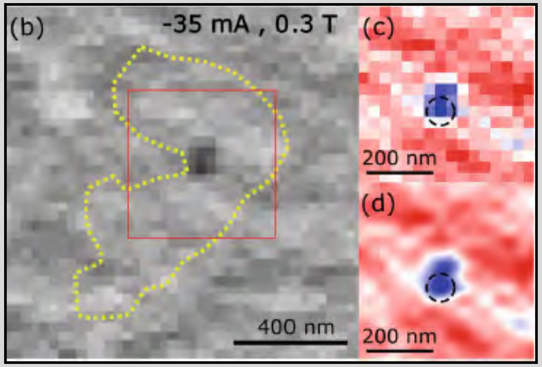
*Macià et al. Nat. Nanotech., **9**, 992, (2014)*



*Backes et al. PRL **115**, 127205, (2015)*



*Chung et al. PRL,**120**,217204 (2018)*

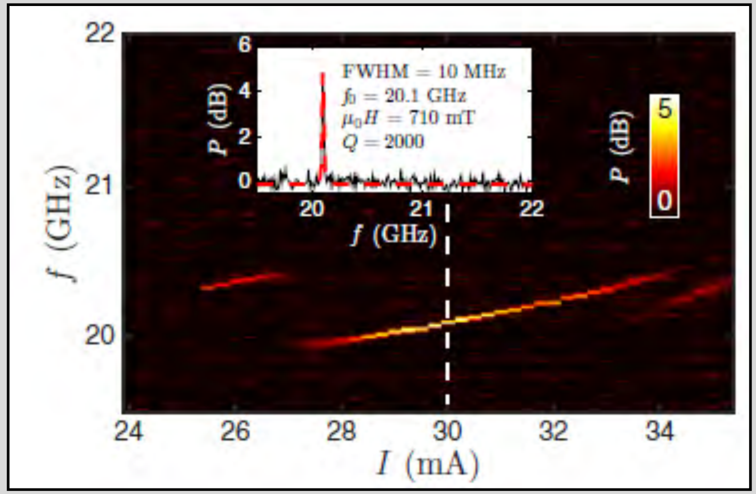


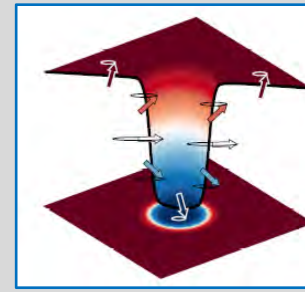
Burgos-Parra et al Sci. Rep. 8, 11533, (2018)

Multistate Oscillators

Non linear Oscillators

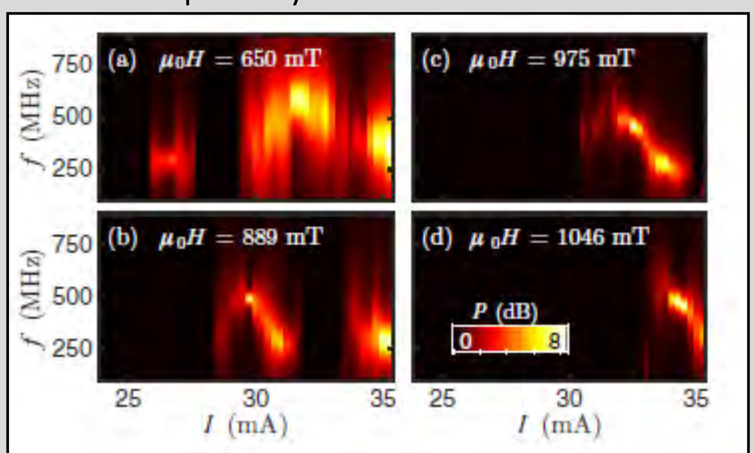
High-frequency oscillations

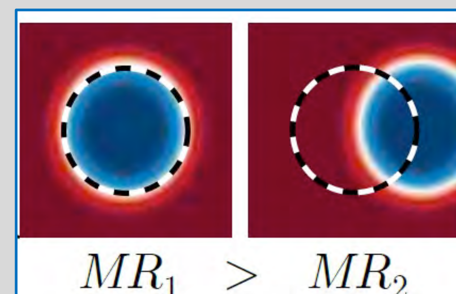




Multistate Oscillators

Low-frequency oscillations





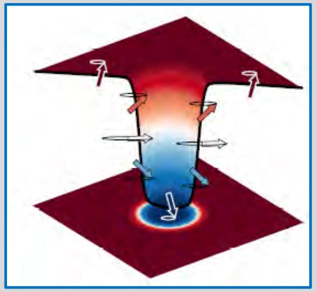
S. Lendínez et al. Phys. Rev. B. 92, 174426 (2015)

UNIVERSITAT DE BARCELONA

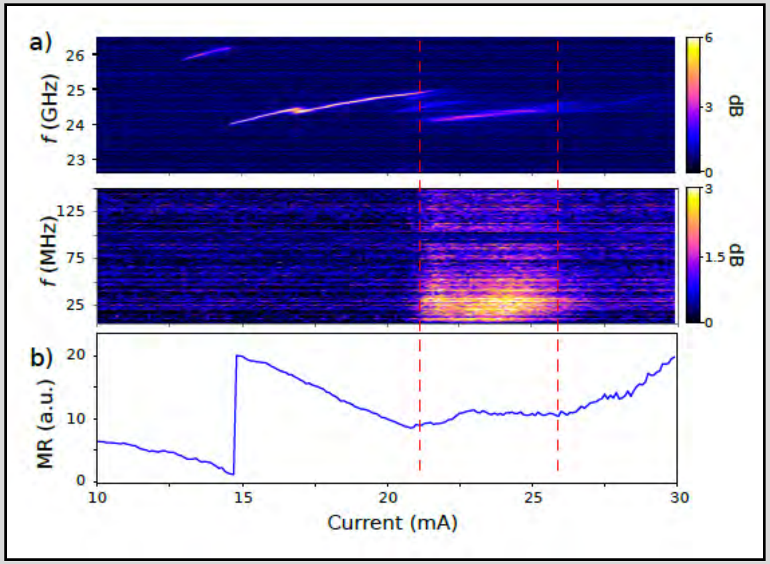
ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Multistate Oscillators

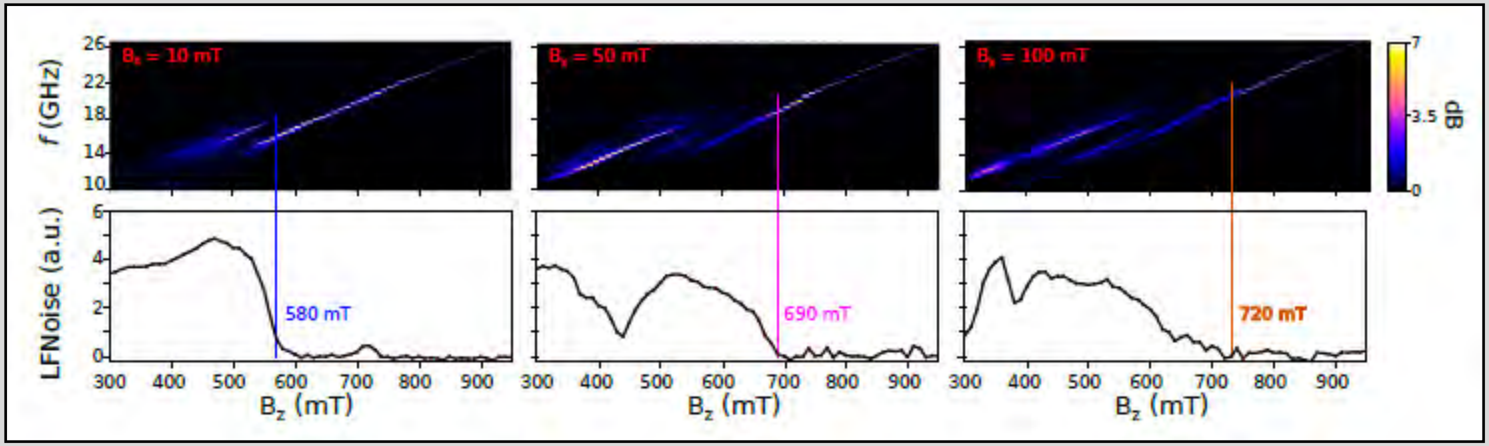
Coexistence of oscillating states



Current dependence



Field dependence



Dynamical Skyrmions

ARTICLE

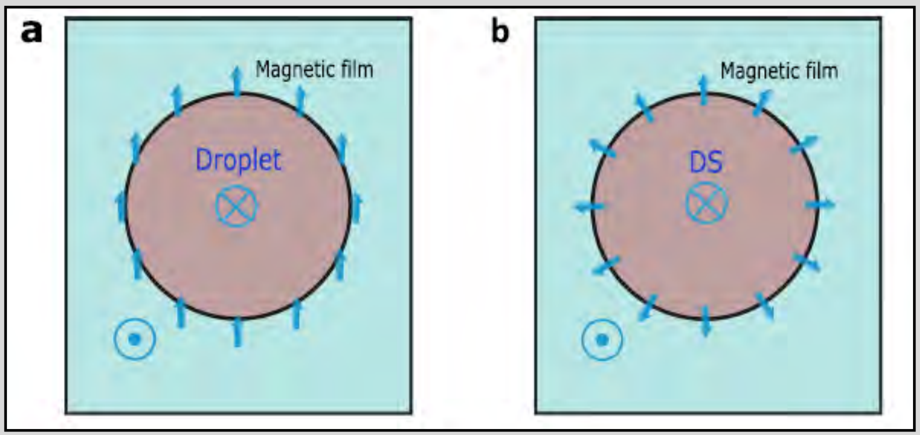
Received 10 Mar 2015 | Accepted 24 Jul 2015 | Published 9 Sep 2015 DOI: 10.1038/ncomms9193 OPEN

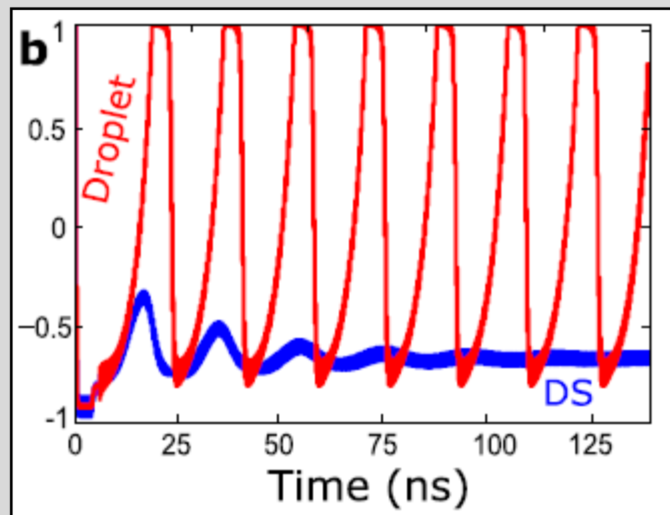
Dynamically stabilized magnetic skyrmions

Y. Zhou[1,2], E. Iacocca[3], A.A. Awad[3], R.K. Dumas[3], F.C. Zhang[2,4,5], H.B. Braun[6,7] & J. Åkerman[3,8]

Magnetic skyrmions are topologically non-trivial spin textures.

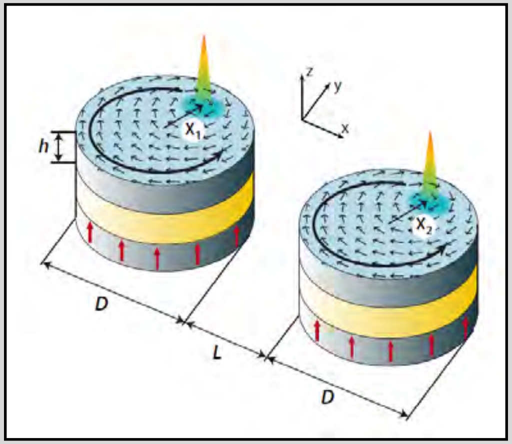
Nanotechnology ***29,*** *325302, (2018)*





Conditions to create DS with no DMI

Spin-Torque Oscillators: Vortex oscillators



- Memory devices
- Radiofrequency oscillators (gyrotropic motion)
- High-frequency detectors

The collective dynamics of arrays of STO with dipolar coupling can be described through the Kuramoto model

SCIENTIFIC REPORTS

OPEN

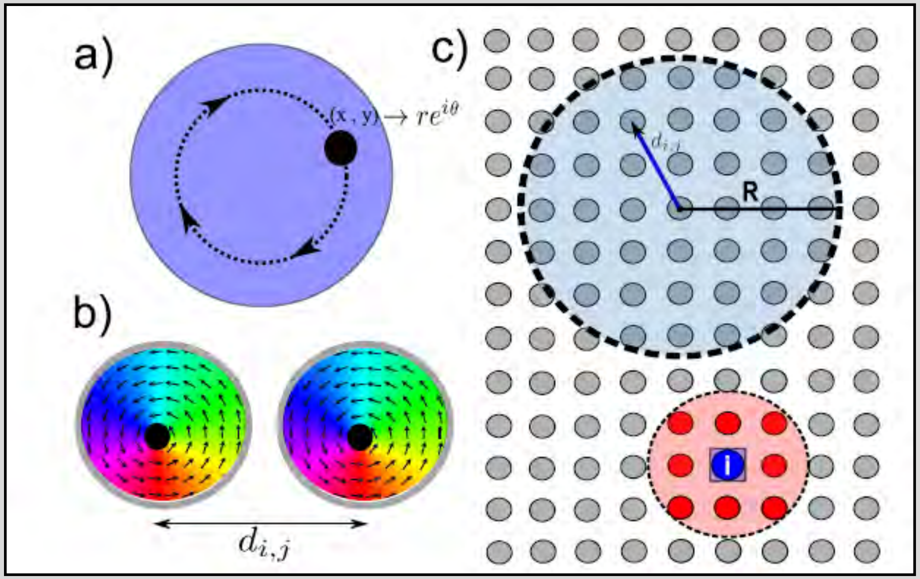
Describing synchronization and topological excitations in arrays of magnetic spin torque oscillators through the Kuramoto model

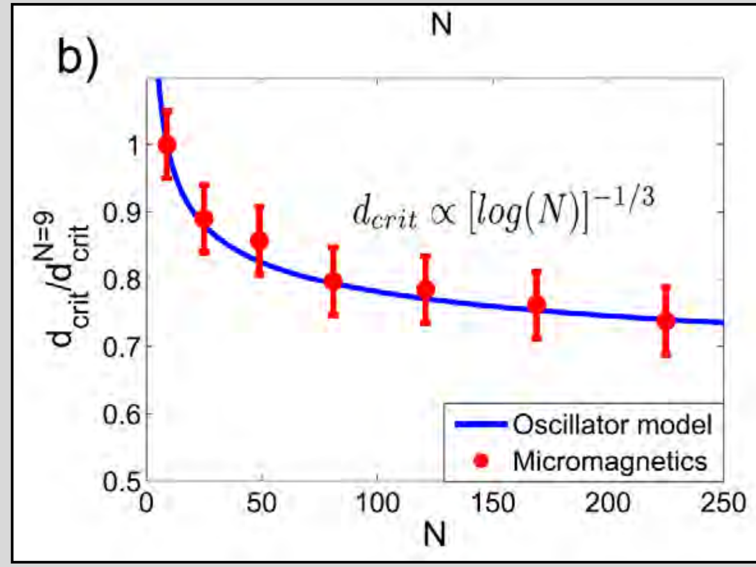
Received: 26 April 2016
Accepted: 10 August 2016
Published: 01 September 2016

Vegard Flovik[1], Ferran Macià[2] & Erik Wahlström[1]

UNIVERSITAT DE BARCELONA

Spin-Torque Oscillators: Vortex oscillators





From Thiele equation for a single vortex to the Kuramoto model

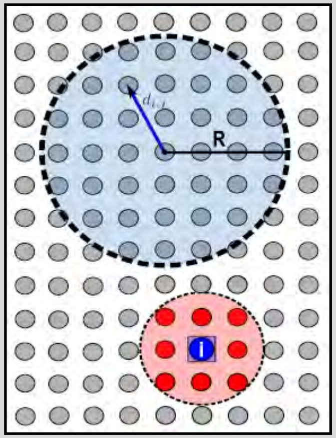
$$\frac{d\theta_i}{dt} = \omega_i + \sum_{j \neq i} \lambda_{ij} \sin(\theta_j - \theta_i).$$

Synchronization in arrays of magnetic vortex oscillators can be described by the Kuramoto model with local coupling

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

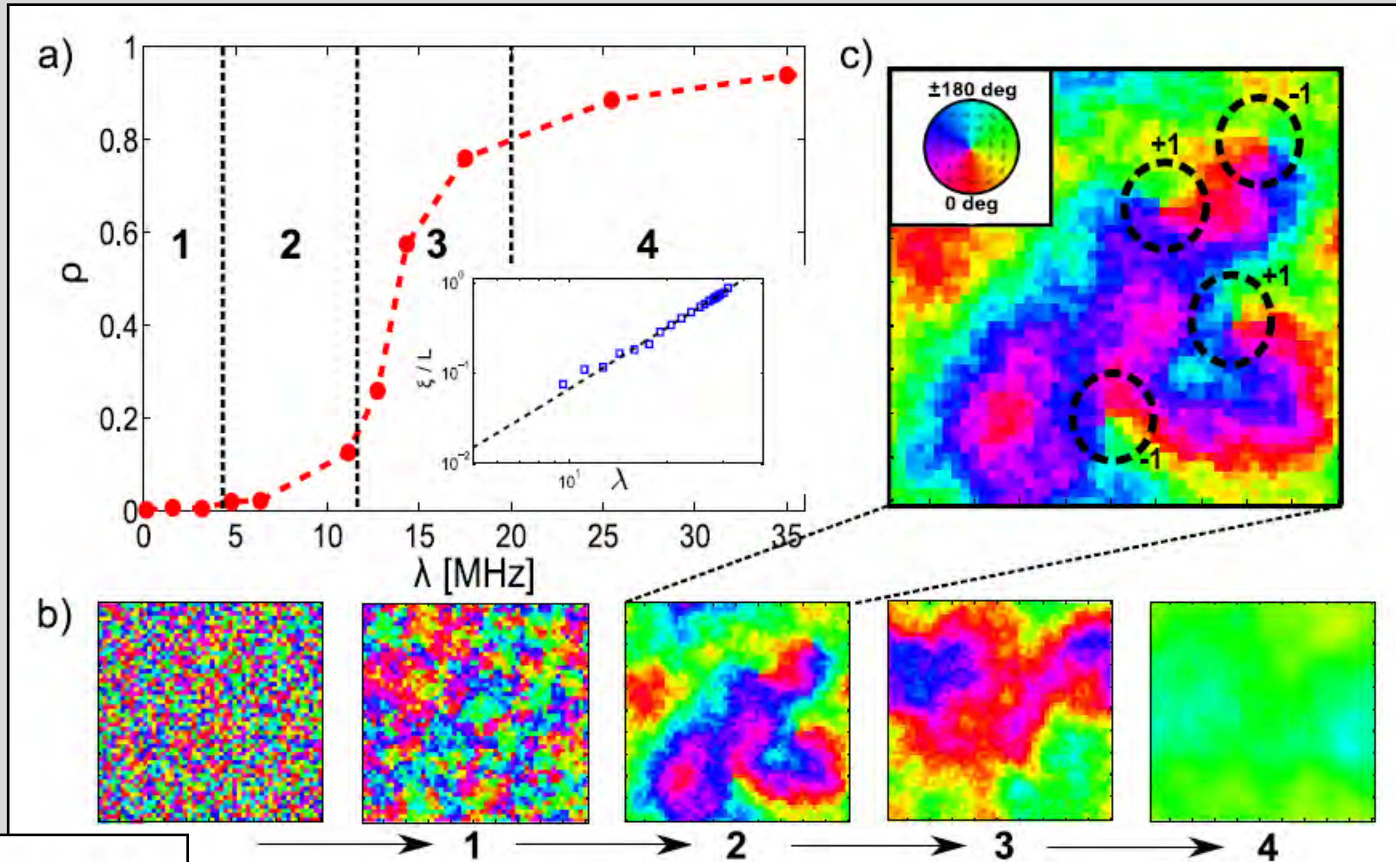
UNIVERSITAT DE BARCELONA

Spin-Torque Oscillators: Vortex oscillators



$$\rho = \frac{1}{N}\left|\sum_j e^{i\cdot\theta_j}\right|$$

$$\frac{d\theta_i}{dt} = \omega_i + \sum_{j\neq i}\lambda_{ij}\sin(\theta_j - \theta_i).$$



Scientific Reports ***6****, 32528 (2016)*

- Finite size effect
- Emerging of topological patterns similar to the vortices in the XY model for magnetism

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

UNIVERSITAT DE BARCELONA

Summary

- Control of spin waves emission for memory and computation
  - Computing with wave fronts

- Study of droplet solitons from STO
  - Stable excitations
  - Additional dynamics (drift resonances)
  - Coexistence of oscillation states

- Dynamical skyrmions

- Synchronization of arrays of vortex oscillators

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Acknowledgments

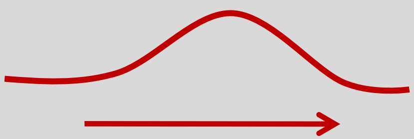
- Sergi Lendínez, Nahuel Statuto, and Joan Manel Hernàndez
- Dirk Backes, Andrew D. Kent and F. C. Hoppensteadt
- Stefano Bonetti, Roopali Kukreja and Hendrik Ohldag

Computing with waves

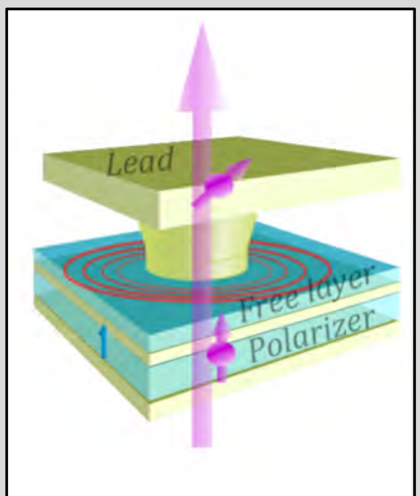
To use the spin-wave patterns for computation we need:

- Detecting spin-wave activity
- Responding by creating new activity

Small current



Incoming wave



GMR-TMR

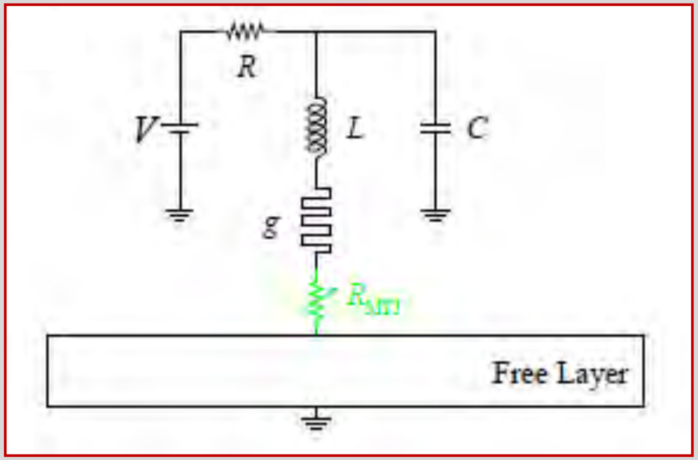
Variable resistance depending on magnetic alignment of the layers

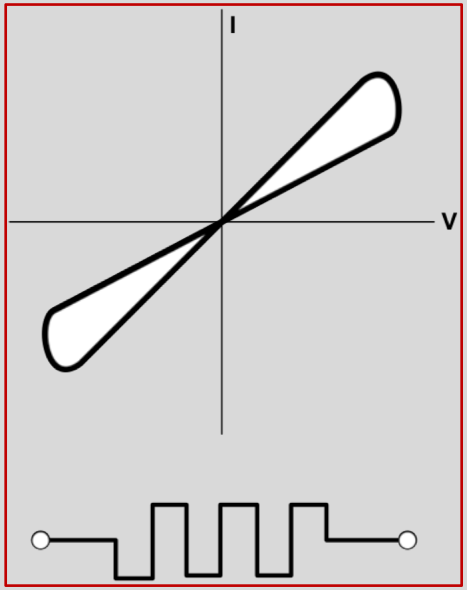
Computing with waves

To use the spin-wave patterns for computation we need:

- Detecting spin-wave activity
- Responding by creating new activity

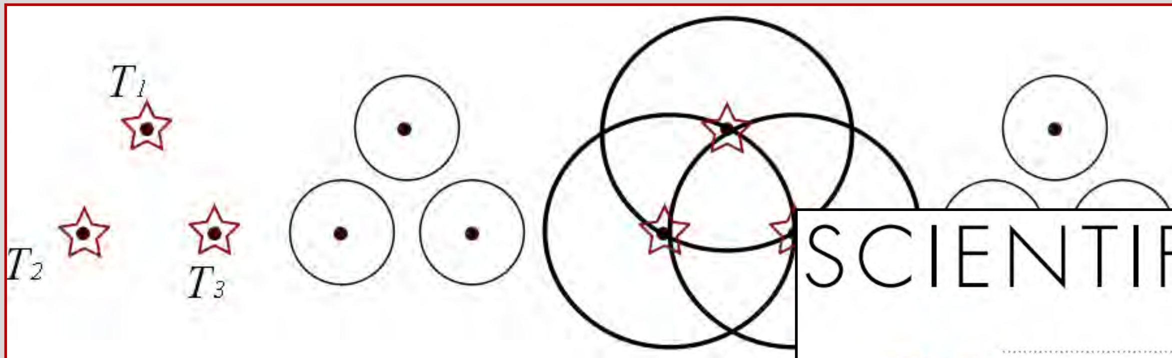
- An integrate-and-fire circuit, where a storage device accumulates charge that is discharged rapidly when a certain threshold level is achieved.

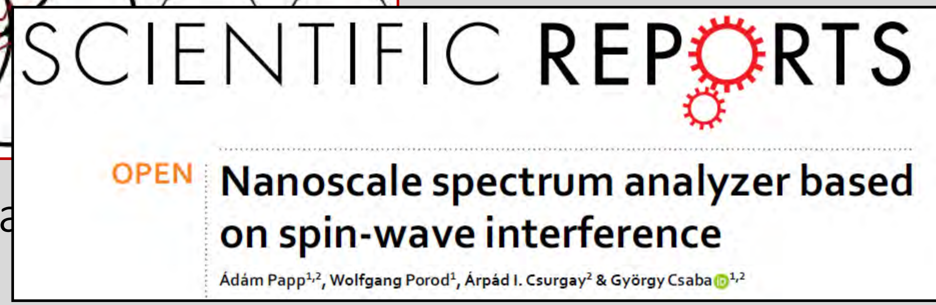




Computing with waves

1. Reverberating structures



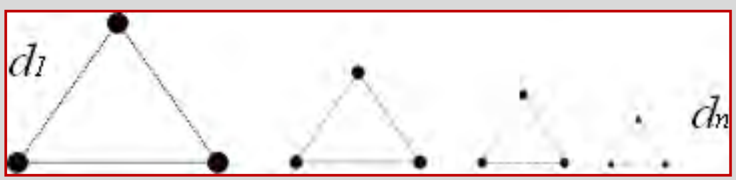

SCIENTIFIC REPORTS

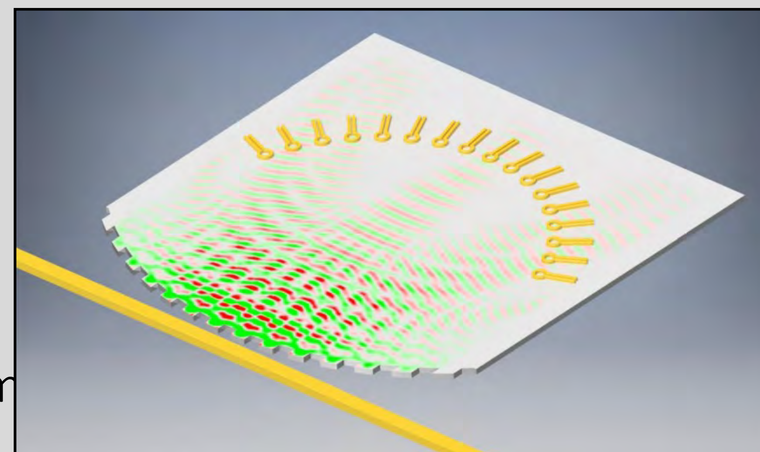
OPEN **Nanoscale spectrum analyzer based on spin-wave interference**

Ádám Papp[1,2], Wolfgang Porod[1], Árpád I. Csurgay[2] & György Csaba[1,2]

Several configurations can mainta
hence, serve as memory unit.

2. Look-up tables



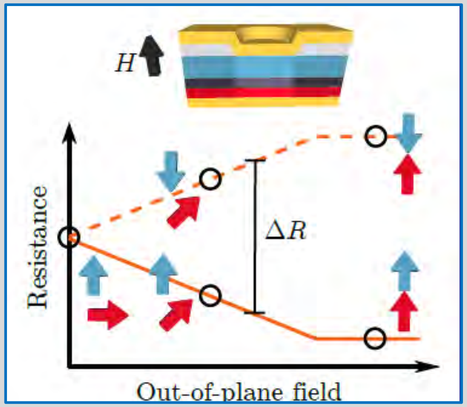


Programming transponder arrangem
frequencies: look-up tables.

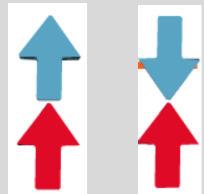
Patent: US9739851B2: Aggregated spin-torque nano-oscillators (2017)

UNIVERSITAT DE BARCELONA

Experimental detection of Droplet Solitons

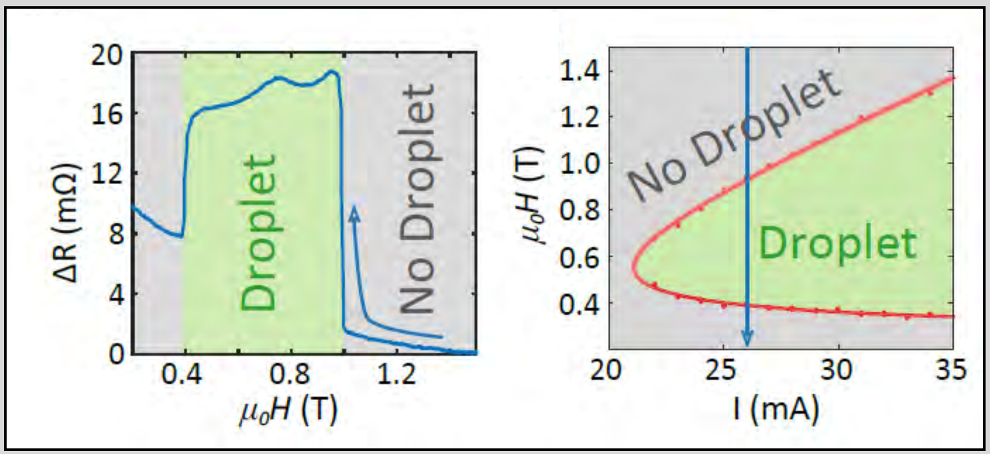


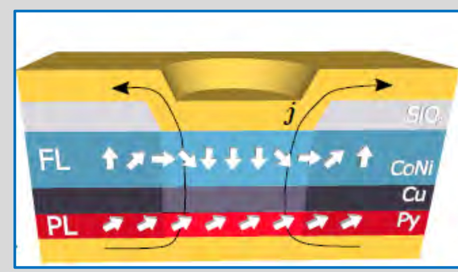
Max MR ~0.3%



*F. Macià et al. Nat.Nanotech., **9**, 992 (2014)*
S. Lendínez et al. Phys. Rev. B. 92, 174426 (2015)

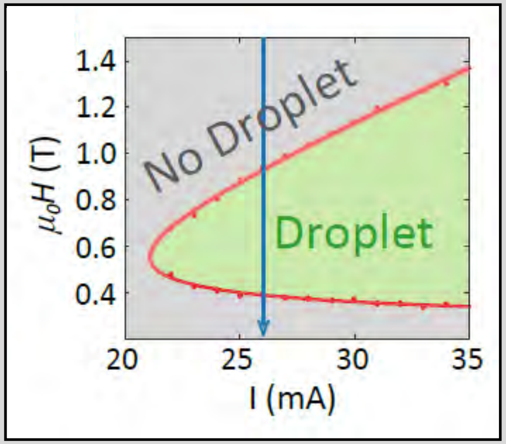
Stability maps





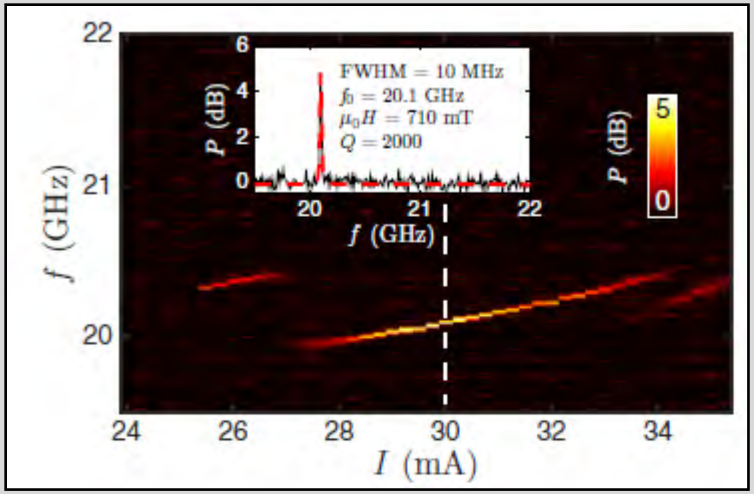
ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

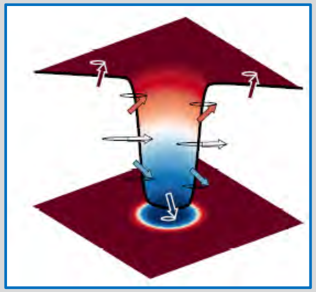
Experimental detection of drift resonances



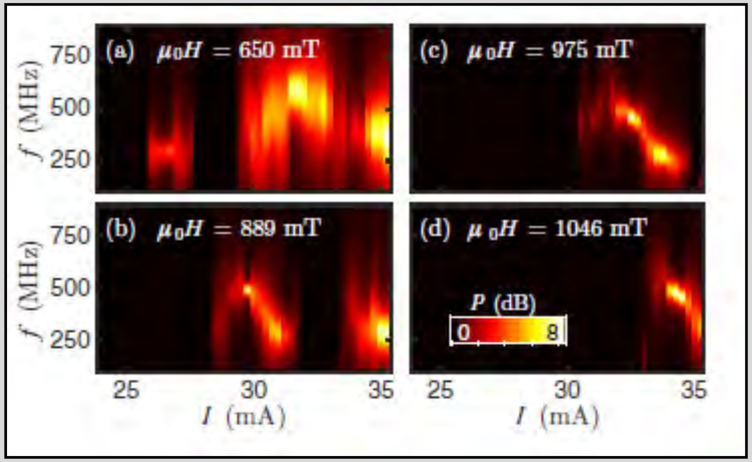
S. Lendínez et al. Phys. Rev. B. 92, 174426 (2015)

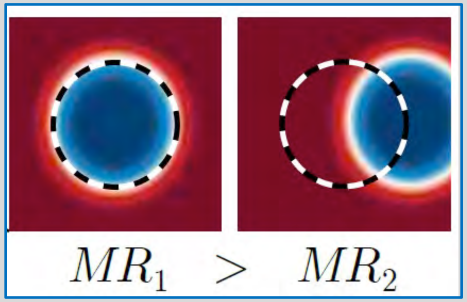
High-frequency oscillations





Low-frequency oscillations

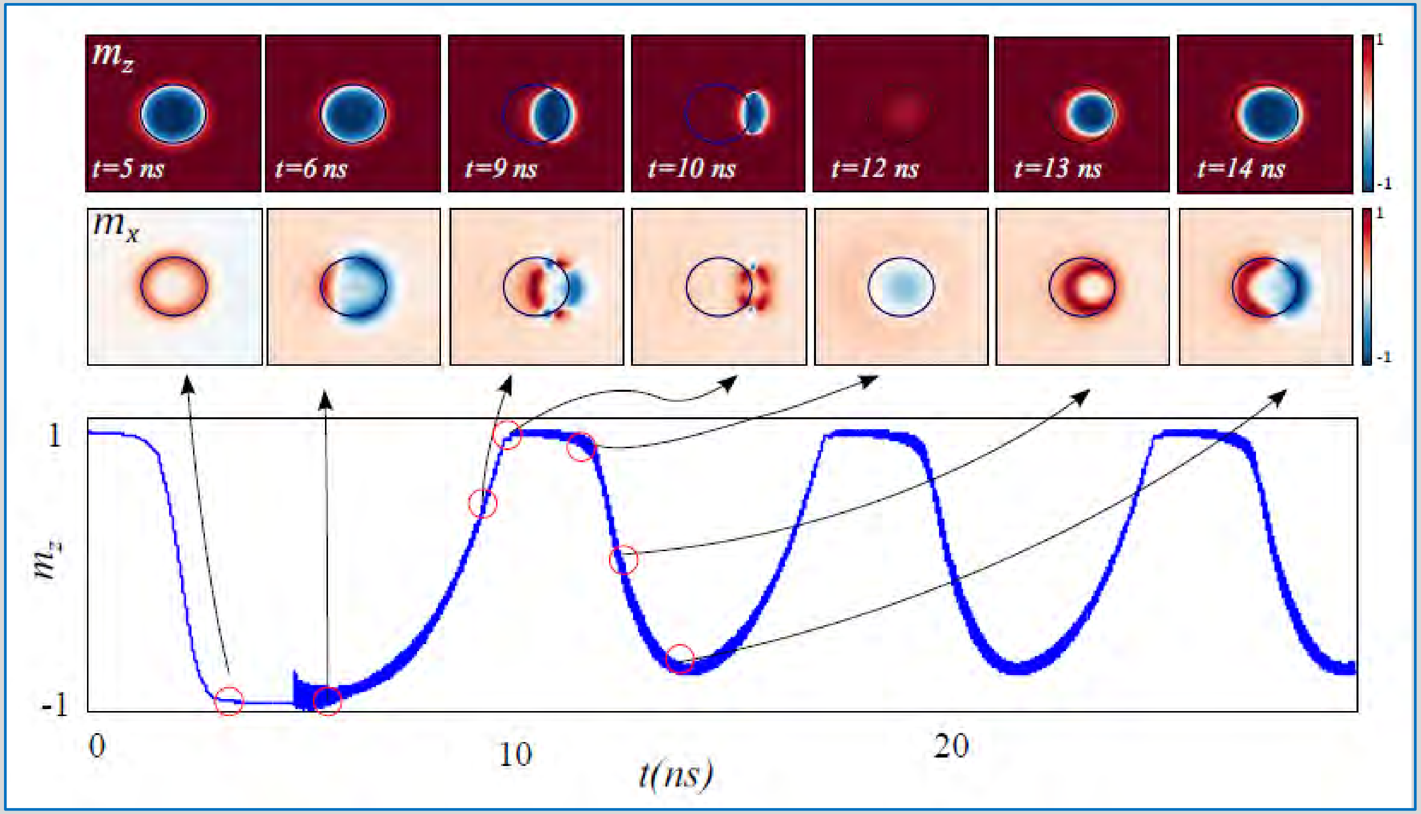




Drift resonances in droplet solitons

Simulated the LLG equation with the measured parameters (FMR) and with no fitting parameters: Dimensions, anisotropies, spin torque polarization.

Effect of a small (10%) in-plane field



Frequency of ~80 MHz

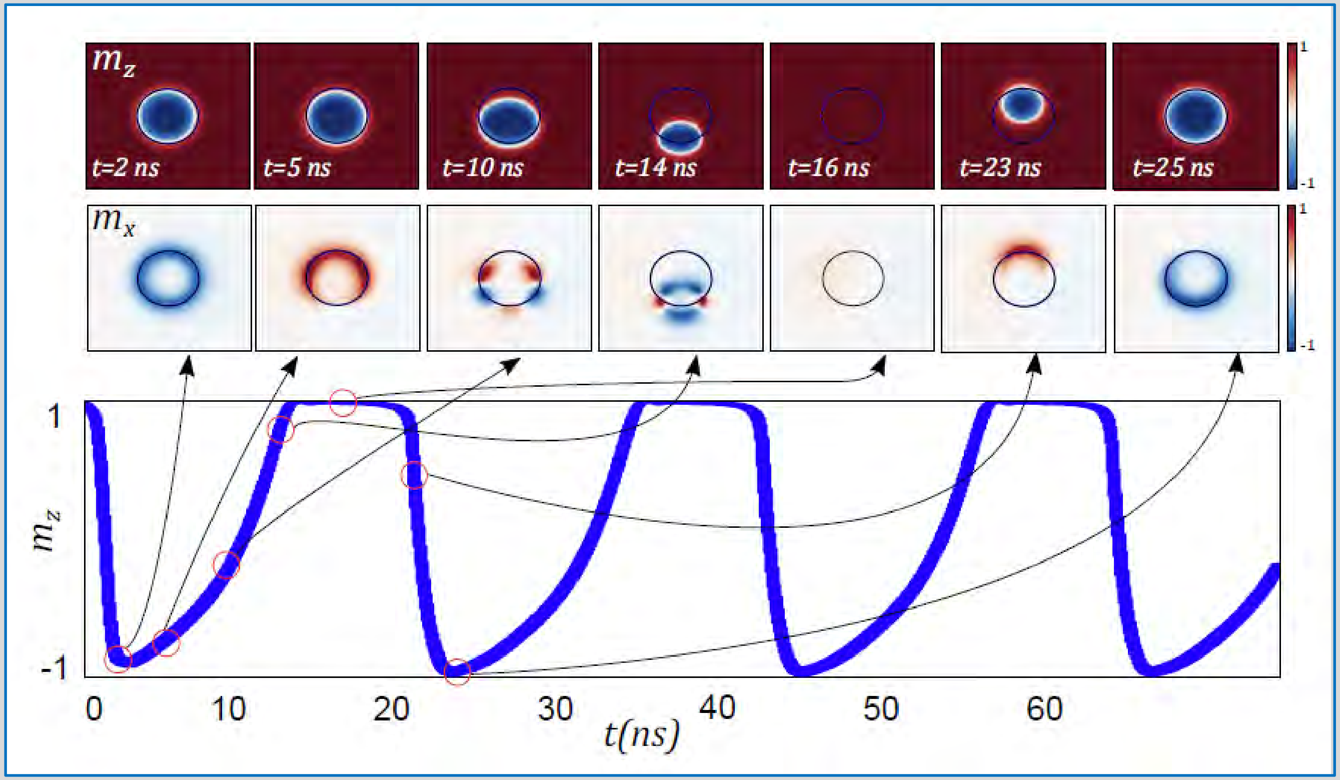
*S. Lendínez et al. Phys. Rev. B. **92**, 174426 (2015)*

Universitat de Barcelona

Drift resonances in droplet solitons

Simulated the LLG equation with the measure parameters (FMR) and with no fitting parameters

Variation of 1% in the anisotropy in the contact region



Frequency of ~50 MHz

S. Lendínez et al. Phys. Rev. B. ***92****, 174426 (2015)*

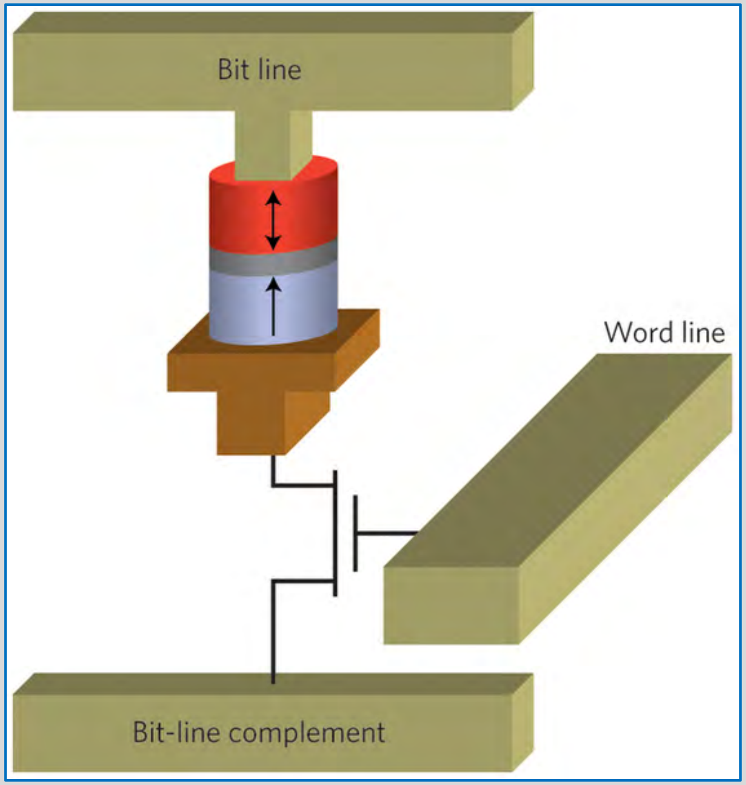
ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Temperature dependence of Droplet Solitons

The physics governing transitions between static magnetic states under the STT effect in bistable nanomagnets, such as those incorporated in magnetic tunnel junction (MTJ) pillars, are typically described through statistical mechanics

Thermal assisted switching

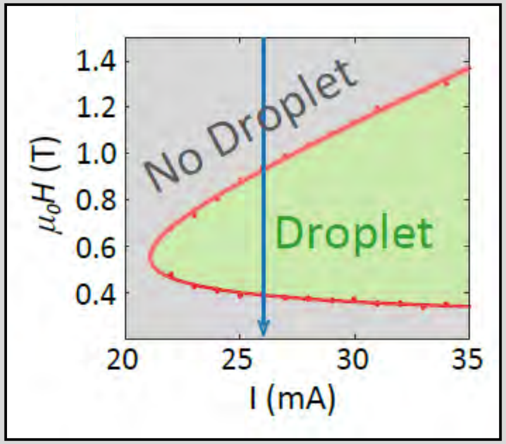
STT-MRAM bit cell



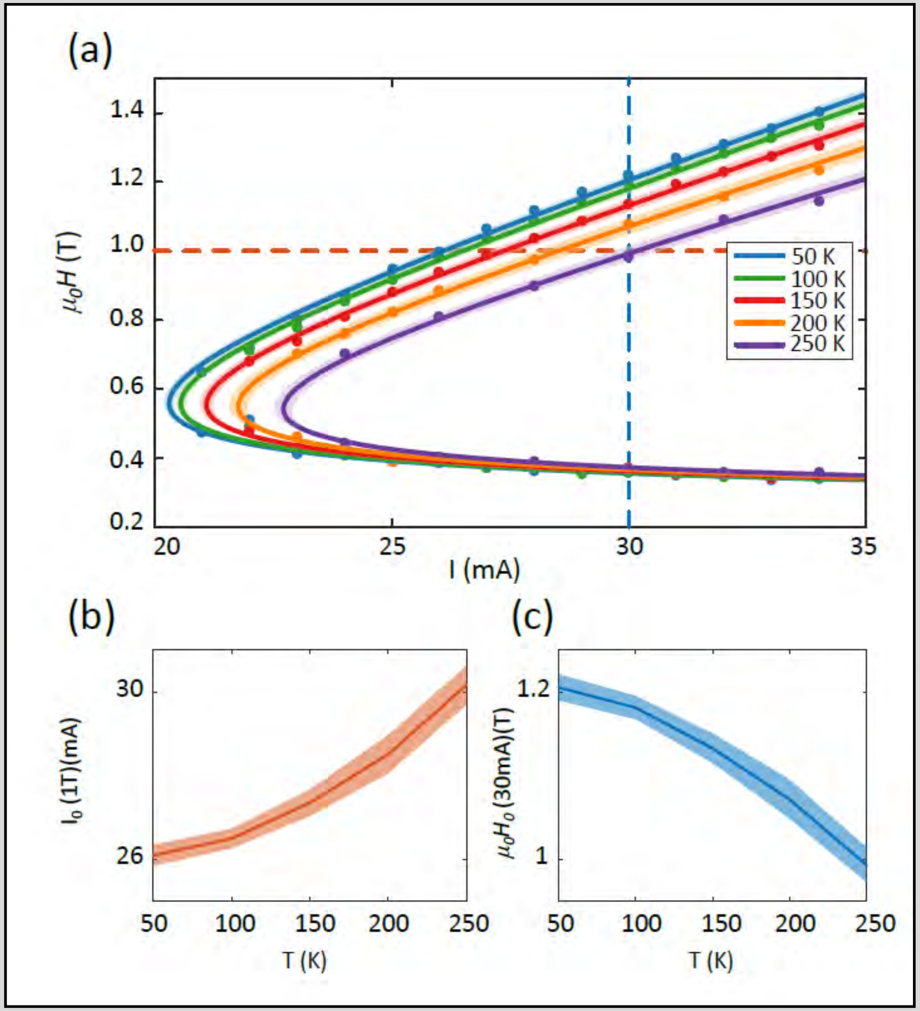
From Nat Nanotechnology 10, 187–191 (2015)

INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Temperature dependence of Droplet Solitons



Nucleation of droplet solitons requires higher current densities at higher temperatures, in contrast to typical spin-transfer torque induced switching between static magnetic states.

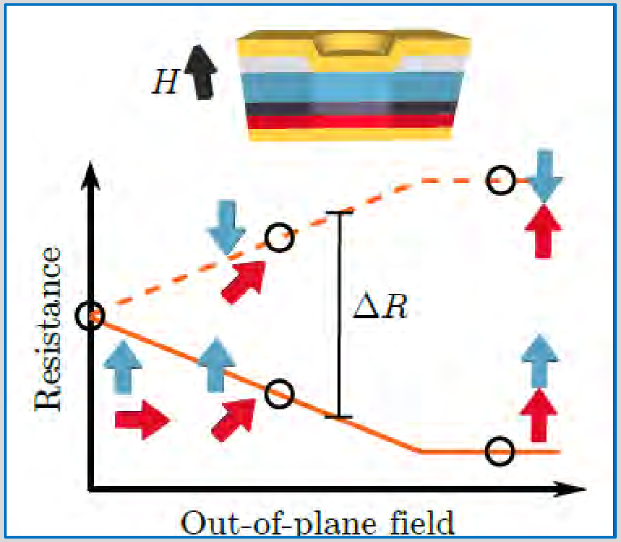


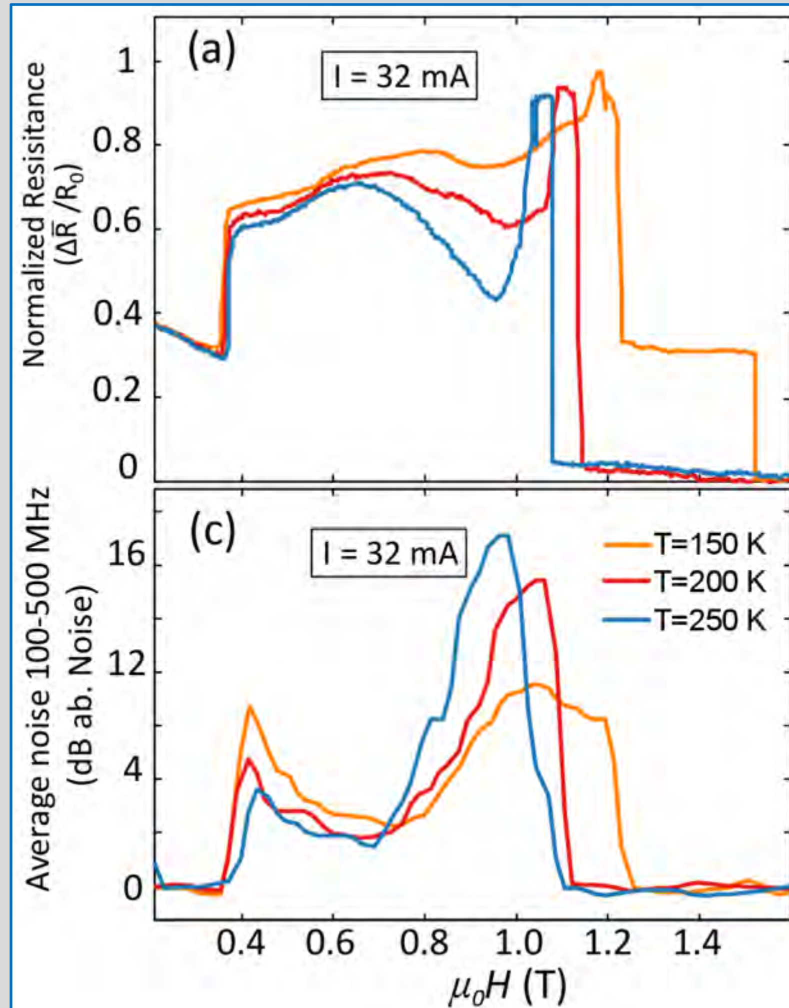
S. Lendínez et al. arXiv:1610.00931 (2016)

UNIVERSITAT DE BARCELONA

ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

Experimental detection of Droplet Solitons



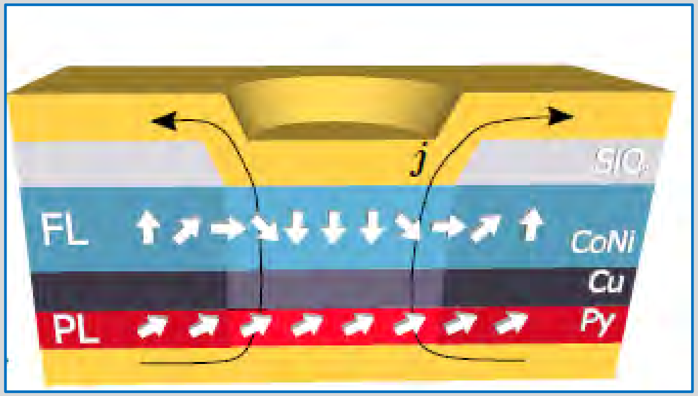


S. Lendínez et al. arXiv:1610.00931 (2016)

There is a correlation between states with an incomplete reversal of the magnetization and states showing a stronger drift-resonance signal.

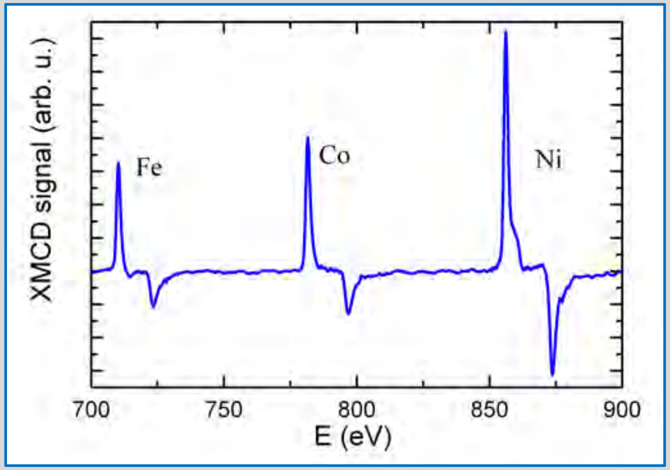
STT effect is more complex in dynamic solitons, and probably other collective dynamic spin excitations, than in nanopillars.

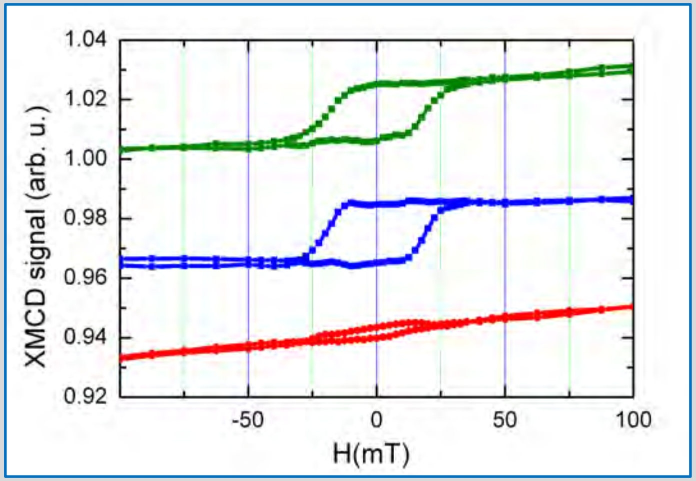
Imaging Droplet solitons with XMCD



- Out-of-plane free layer CoNi (1-2 nm)
- In-plane fixed polarizing layer Py (5-10 nm)
- Contact diameter 80-150 nm

XMCD





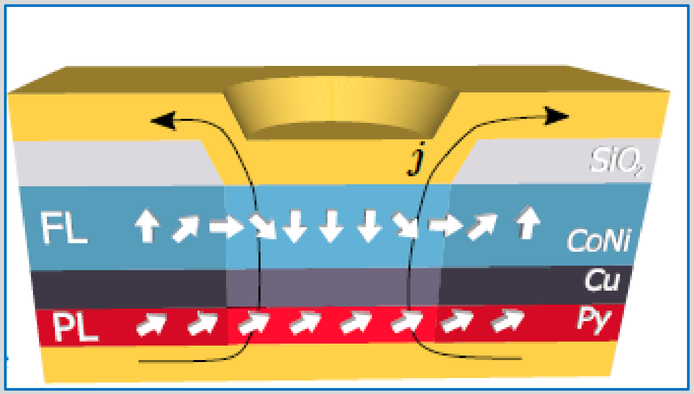
Ni

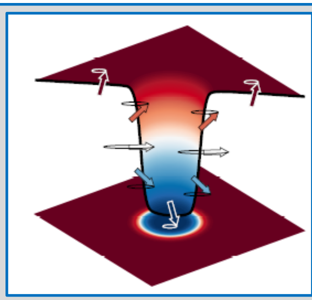
Co

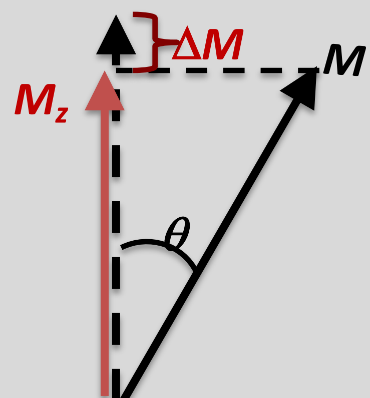
Py (FeNi)

Imaging Droplet solitons with XMCD

The x-rays are focused to a 35 nm spot using a zone-plate, determining the spatial resolution.



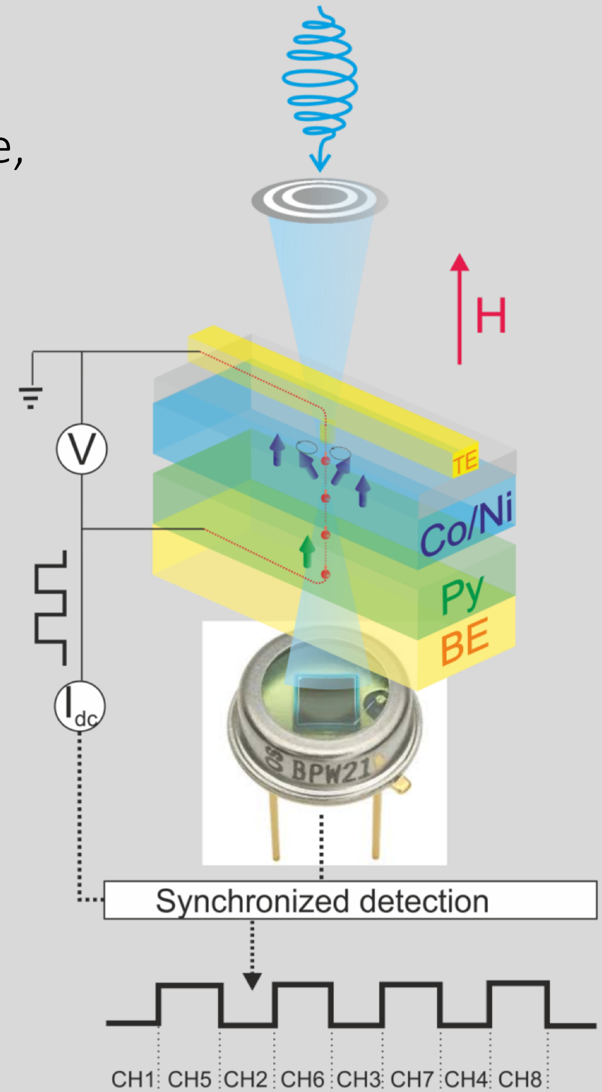




ΔM: Static XMCD

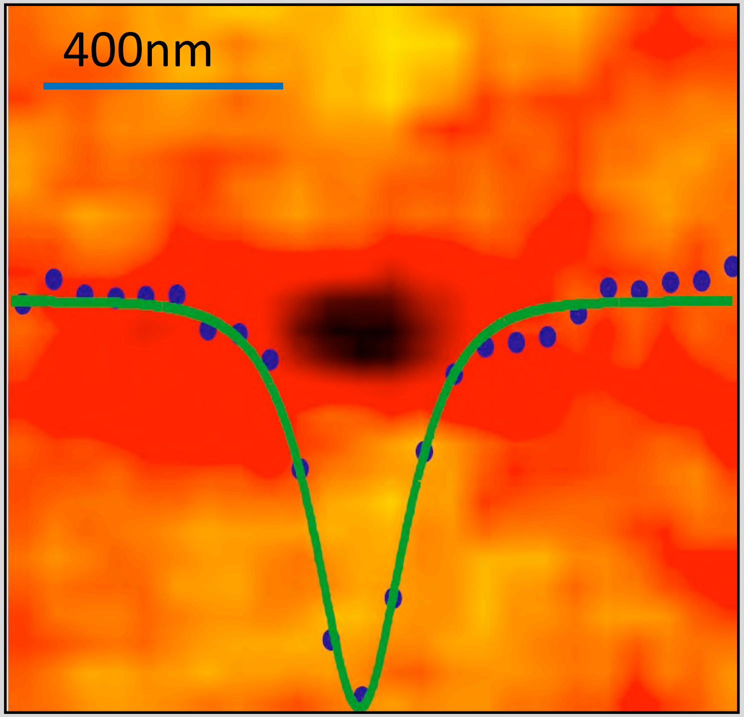
SSRL (SLAC) BL 13.1

Phys. Rev. Lett. ***115****, 127205 (2015)*



Imaging Droplet solitons with XMCD

SSRL (SLAC) BL 13.1



Phys. Rev. Lett. ***115****, 127205 (2015)*

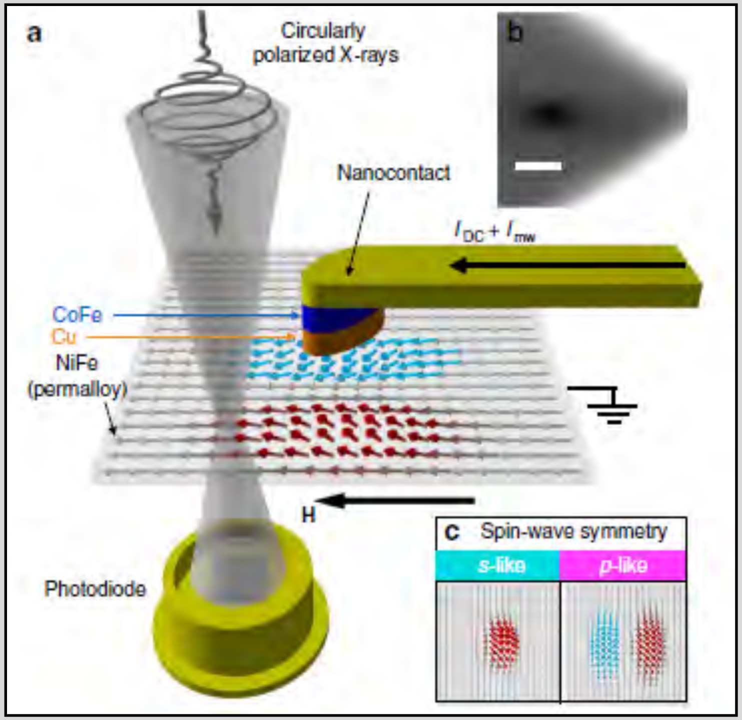
- Exact profile imaging of a soliton mode
- Peak widths between 70 and 85 nm (nominal radius is 75 nm)

We obtained precession angles of about 20-30 degrees

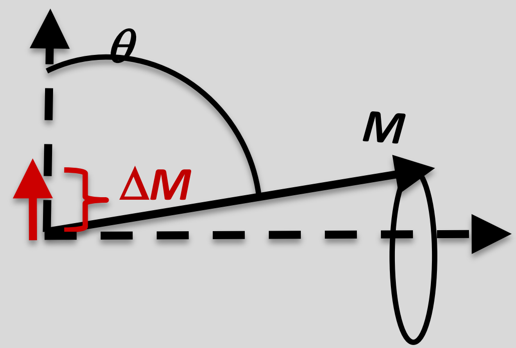
It does not correspond to a full reversal!

Time resolved direct Imaging of spin waves in STO

The sample comprises a NiFe(5nm), Cu(4nm) and CoFe(8nm) multilayer, where the Cu and CoFe layer are patterned into an ellipse of 150 nm 50 nm, while the NiFe layer is a larger mesa

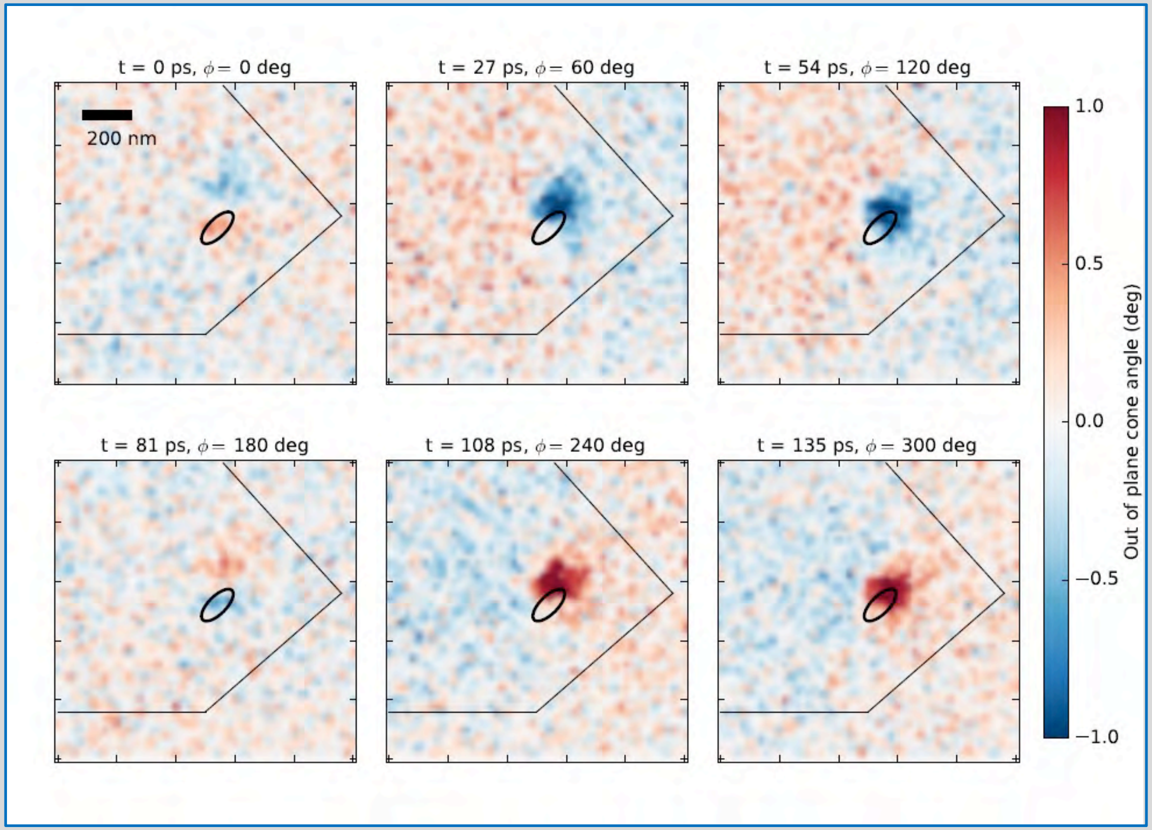


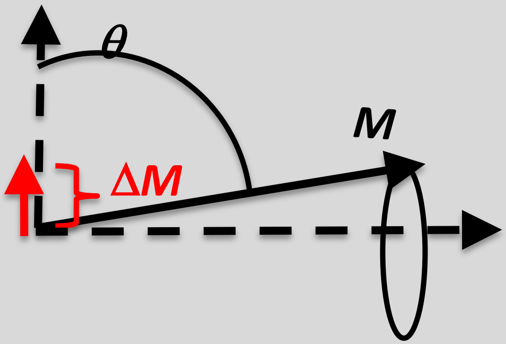
Nature Communications ***6****, 8889, 2015*



Observation of the out of plane component of the magnetization (oscillating component).

Time resolved direct Imaging of spin waves in STO





Nature Communications ***6****, 8889, 2015*

The Oersted fields combined with the dipolar fields create a magnetic field distribution that localizes the spin wave excitation perpendicular to the direction of the applied field

UNIVERSITAT DE BARCELONA

Dynamical skyrmions

ARTICLE

Received 10 Mar 2015 | Accepted 24 Jul 2015 | Published 9 Sep 2015 DOI: 10.1038/ncomms9193 OPEN

Dynamically stabilized magnetic skyrmions

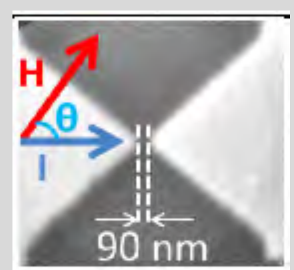
Y. Zhou[1,2], E. Iacocca[3], A.A. Awad[3], R.K. Dumas[3], F.C. Zhang[2,4,5], H.B. Braun[6,7] & J. Åkerman[3,8]

Magnetic skyrmions are topologically non-trivial spin textures. Droplet solitons can be stabilized as dynamical skirmions in presence of DMI interaction.

PRL 114, 137201 (2015) PHYSICAL REVIEW LETTERS week ending 3 APRIL 2015

Dynamical Skyrmion State in a Spin Current Nano-Oscillator with Perpendicular Magnetic Anisotropy

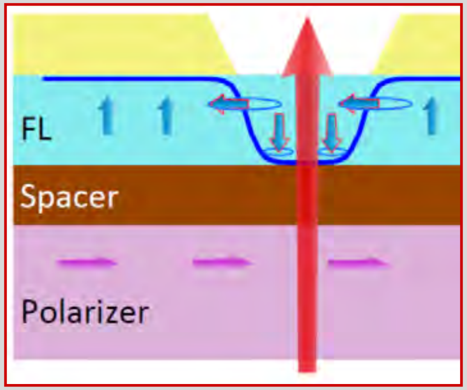
R. H. Liu (刘荣华),* W. L. Lim, and S. Urazhdin†



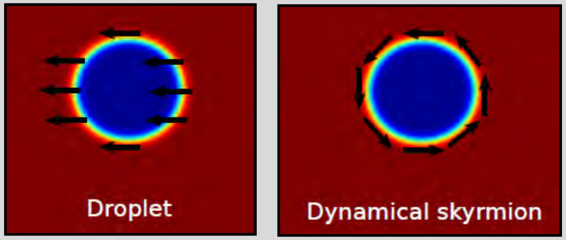
ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

UNIVERSITAT DE BARCELONA

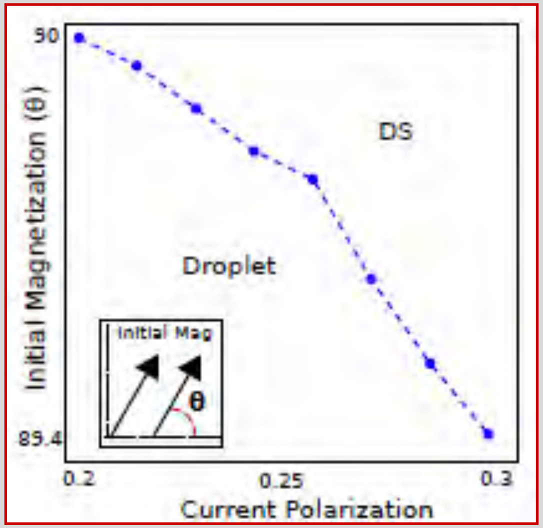
Dynamical skyrmions



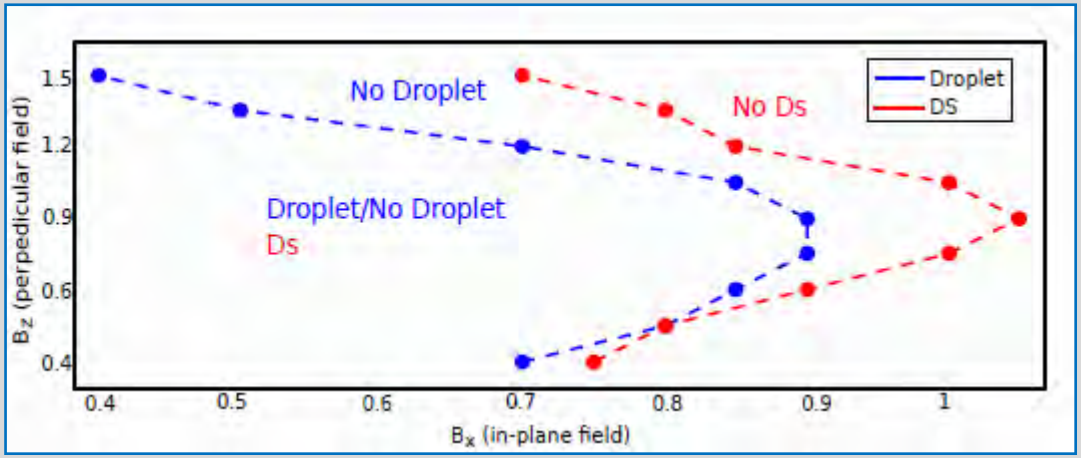
The Oersted fields can imprint the topology to the droplet excitation



The initial condition determines whether the spin excitation is either a droplet or a dynamical skyrmion



Stability analisis



ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

UNIVERSITAT DE BARCELONA

Summary

- Control of spin waves emission for memory and computation
- Study of droplet solitons from STO
  - Stable excitations
  - Additional dynamics (drift resonances)
  - Competition between phonons and magnons
- Direct imaging of magnetic spin wave excitations from STO
  - Droplet solitons
  - Propagating modes

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

UNIVERSITAT DE BARCELONA

Acknowledgments

UNIVERSITAT DE BARCELONA

NYU

CIC nanoGUNE
nanoscience cooperative research center

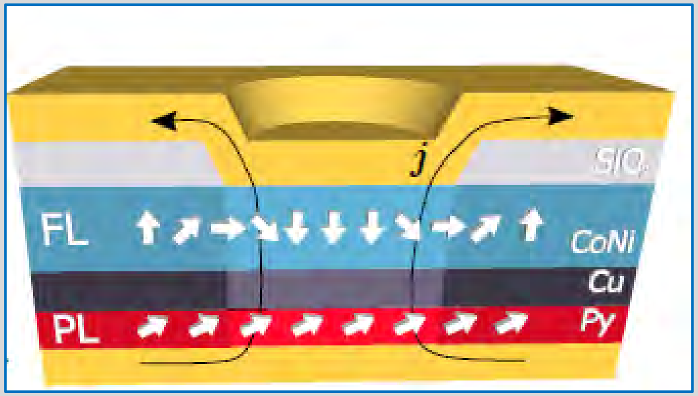
SLAC NATIONAL ACCELERATOR LABORATORY

- Sergi Lendínez, Nahuel Statuto, and Joan Manel Hernàndez
- Dirk Backes, Andrew D. Kent and F. C. Hoppensteadt
- Saül Vélez, Luis Hueso and Fèlix Casanova
- Stefano Bonetti, Roopali Kukreja and Hendrik Ohldag

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA

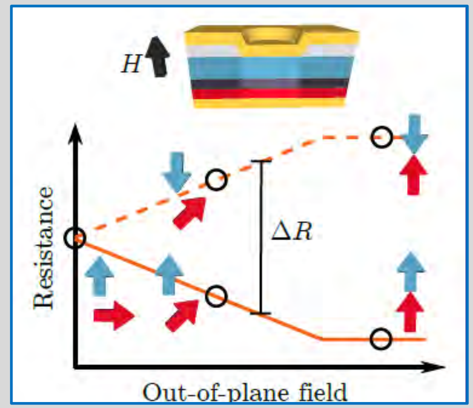
UNIVERSITAT DE BARCELONA

Experimental detection of Droplet Solitons

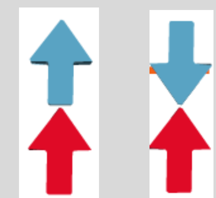


*F. Macià et al. Nat.Nanotech., **9**, 992 (2014)*
S. Lendínez et al. Phys. Rev. B. 92, 174426 (2015)

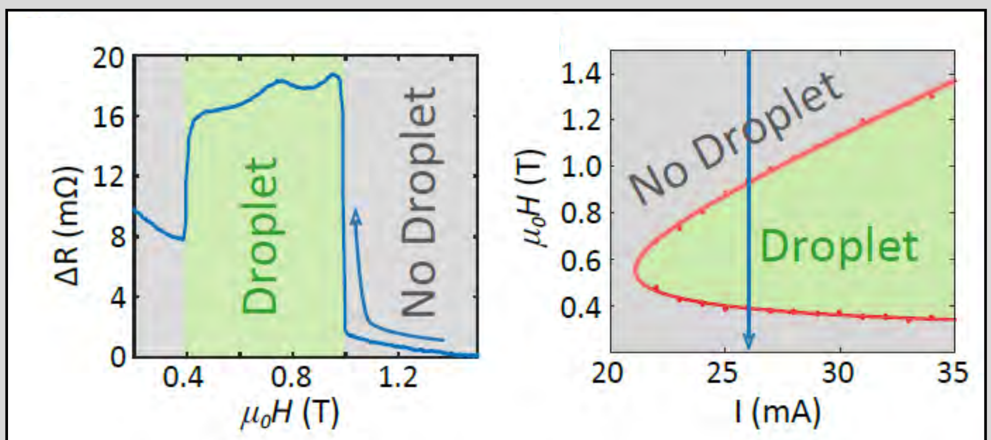
- Out-of-plane free layer CoNi
- In-plane fixed polarizing layer Py
- Contact diameter 80-150 nm



Max MR ~0.3%



- Stability maps



ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA