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Alexander von Humboldt Stiftung/Foundation

Current- and field- induced magnetization dynamics and magnetic configurations in cylindrical nanowires

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Outline

- **Applications and advantages of cylindrical nanowires**

- **Current-induced and field-induced dynamics in nanowires:**

1. Control of vortex structures.
2. Bloch Point propagation under spin-polarized current and Oersted field.

- **Non-trivial topological structures, pinning and field-induced processes:**

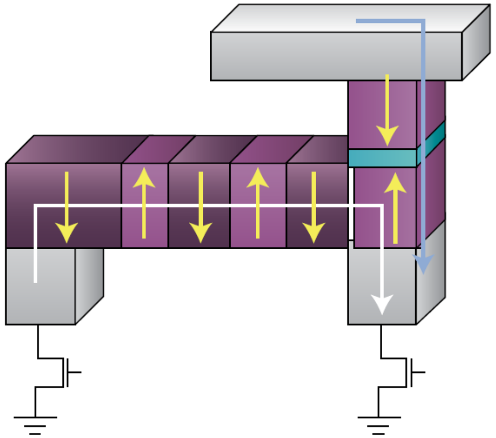
3. Magnetization pinning and the corkscrew mechanism.
4. Ratchet effect in magnetic nanowires.
5. Multi-domain structures in chemically modulated nanowires.
6. Stochastic vs. deterministic switching in multisegmented nanowires.

Applications of magnetic cylindrical nanowires

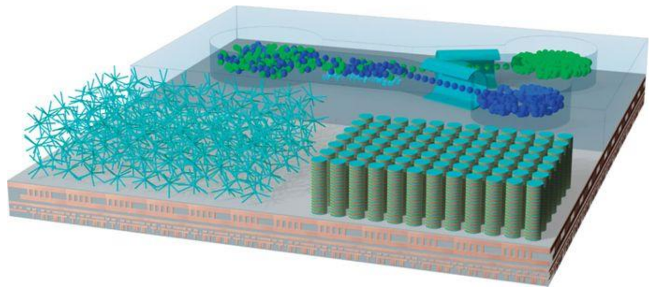
3D-Magnetic recording, storage & information technologies

B. Dieny et al., *Nat Electron* **3**, 446–459 (2020).

S. S. P. Parkin et al. *Science* **320** (2008)

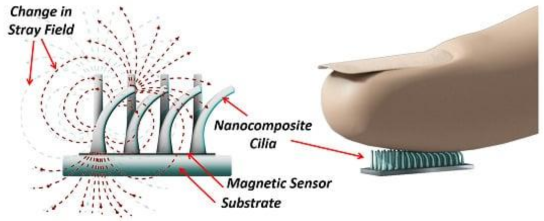


Spintronics, electronics & logic devices



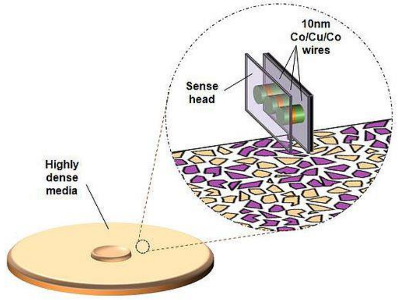
A. Fernandez-Pacheco et al. Nat. Commun. 8 (2017)

Sensors & actuators



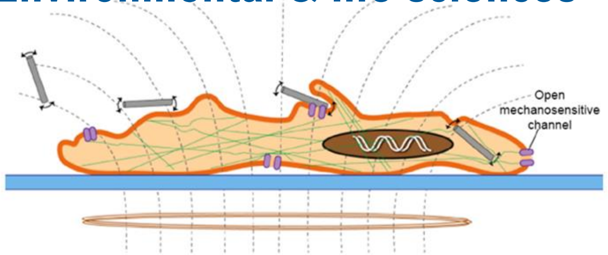
Ahmed Alfadhel *et al.*, Sensors, 16(5), 650 (2016)

Permanent magnets & energy conversion



M. M. Maqableh et al., IEEE Trans Mag Vol. 48, 5 (2012)

Environmental & life sciences

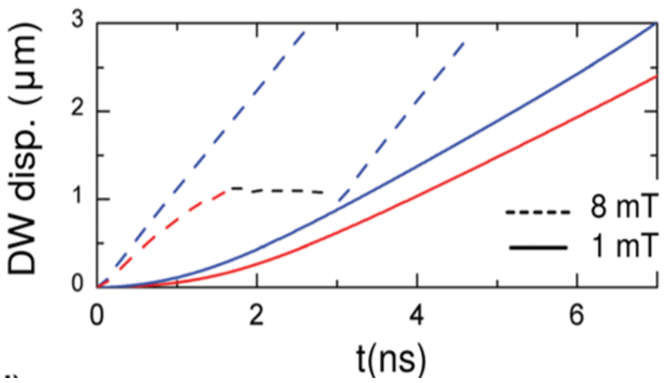


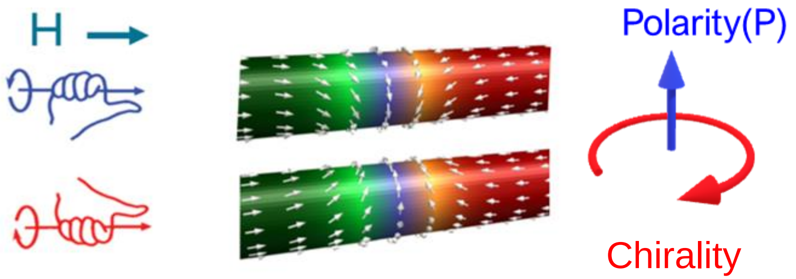
M.F. Contreras et al., Int. J. Nanomedicine, 10, (2015)

Advantages of cylindrical nanowires

- Building blocks for 3D magnetic nanoarchitectures
- **No Walker breakdown** i.e., domain Wall reach velocities up to 2-10 km/s.
- **Curvature** induces non-trivial topological magnetic structures and **magnetochiral effects.**
- Additional features: inexpensive fabrication methods, shape anisotropy, etc.

Assymetric propagation of domains walls with different chirality





R. Hertel *et al*., J. *Phys.: Condens. Matter* **28** 483002 2016

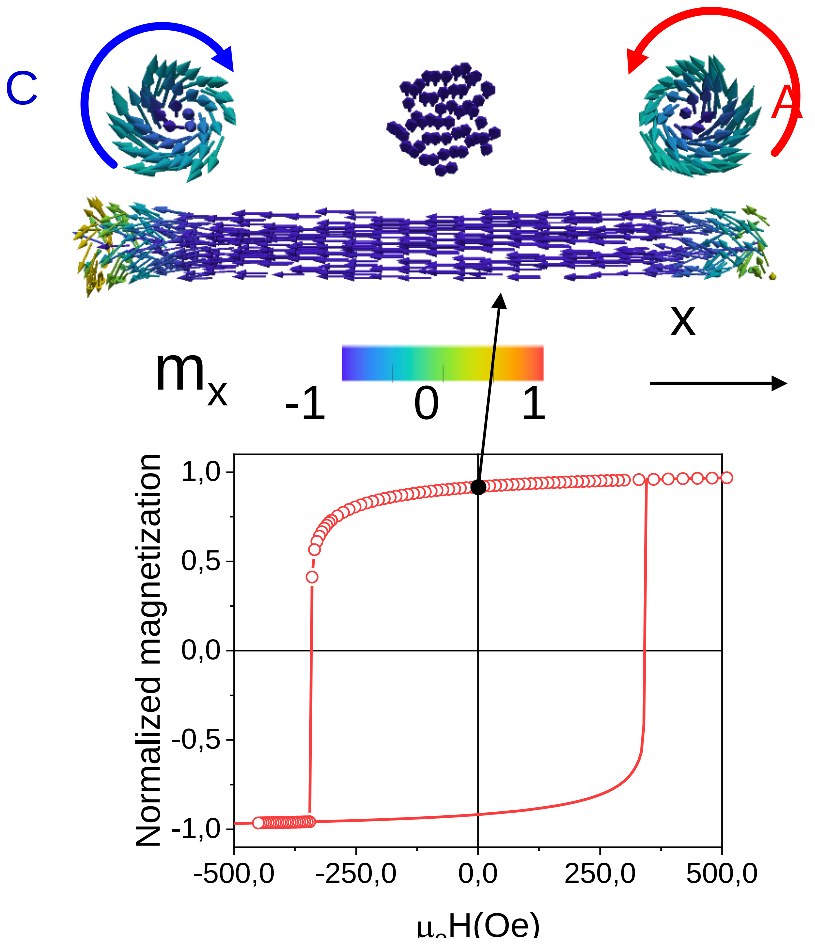
1 | Control of vortex structures in cylindrical nanowires

by means of current and Oersted

Magnetization at the remanent state

- **Magnetic vortices manifest as**: magnetic domains, domain walls or as precursors of the magnetization reversal.
- Magnetic recording and spintronic applications of nanowires require the control of vortex configurations.

- **Our aim:** to find the conditions for a minimal and efficient manipulation of vortex structures by means of electric current J and field H, *i.e.* the conditions for which one or another vortex configuration (V and P) is set.



Fernandez-Roldan *et al.*, *Phys. Rev. B* **102**, 024421 (2020)

1 | Control of vortex structures in cylindrical nanowires

by means of current and Oersted

Magnetization-current interaction:

- Zhang-Li spin transfer [S. Zhang *et al*.,PRL 93, 127204 (2004)]

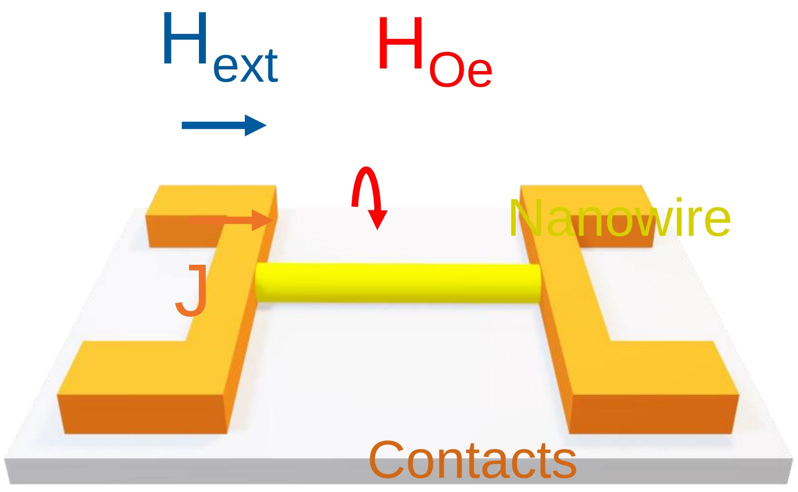
$$T_{ZL} = \frac{1}{1+\alpha^2}\Big((1+\xi\alpha)\ m \times (\, m \times (u \cdot \nabla) m) + (\xi - \alpha) m \times \big((u \cdot \nabla) m\big)\Big)$$

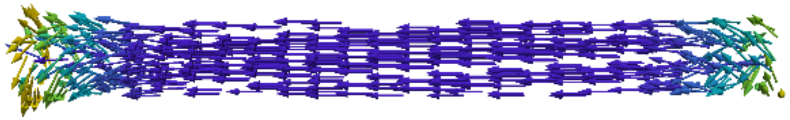
where $u = \frac{P\ \mu_B}{2\ e\ \gamma_0 M_S\ (1+\xi^2)}\ J$

- $H_{Oersted}$

Permalloy standard parameters:

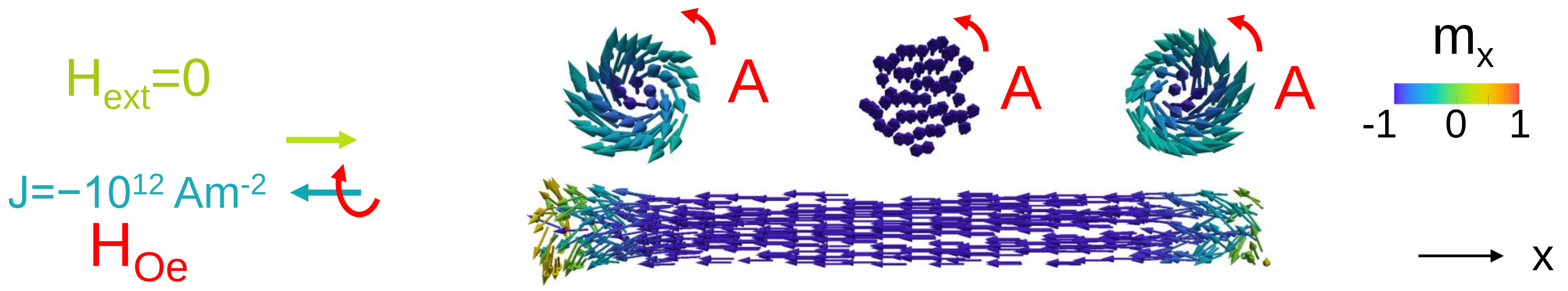
- $\mu_o M_S$ =1 T, $A_{ex} = 13 \cdot 10^{-12}$ Jm^{-1}, $\alpha = 0.02$
- Non-adiabaticity of STT $\xi = 0.1$
- Current polarization $P = 0.56\ \cdot$
- H_{ext} up to 500 Oe, and J up to the max. value of 10^{12} Am^{-2}



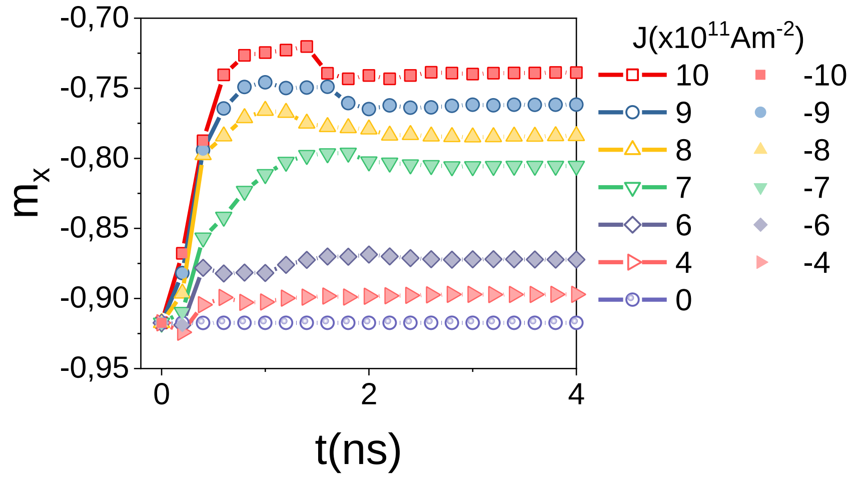


Fernandez-Roldan *et al*., *Phys. Rev. B* **102**, 024421 (2020)

Magnetization dynamics at H_{ext}=0

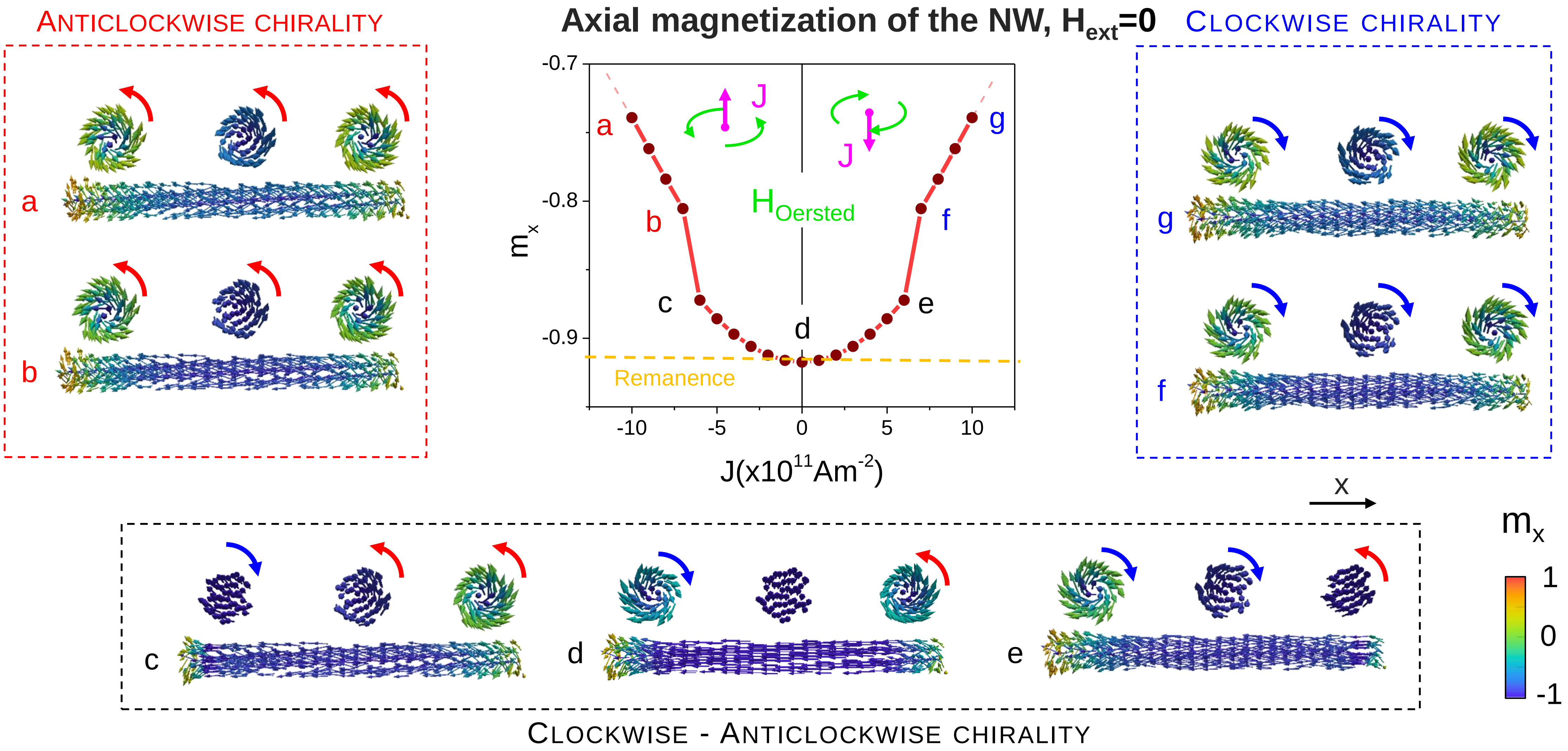


Axial component of magnetization vs. Time (H_{ext}=0)



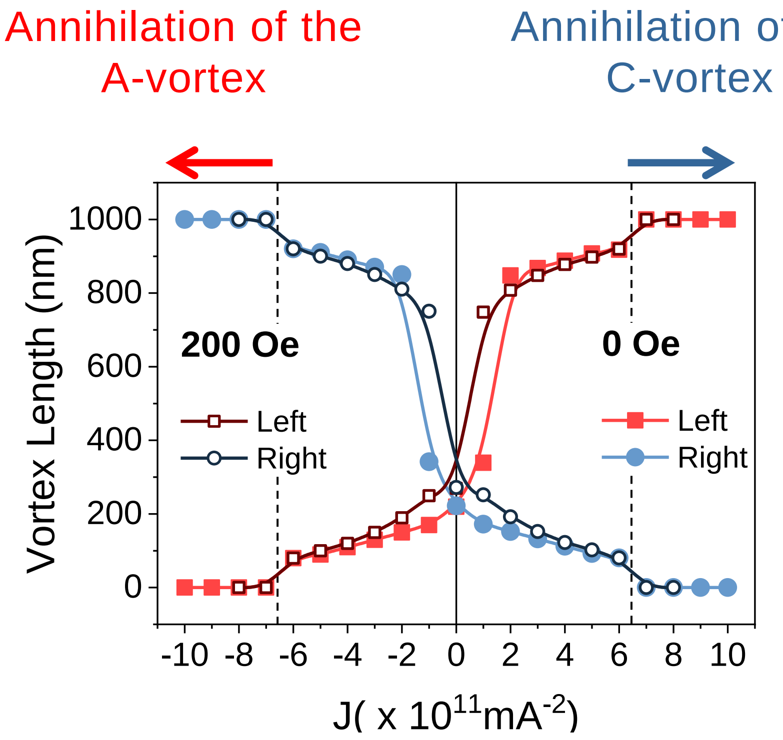
- The nanowire reaches a stationary state in 3-4 ns for every J, irrespectively of the current direction.
- The stationary state has a higher value of axial magnetization then the remanent state

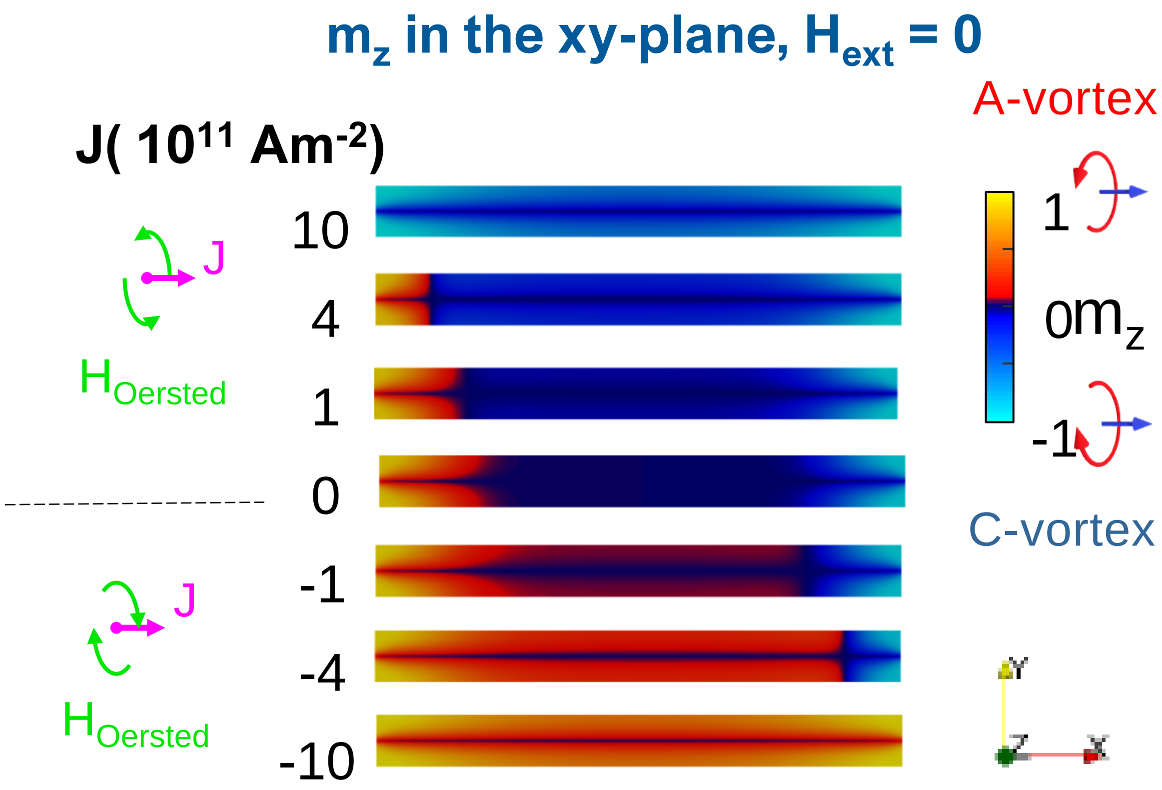
Stationary magnetic states after few nanoseconds, $H_{ext} = 0$



Lengths of the vortex domains

measured from the Left/Right end of the NW

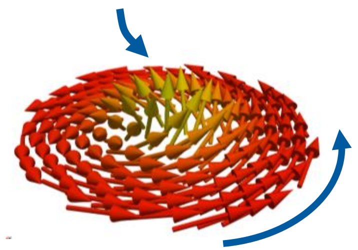


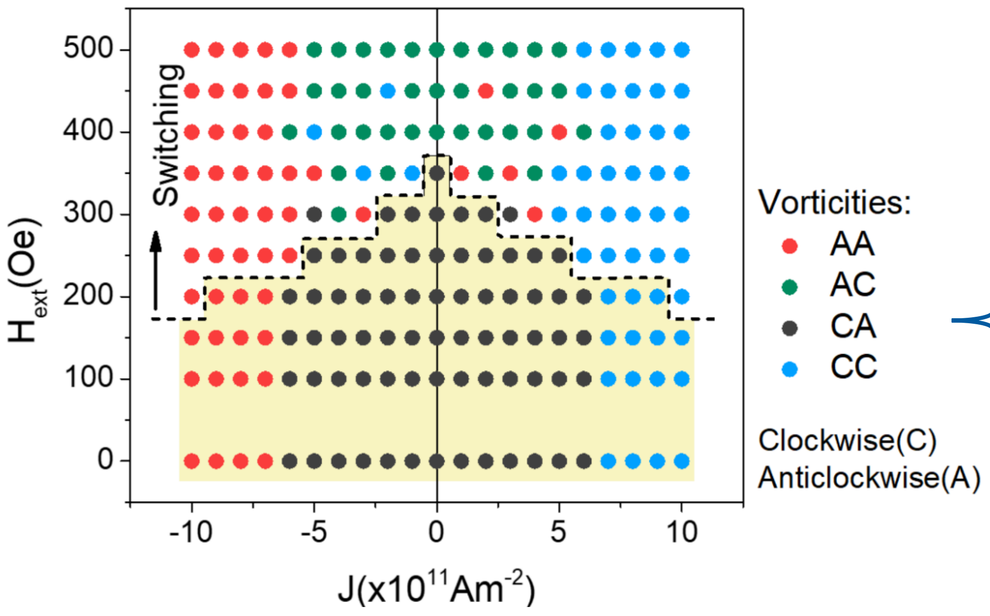


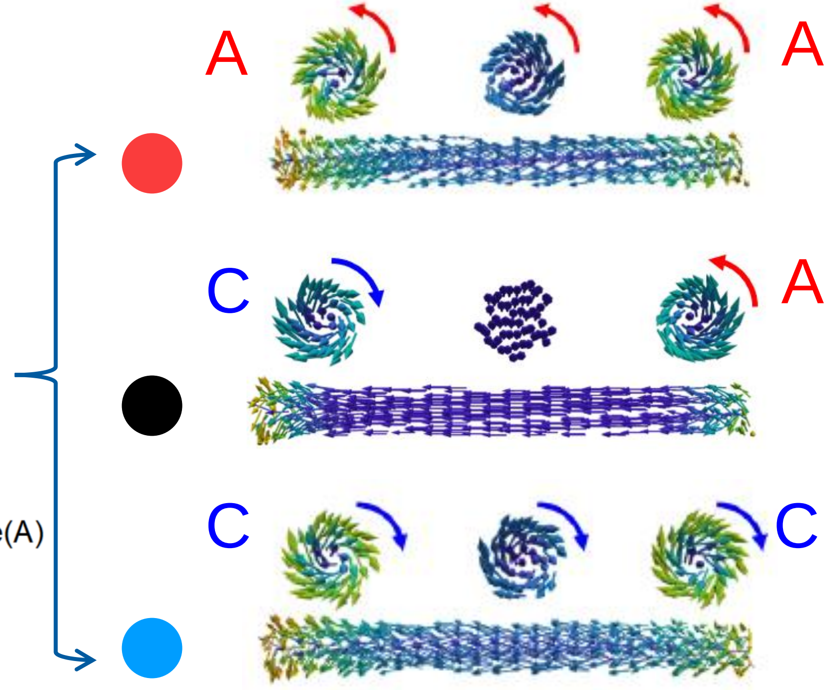
- **Under action of a current alone is posible to switch the chirality of the vortex structure** towards the direction of the $H_{oersted}$.
- No change in the direction of the magnetization in the core → Assitance of H_{ext}

After the application of a long current pulse we observe…

vortices with Clockwise (C) /Anticlockwise (A) sense of rotation at each end of the nanowire





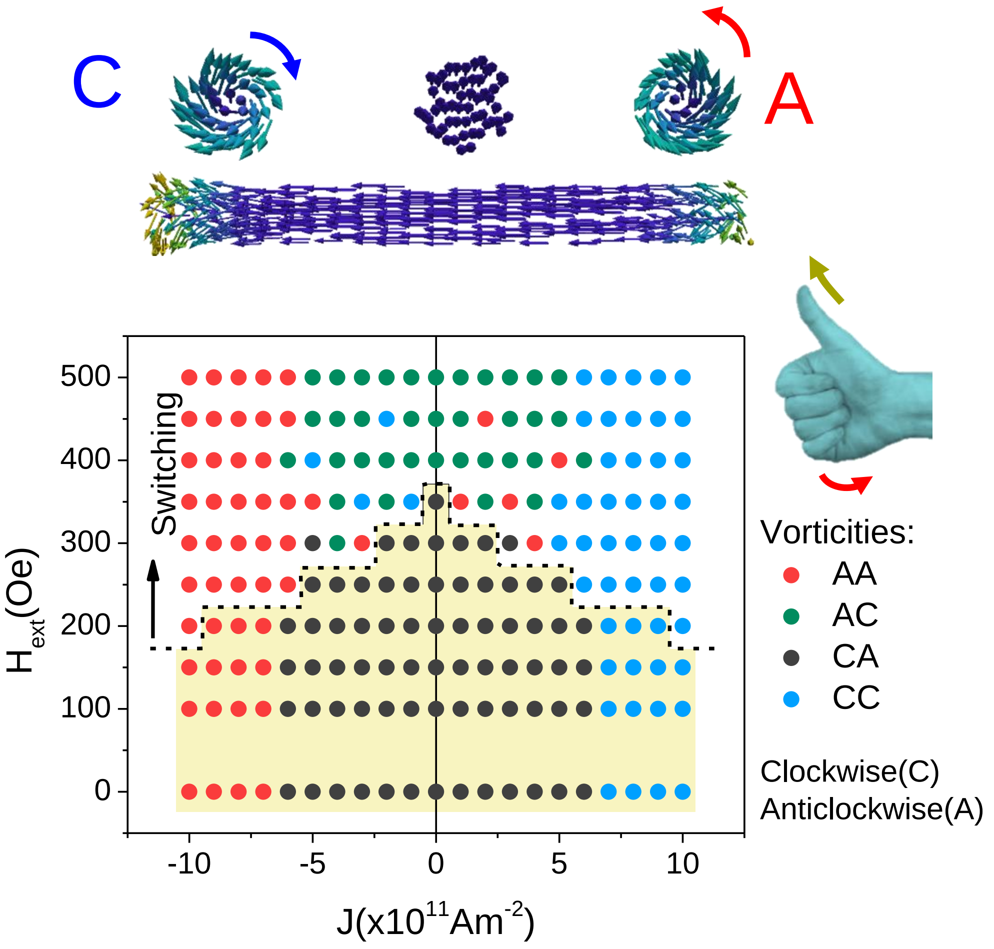


- **A vortex which has the same circulation as the Oersted field expands.**
- The circulation of pair of vortices is controlled by small and shot (ns) current pulses→ Control of domain wall precursors and domains
- **The magnetization switching requires** the assistance of an applied field ($H_{switching}$<$H_{coercive}$)
- The circulation of the vortices is only predictable if the axial component switches

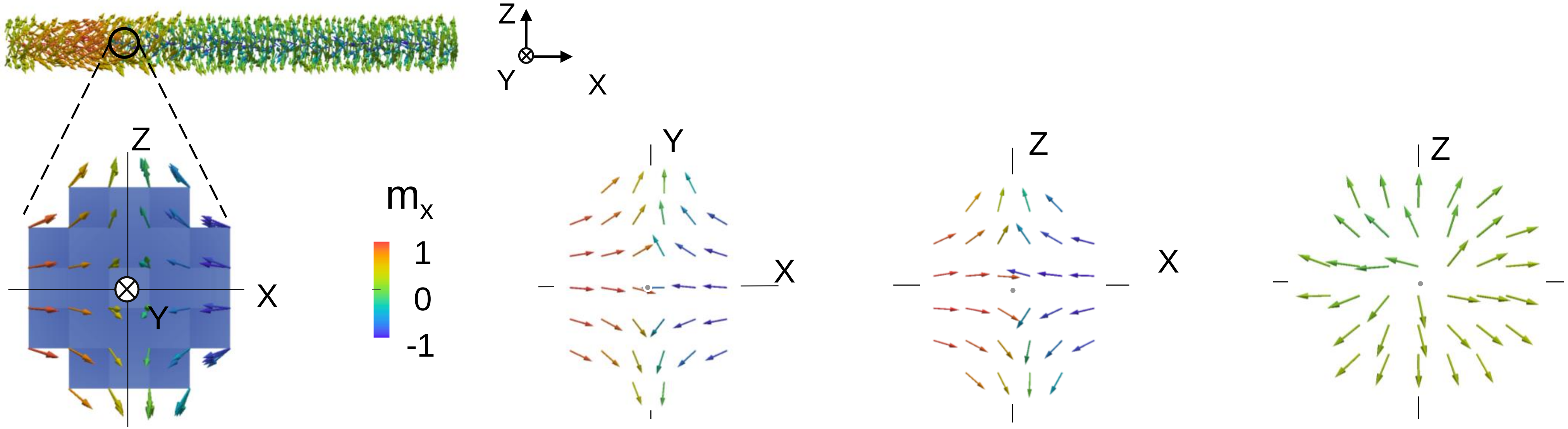
Fernandez-Roldan *et al.*, *Phys. Rev. B* **102**, 024421 (2020)

We have investigated the dynamics of two domain walls naturally nucleated at the nanowire ends:

1. **The magnetic vortex pattern (V, P) is set via Oersted field** by the selection of appropriate H_{ext} and J
2. **The magnetization switching (P) occurs only** under the application of a simultaneous minimum H_{ext}.
3. **This state diagram will assist experimental realizations** of current-induced domain wall dynamics in cylindrical NWs.



Switching of magnetization through the propagation of a Bloch Point



- **The dynamics of the axial component is independent** of the current direction
- The switching of the magnetization in the cores is mediated by the propagation of a **Bloch Point**

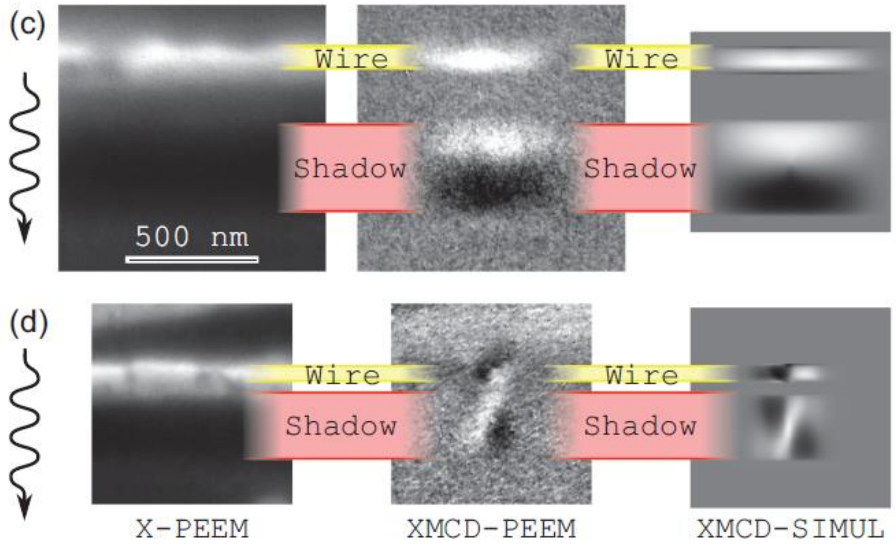
Fernandez-Roldan *et al.*, *Phys. Rev. B* **102**, 024421 (2020)

The Bloch Point domain wall as information carrier

XMCD-PEEM observation in cylindrical nanowires

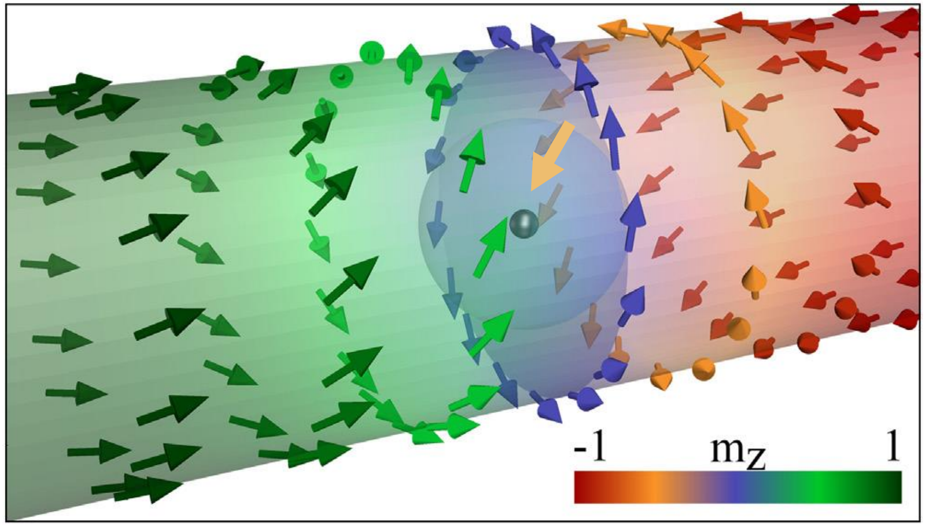
BPW

VADW



DaCol et al., *PRB* **89**, 180405(R) (2014)

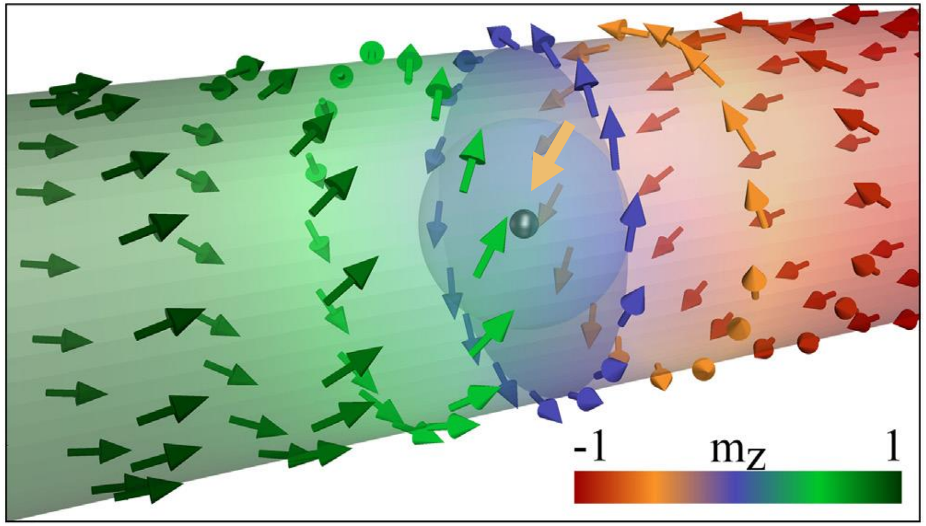
A Bloch Point domain wall



R. Hertel, J. Phys.: *Condens. Matter* **28,** 483002 (2016)

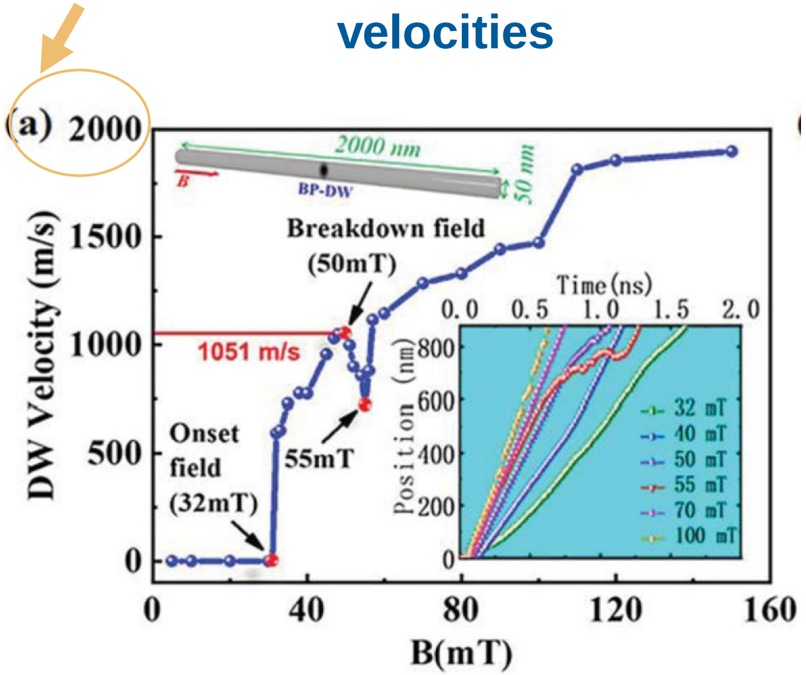
The Bloch Point domain wall as information carrier

A Bloch Point domain wall



R. Hertel, J. Phys.: *Condens. Matter* **28,** 483002 (2016)

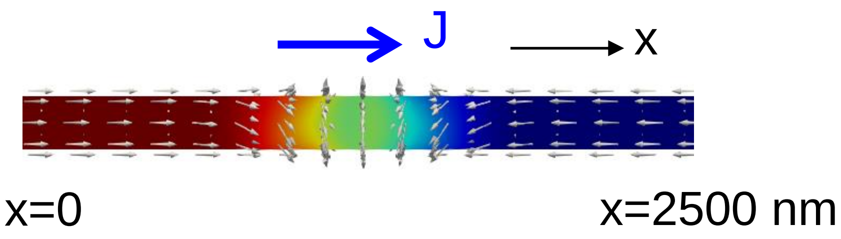
Field-driven Bloch Points reach high velocities

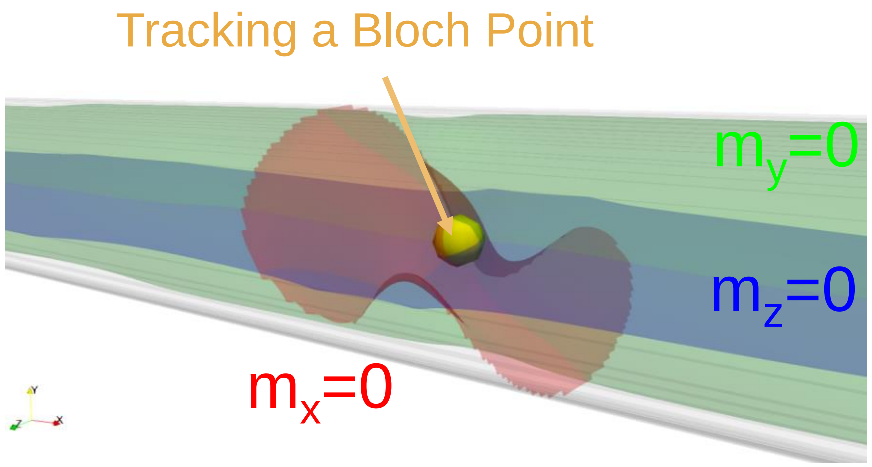


X.P. Ma et al., *Appl. Phys. Lett*. **117**, 062402 (2020);

- The Bloch Point wall carries a topological defect in its centre, where the magnetization vanishes.

2 | Bloch Point propagation under spin-polarized current and Oersted field



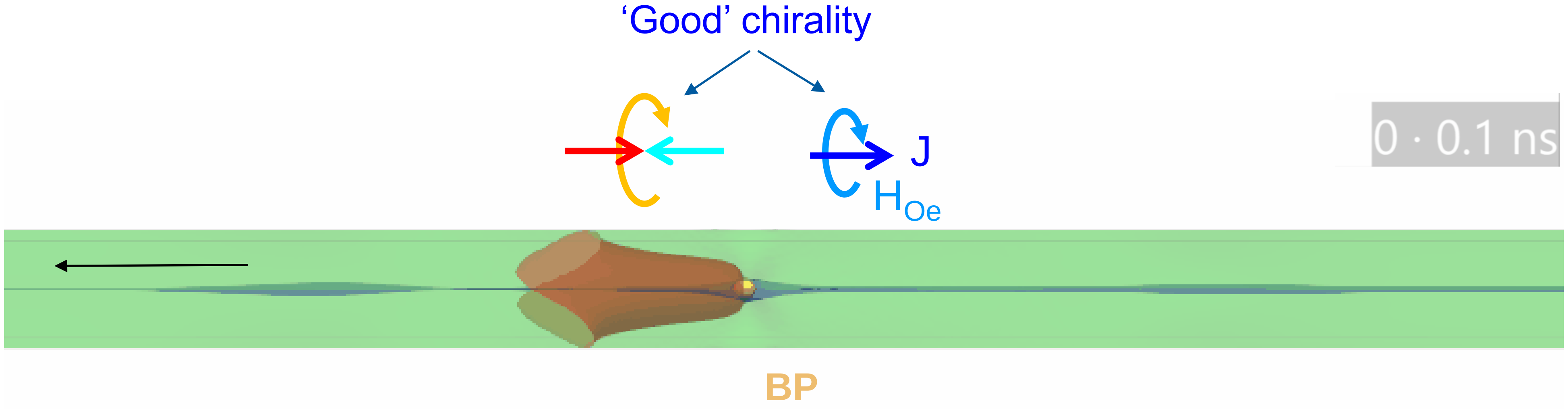


- A head-to-head Bloch Point Wall in a Ni nanowire (diameter 100 nm)
- Typical current densities J in experiments [Schöbitz et al. *Phys. Rev. B* 2021]: $J=10^{11}$-10^{12} Am^{-2}
- Low J to prevent excessive Joule heating [M. Proenca et al. *Sci. Rep*. **9**, 17339 (2019)]
- Oersted field + Zahn-Li spin transfer torque. Details: J.A. Fernandez-Roldan et al., *Phys. Rev. B* **102**, 024421 (2020)

Jose A. Fernandez-Roldan et al., (Submitted soon)

2 | Bloch Point propagation under spin-polarized current and Oersted field

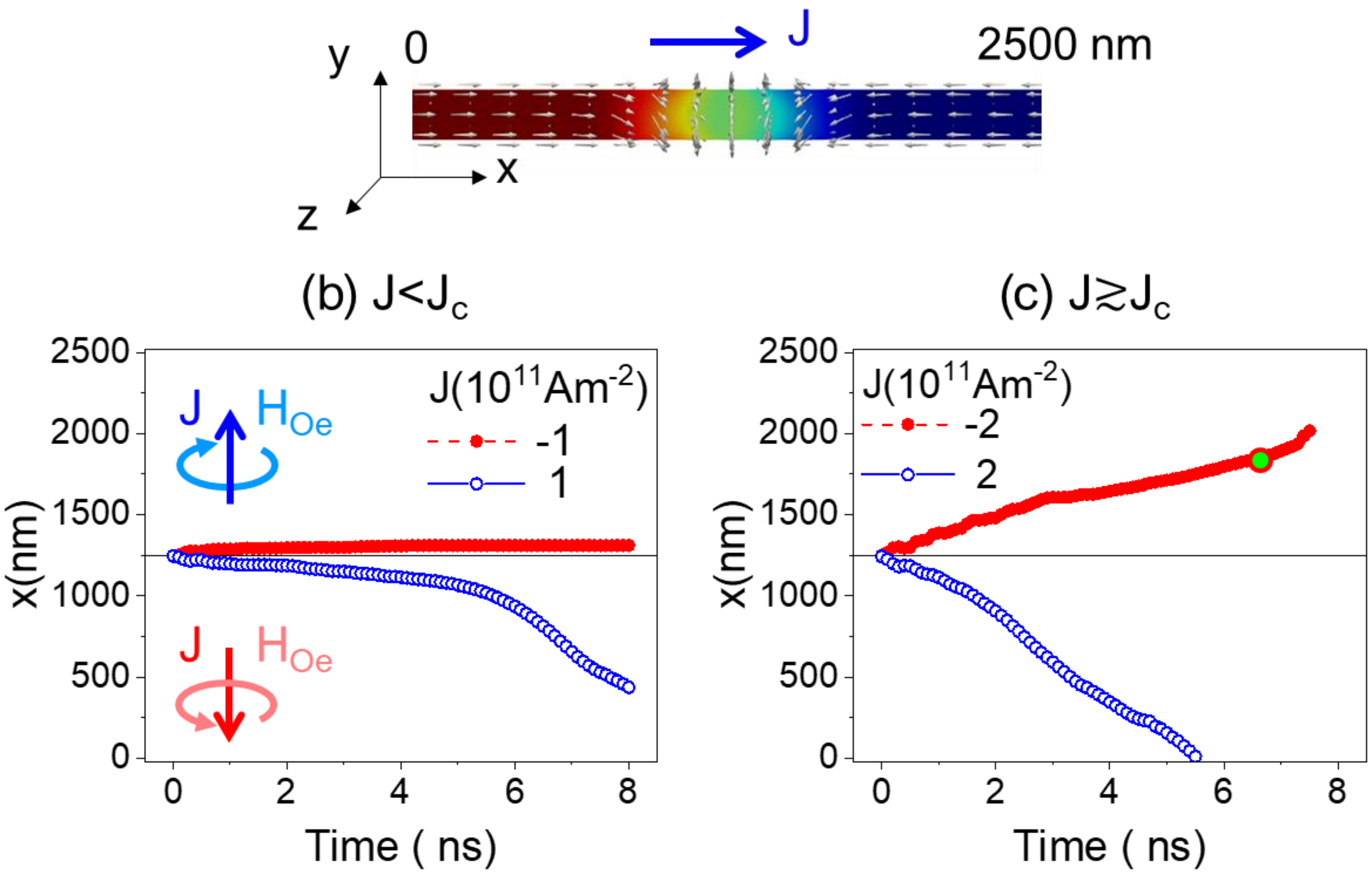
Example J= $+3\cdot10^{11}$ Am^{-2}



- The propagation of a pre-nucleated Bloch Point with 'good' chirality occurs along the axis of the nanowire in the sense opposite to the applied current accompanied by spin wave emission.

Jose A. Fernandez-Roldan et al., (Submitted soon)

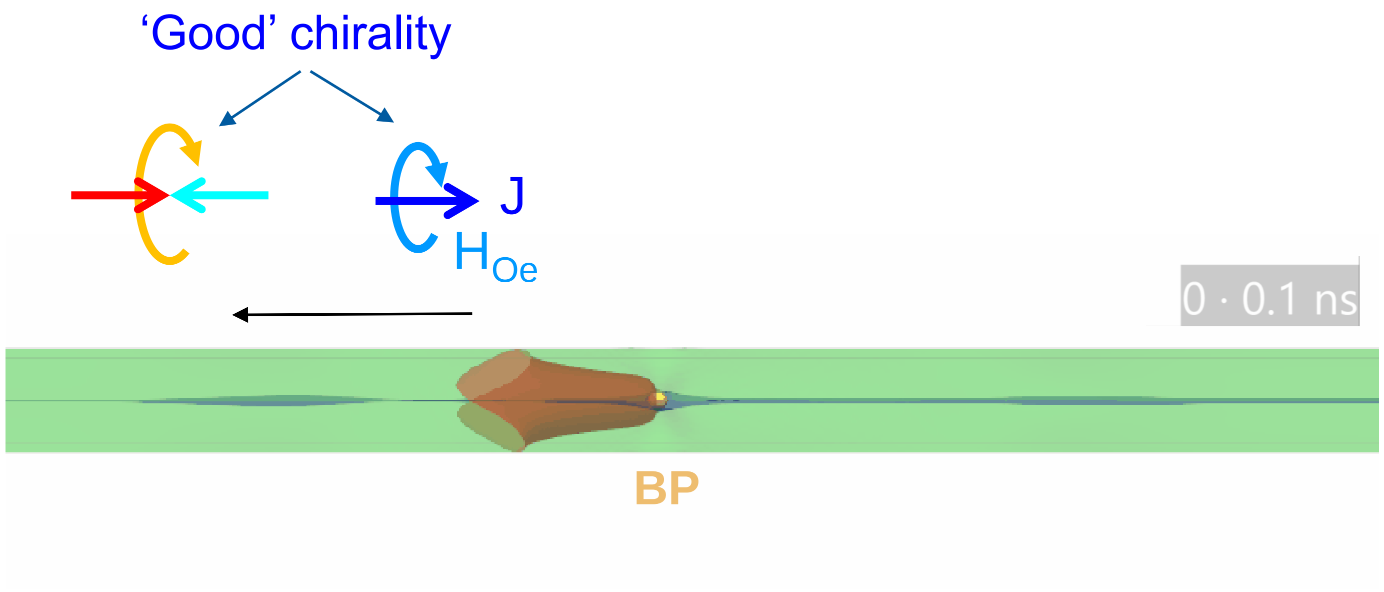
2 | Bloch Point propagation under spin-polarized current and Oersted field

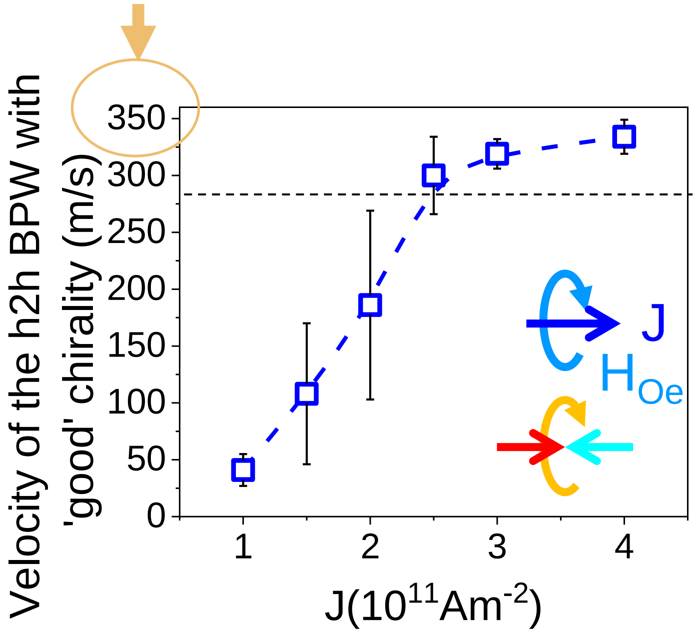


The Bloch point propagates opposite to the current direction along the axis of the nanowire

2 | Bloch Point propagation under spin-polarized current and Oersted field

Example J= +3·10^{11} Am^{-2}

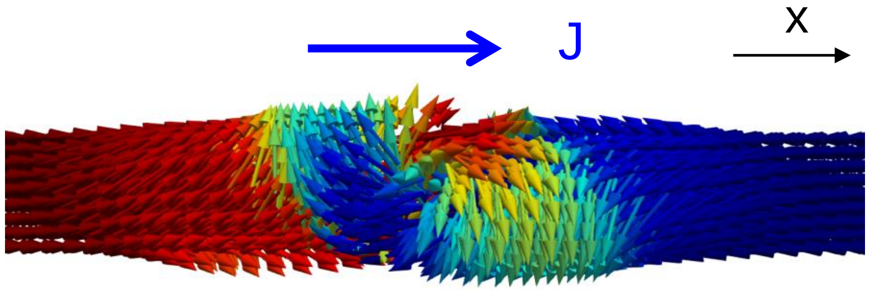


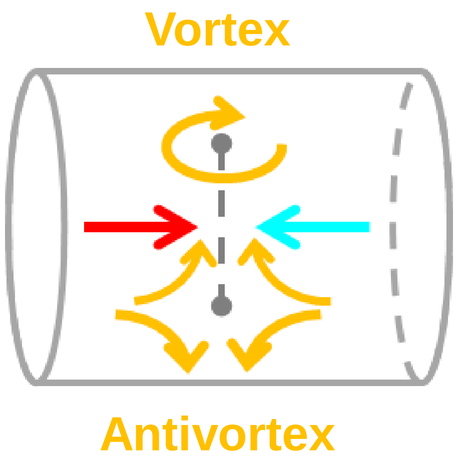


- A drastic reduction of the velocity occurs above a critical current.
- This arises from the Oersted-field-induced- widening of the wall in the wire.
- $\vec{v} \propto \left(\frac{D}{\Delta}\right)\vec{J}$ where D is the diameter of the nanowire, Δ the instantaneous BPW width

2 | Bloch Point propagation under spin-polarized current and Oersted field

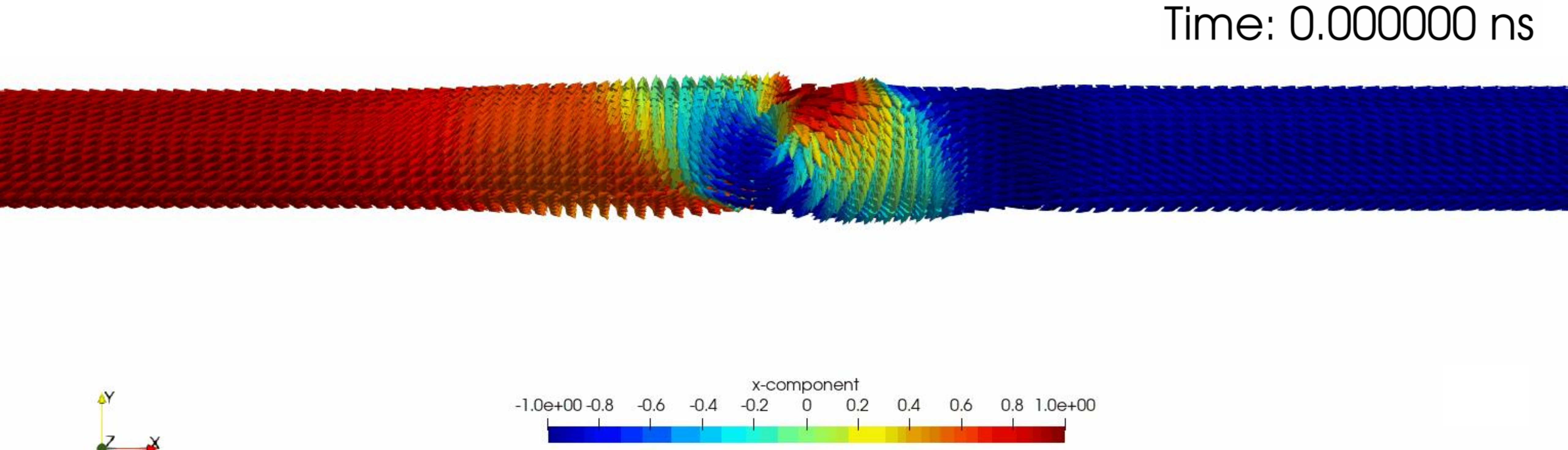
However, Bloch points also nucleate in domain wall transformations



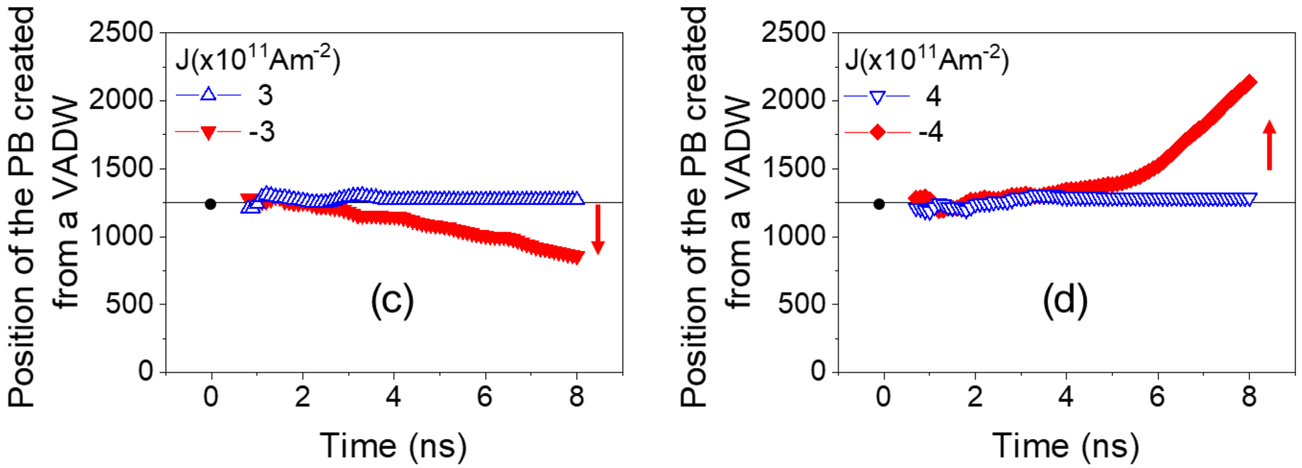


2 | Bloch Point propagation under spin-polarized current and Oersted field

Example: $J=-3 \cdot 10^{11}\ Am^{-2}$



2 | Bloch Point propagation under spin-polarized current and Oersted field



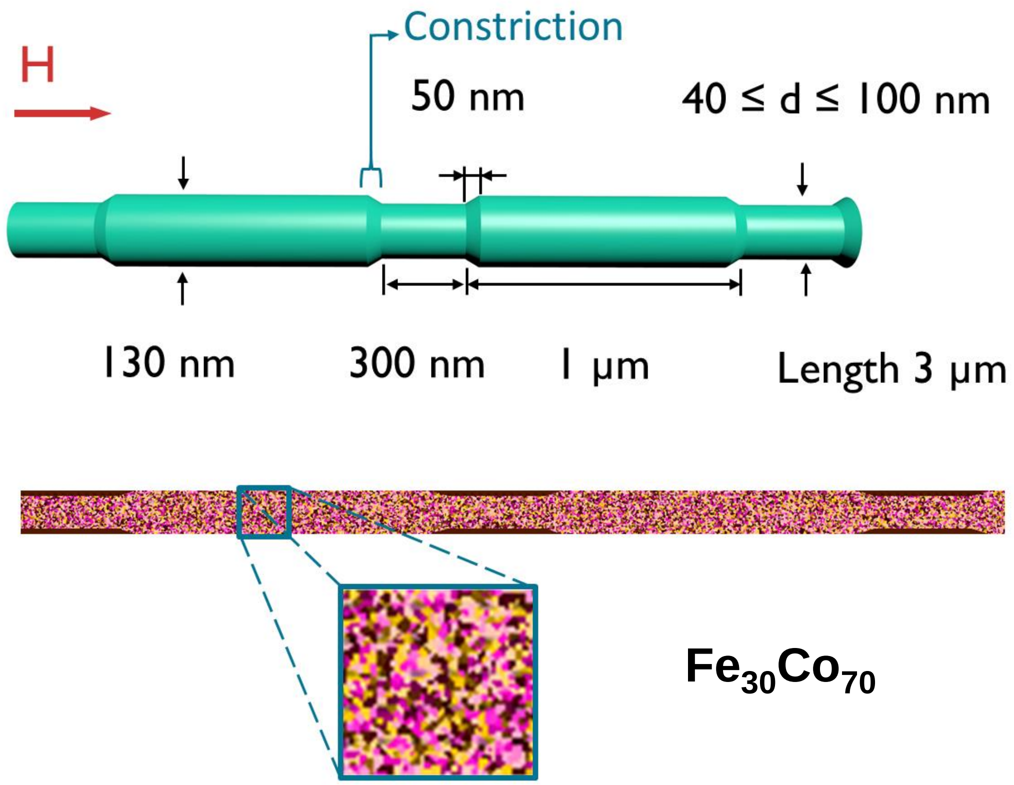
- This Bloch Point can propagate in any direction, irrespectively of the direction of J.
- Unlike pre-nucleated Bloch Points, these Bloch point carry an initial momentum.
- Besides, the Bloch Point motion during its injection indicates that it has dynamic inertia

2 | Bloch Point propagation under spin-polarized current and Oersted field

1. **Prenucleated Bloch Points (BPs) propagate in the direction of –J** with velocities close to 350 m/s .
2. **Velocities are suppressed by the Oersted field** through the widening of the wall width above a critical J.
3. **The initial momentum of the BP plays a major role in its dynamics** that has not been envisaged up to know.
4. Particularly, BP momentum requires a deeper investigation for the control of the BP for spintronis applications of nanowires.

3 | Magnetization pinning in FeCo modulated nanowires

The model



$Fe_{30}Co_{70}$

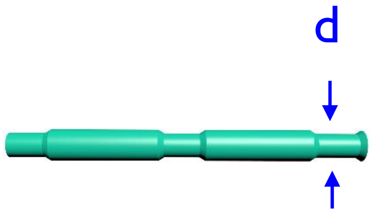
- The small diameter ***d* has been varied to observe pinning at constrictions.**
- **The effect of the particular grain nanostructure is typically neglected** in micromagnetic models of cylindrical nanowires.
- **Let's evaluate the hysteresis loop** for different grain nanostructures and small diameters *d*

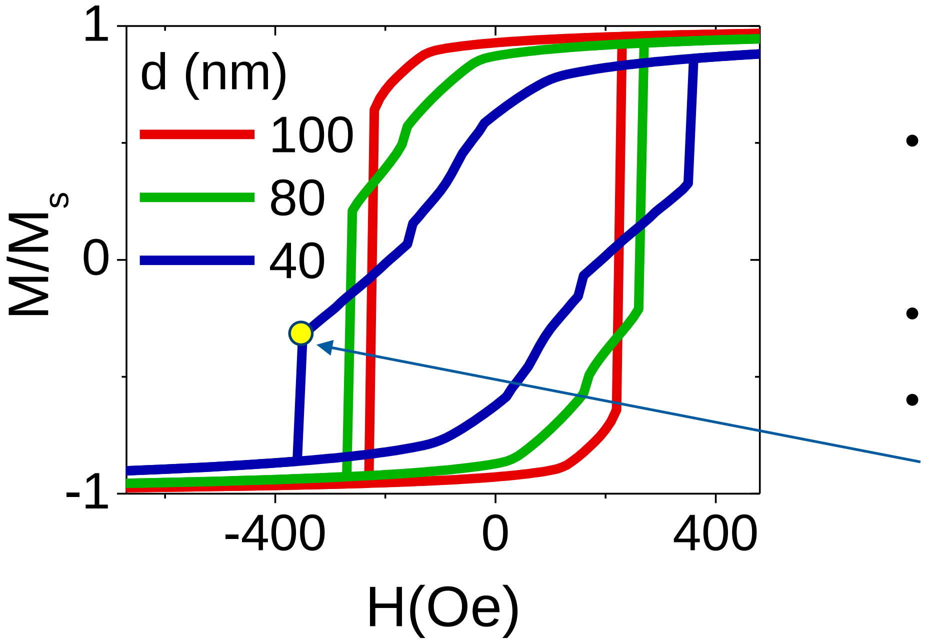
J. A. Fernandez-Roldan et al. *Nanoscale* **10**, 5923–5927 (2018)

3 | Magnetization pinning in FeCo modulated nanowires

Hysteresis loop and magnetization switching

Hysteresis loop for a selected grain distribution





- The hysteresis loop is largely influenced by the disorder
- We observe a strong pinning if d< 100 nm.
- **What does occur before the magnetization switching?**

J. A. Fernandez-Roldan et al. *Nanoscale* **10**, 5923–5927 (2018)

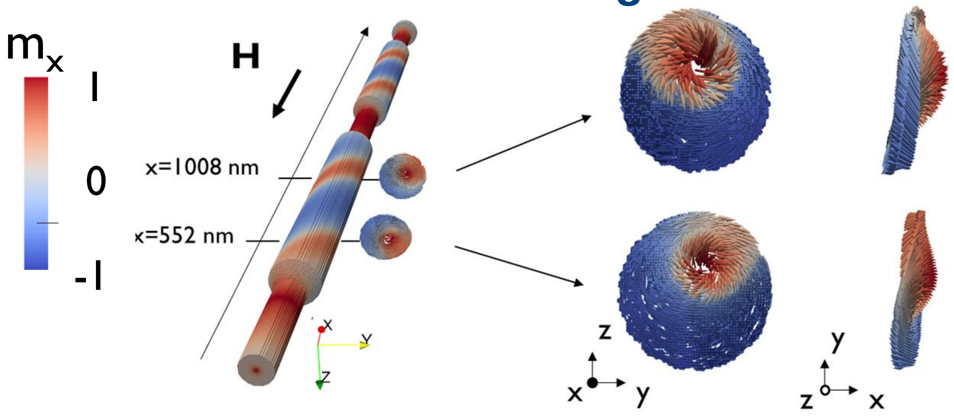
3 | Magnetization pinning in FeCo modulated nanowires

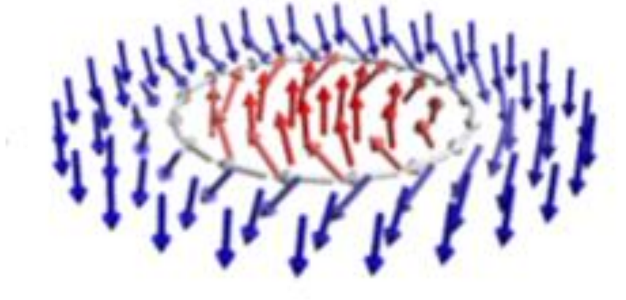
Skyrmion tubes are formed and stable for different granular distributions

Skyrmion

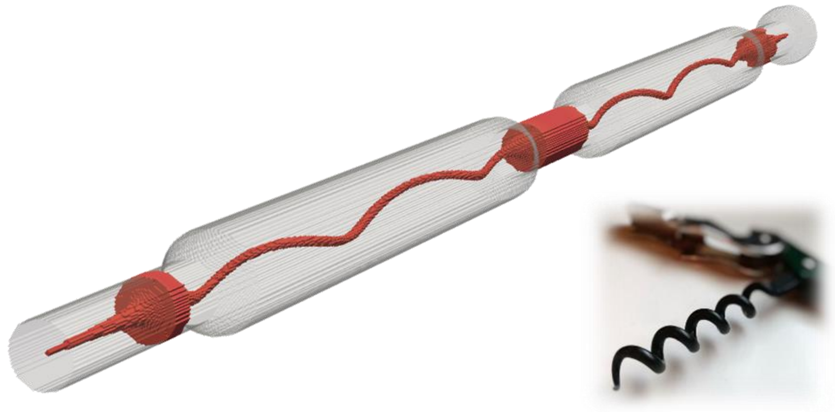
M. Charilaou et al. PRB, 95 (2017), 024409.

What occur's to the magnetization before the switching?





The core of the pinned skyrmion tube describes an helix



Vortices are transformed into skyrmions at H<0. We observe the formation of **Bloch Skyrmion tubes** for the first time :

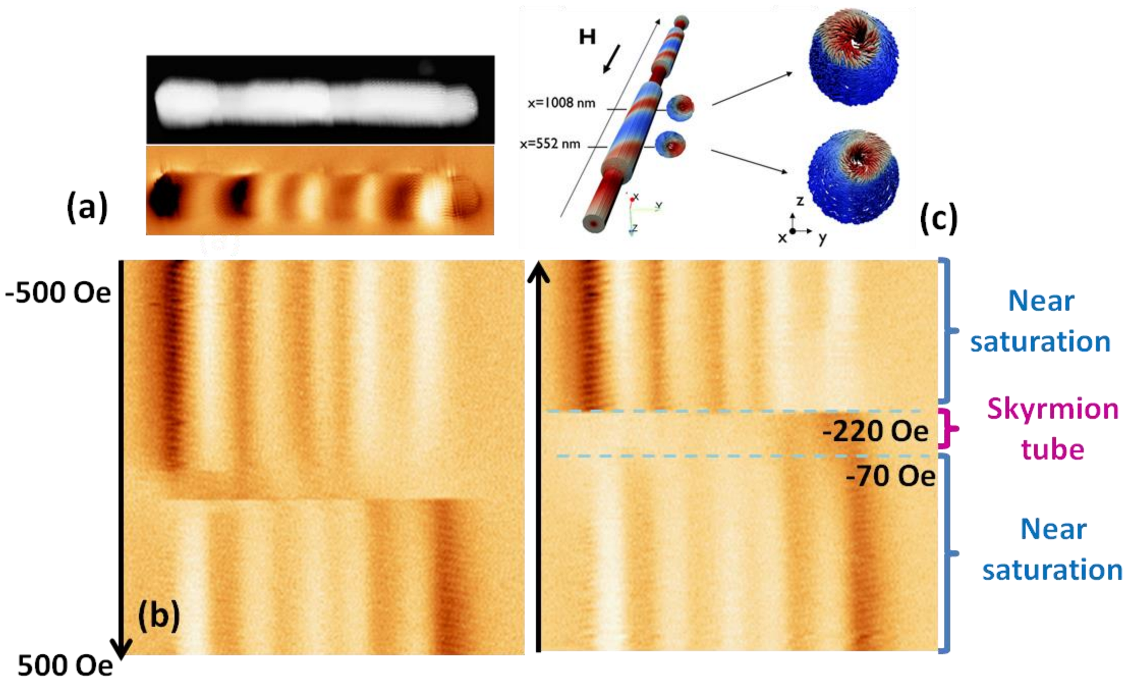
- Skyrmion tubes stabilized by confinement (circular geometry).
- **No intrinsic DMI involved.**
- They have same topology and non zero topological charge than "standard" Bloch skyrmions.

J. A. Fernandez-Roldan et al. *Nanoscale* **10**, 5923–5927 (2018)

3 | Magnetization pinning in FeCo modulated nanowires

MFM evidence of Skyrmion tubes in Modulated FeCo nanowires

Topographic and magnetic images

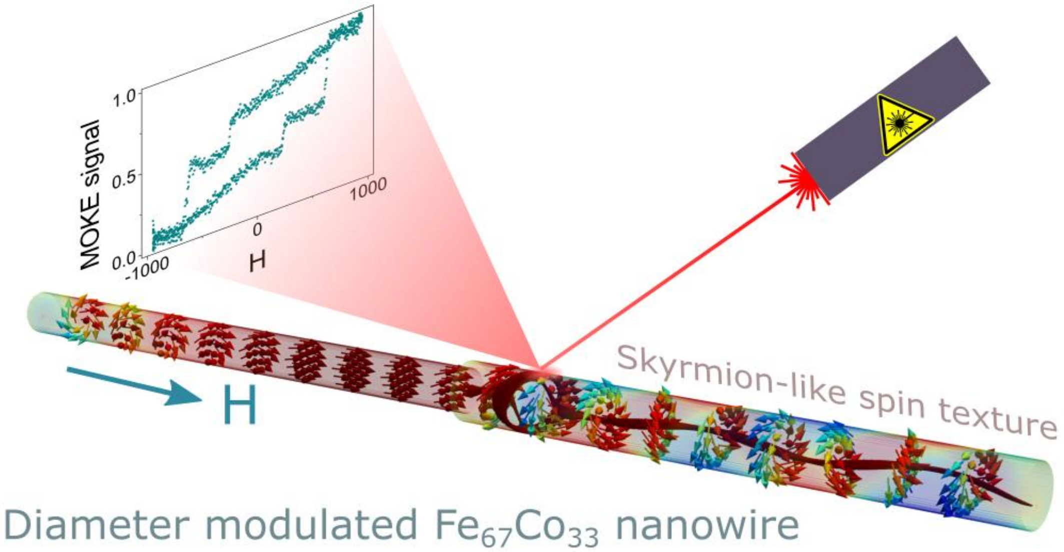


- The magnetic contrast vanished in a certain range of values of the field, previous the magnetization switching.
- The magnetic state of the nanowire in this field range has a low stray field, as skyrmion tubes.

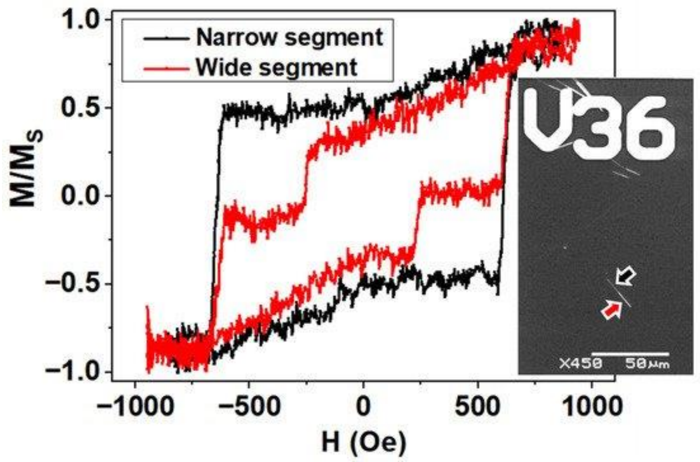
E. Berganza et al., *Materials* **2021**, 14(19), 5671

3 | Magnetization pinning in FeCo modulated nanowires

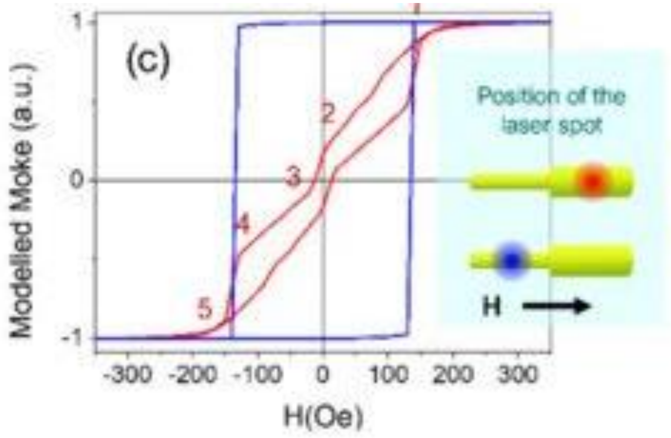
MOKE evidence in a bisegmented FeCo nanowire



nanoMOKE



Modelled MOKE from micromagnetic simulations

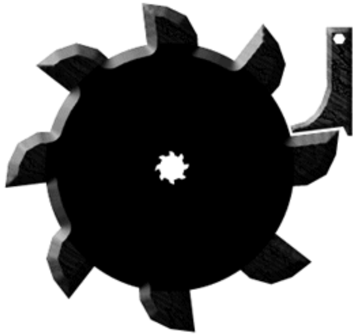


- J. García, et al,. Nanomaterials 11(11), 3077 (2021).
- Related work: EM Palmero et al., Nano Research 12 (7), 1547-1553 (2019)

4 | Ratchet effect in magnetic nanowires

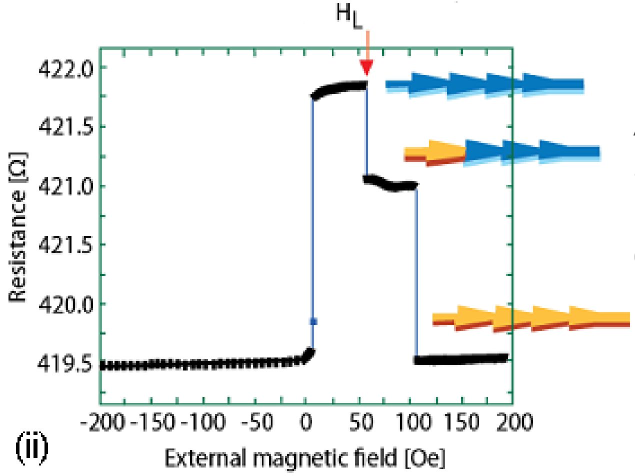
The direction of the reversal process is tailored through compositional modulation

What's a Ratchet ?



A ratchet potential

Resistance of a NiFe/Cu/NiFe nanostrip with notches



A. Himeno et al. J. Appl. Phys. **97**, 066101 (2005)

- **Several systems**: bilayer graphene, antidots arrays, colloidal systems, optical traps, moving cells, skyrmions and domain wall ratchets in shift registers.
- **In nanowires**: artificial necks and notches in a magnetic wire work as a pinning potential for a DW motion.

C. Bran, J.A. Fernandez-Roldan, et al., *ACS nano* (2018)

4 | Ratchet effect in magnetic nanowires

Micromagnetic modelling

Multisegmented FeCoCu/Cu NWs with increasing segment length

Length: 3210 nm
Diameter: 80 nm

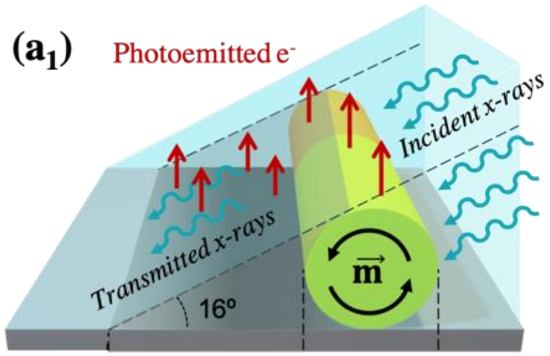
8 segments

- FeCo, Single crystal with *bcc* structure.
- Cu layers considered vacuum

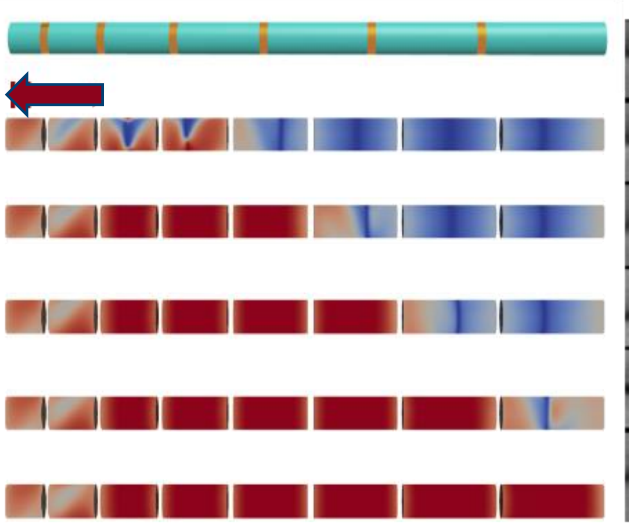
C. Bran, J.A. Fernandez-Roldan, et al., *ACS nano* (2018)

4 | Ratchet effect in magnetic nanowires

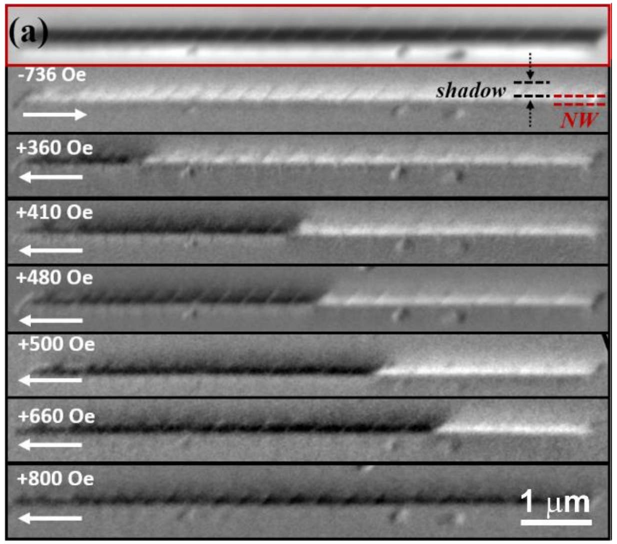
The direction of the reversal process is tailored through compositional modulation



Micromagnetic modelling



XMCD-PEEM



Direction of the magnetization

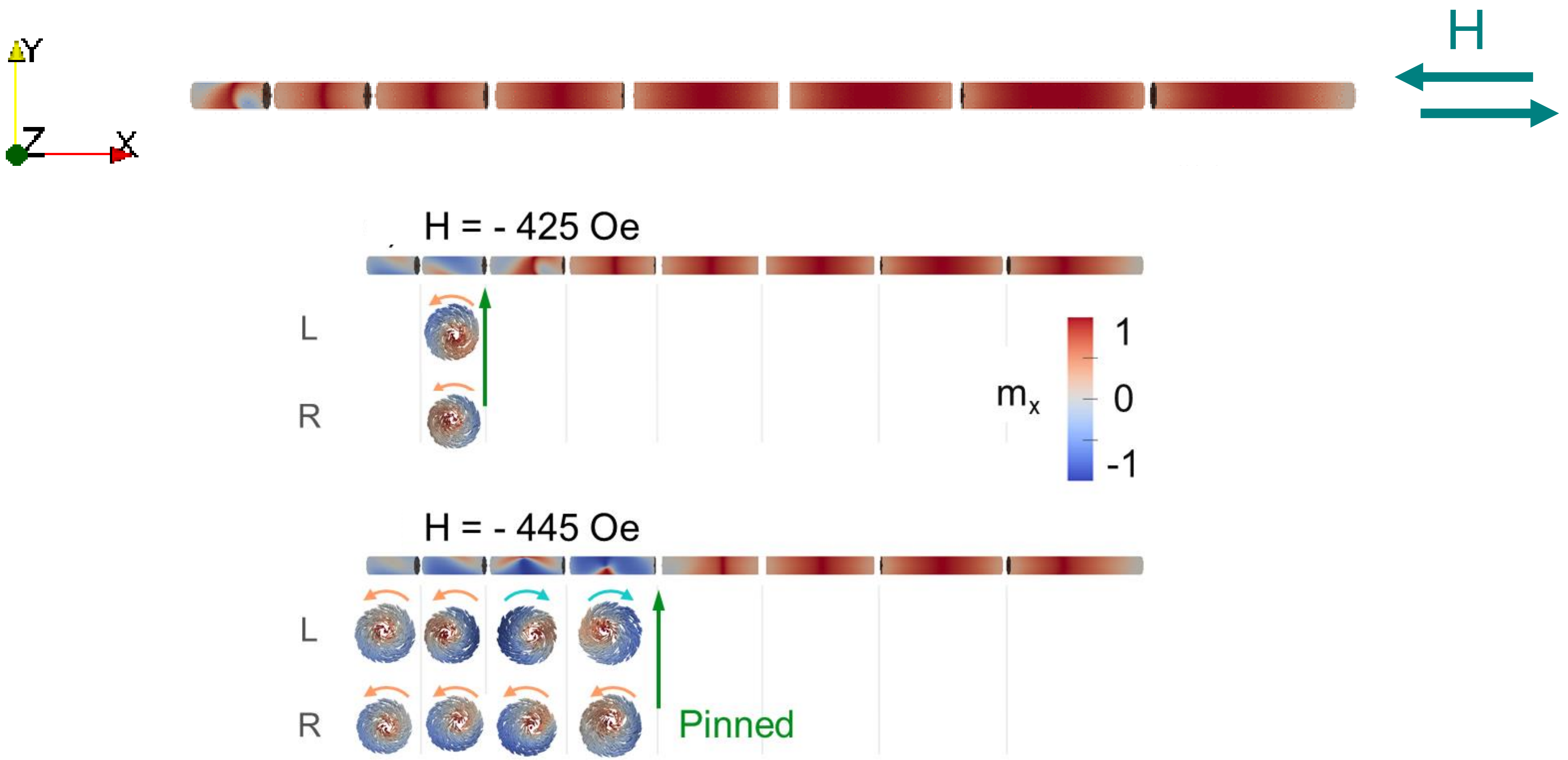
- X-ray Magnetic Circular Dichroism coupled with PhotoElectric Emission Microsopy
- On the right, selected PEEM images under increasing applied field along the leftward ***direction***.

C. Bran, J.A. Fernandez-Roldan, et al., *ACS nano* (2018)

4 | Ratchet effect in magnetic nanowires

Magnetization reversal

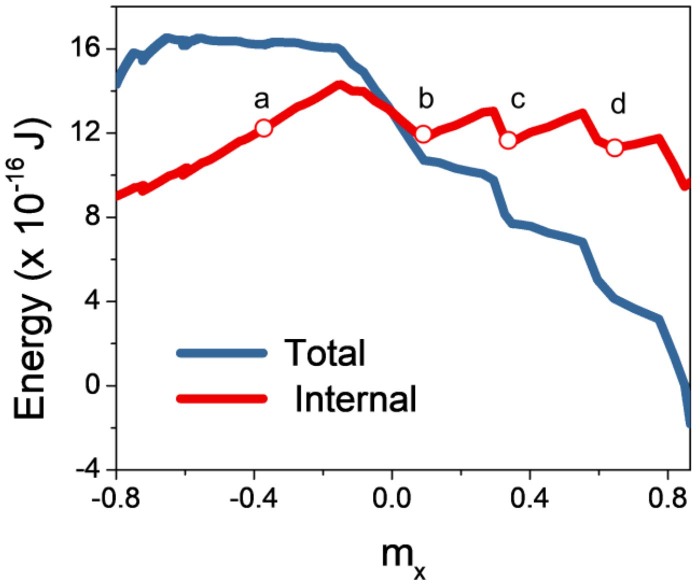
- Demagnetization starts irrespectively of the applied field direction at the end with shorter segments
- Vortices and skyrmion tubes states are formed in each segment, followed by its collapse.



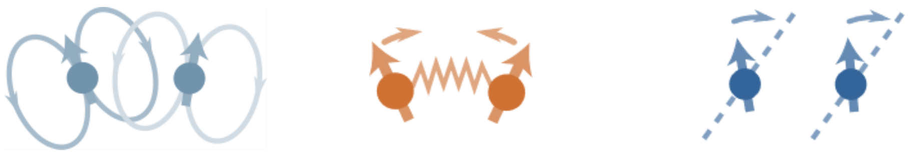
4 | Ratchet effect in magnetic nanowires

Unidirectional magnetization reversal

Ratchet-like potential



Internal energy = **Magnetostatic** + **Exchange** + **Crystalline anisotropy**.



Total energy = **Internal** + **Zeeman**.

- **Cu spacers** promote sequential magnetization reversal and magnetostatic coupling.
- **Large segments** demagnetize simultaneously while the propagation is also sequential. Configurations may be stabilized by the presence of defects in real experiments.
- Ratchet-like potential created by the increasing shape anisotropy.

5 | Multi-domain structures in compositionally modulated nanowires

- $Co_{85}Ni_{15}$/Ni periodically multisegmented cylindrical nanowires with different lengths of the CoNi segment

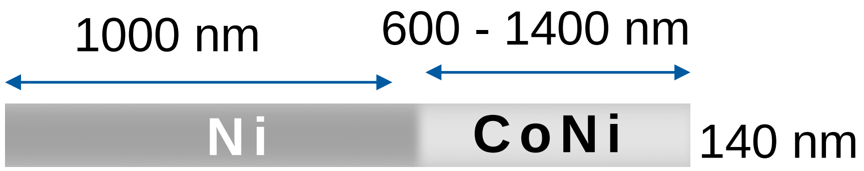
XMCD-PEEM

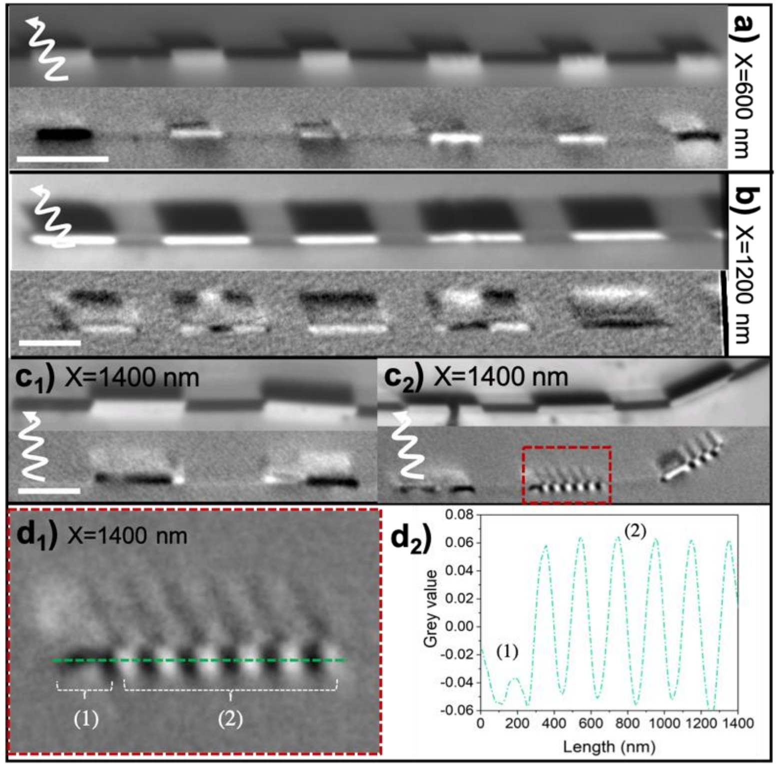
Length of the CoNi segment

600 nm

1200 nm

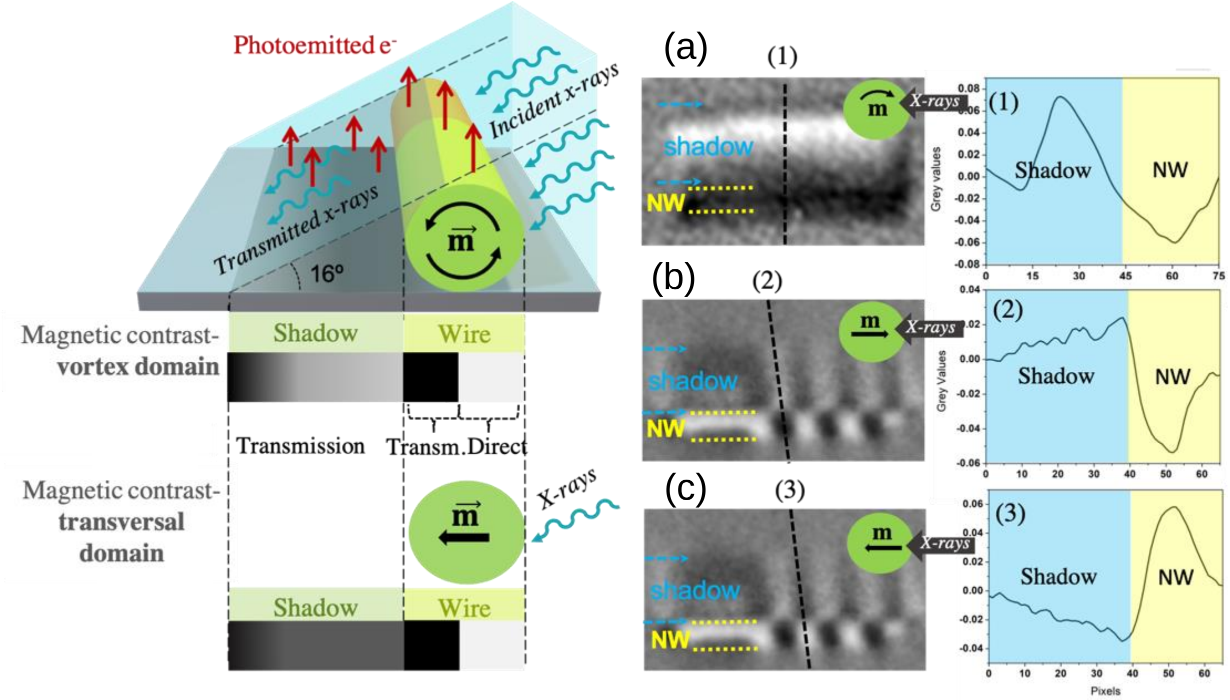
1400 nm





C. Bran, J.A. Fernandez-Roldan, et al., *ACS nano* 2020

5 | Multi-domain structures in compositionally modulated nanowires



Vortex domain

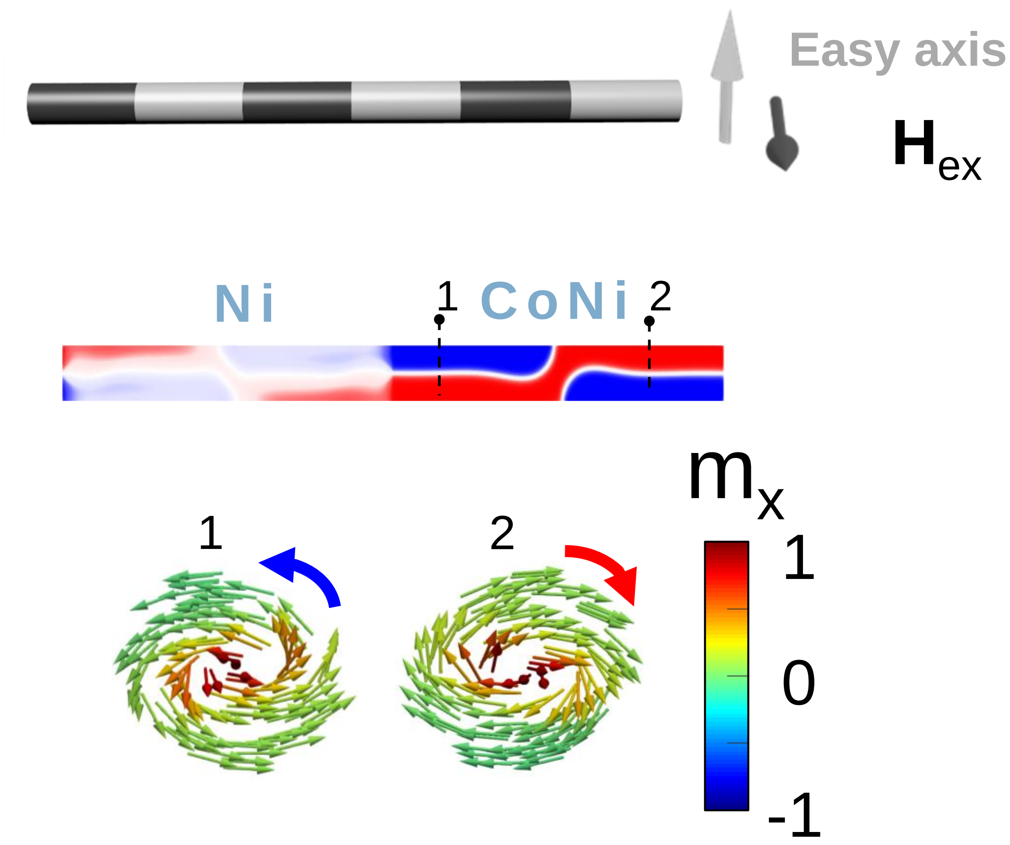
Transversal domain
antiparallel to the X-ray beam

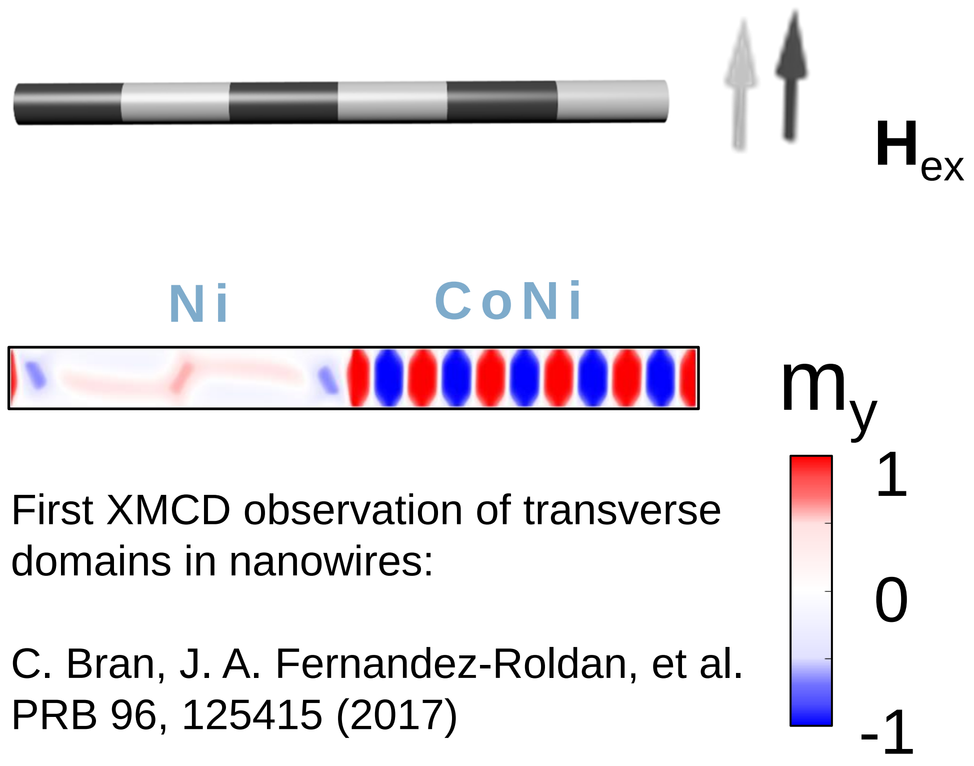
Transversal domain
parallel to the X-ray beam

XMCD contrast on the wire and shadow in:
- (a) A vortex domain
- (b)-(c) transversal domains plotted along the dashed black lines marked in the XMCD images.

C. Bran, J.A. Fernandez-Roldan, et al., *ACS nano* 2020

Unveiling the origin of magnetic domains of type vortex or transverse



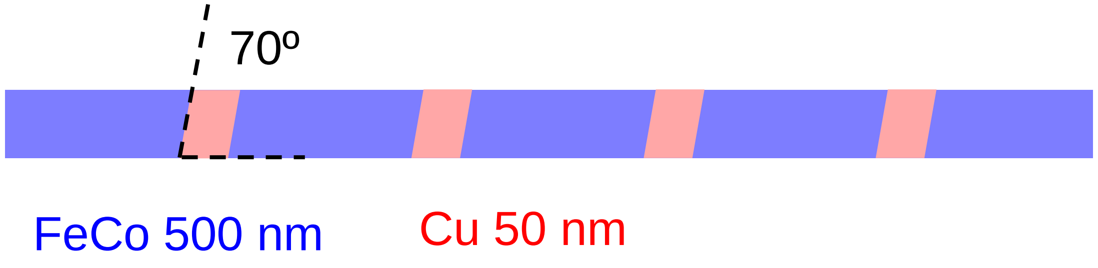


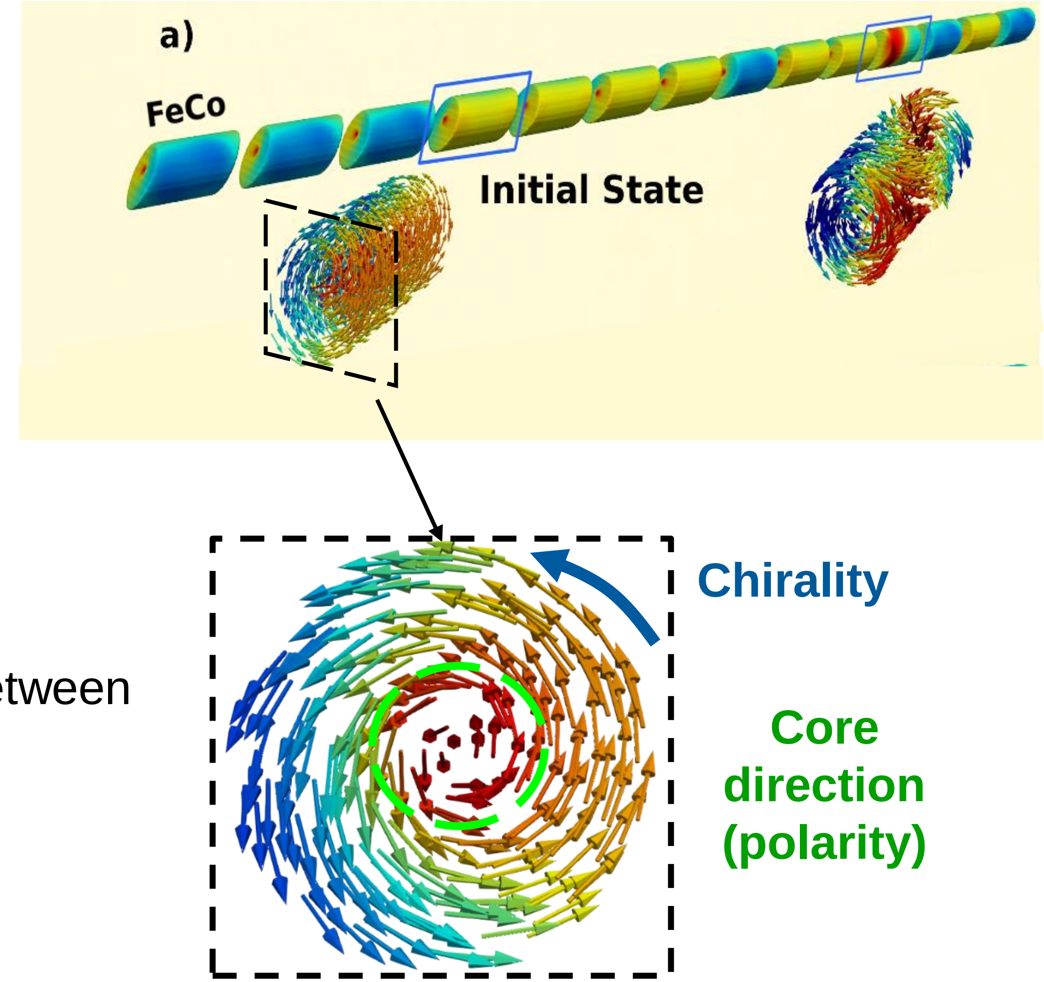
First XMCD observation of transverse domains in nanowires:

C. Bran, J. A. Fernandez-Roldan, et al. PRB 96, 125415 (2017)

C. Bran, J.A. Fernandez-Roldan, et al., *ACS nano* 2020

6 | Stochastic vs. deterministic switching in multisegmented nanowires



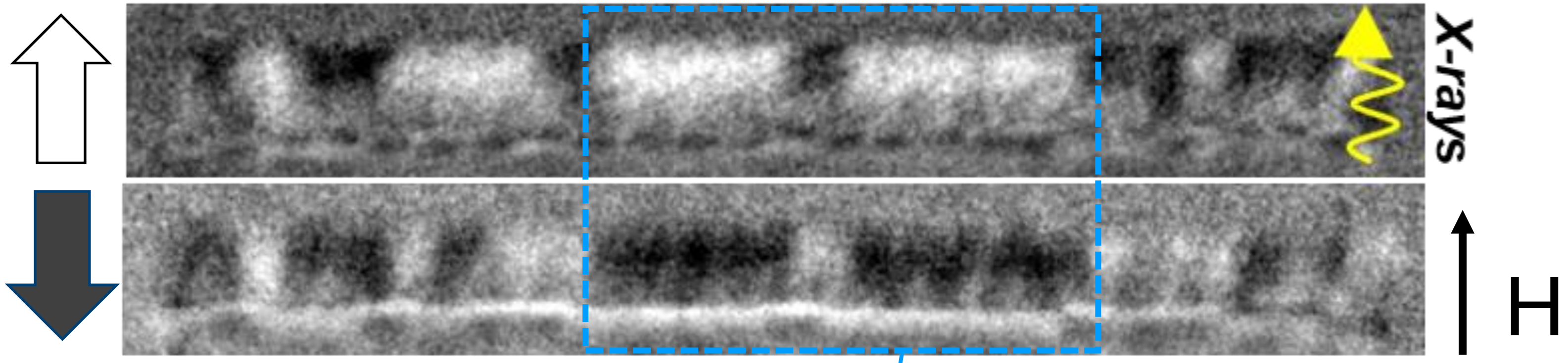


- FeCo-Cu nanowires of 100 nm diameter
- The tilting of 30º degrees of the geometrical surfaces between segments introduces an asymmetry.
- FeCo segments in a 3D vortex state (weakly coupled)

C. Bran et al., *Nanoscale* **13**,12587 (2021)

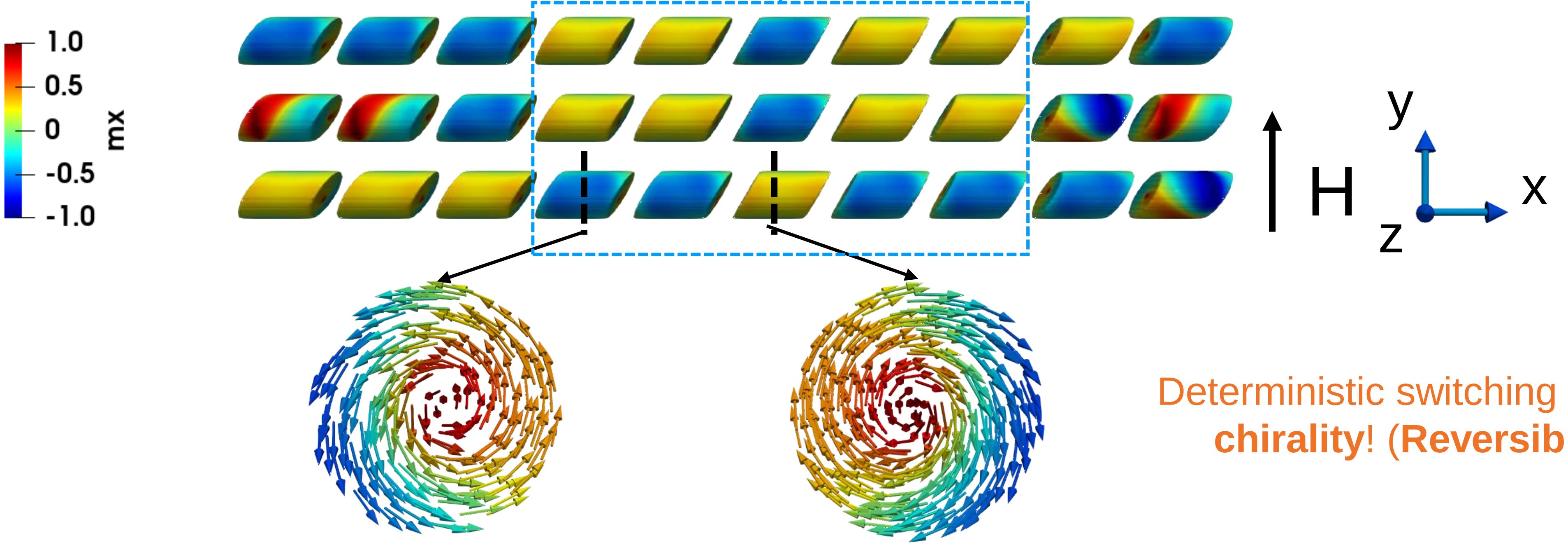
An example:

X-ray Magnetic Circular Dichroism (XMCD-PEEM)



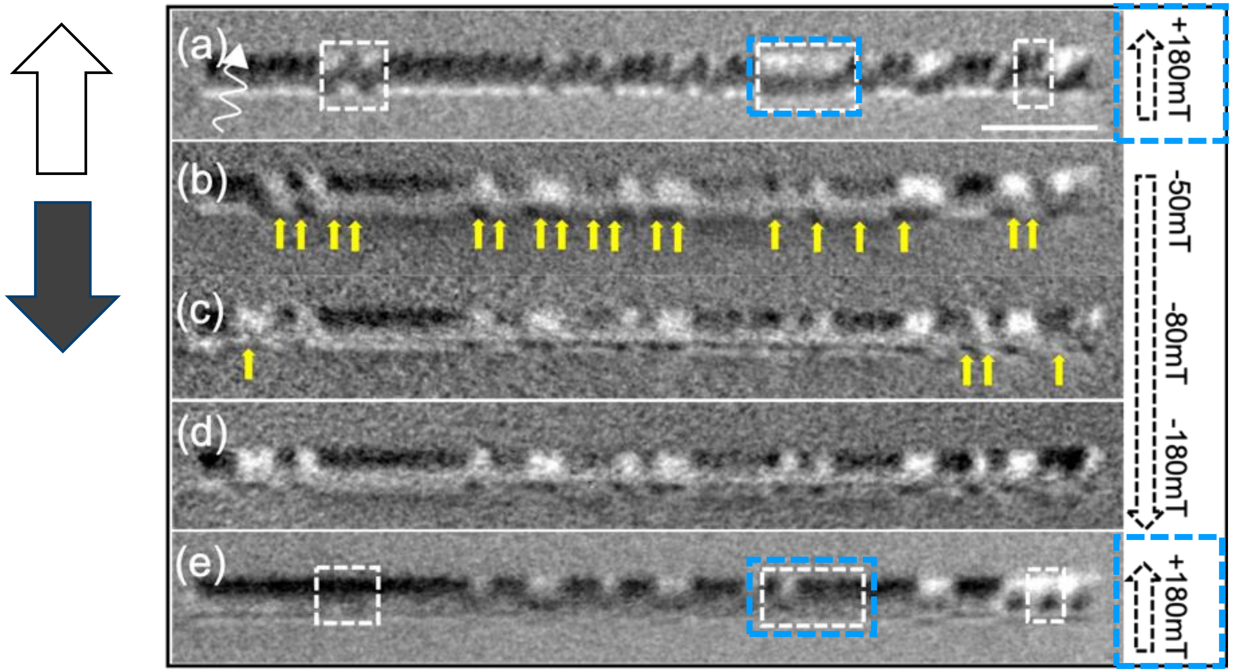
Remanence after H=140 mT

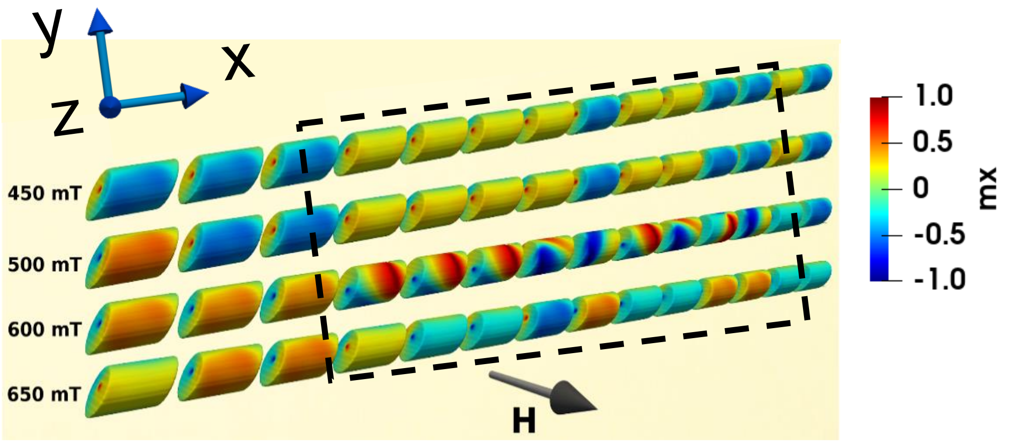
Micromagnetic switching process:



Deterministic switching of the **chirality**! (**Reversible**)

C. Bran et al., *Nanoscale* **13**,12587 (2021)





Stochastic switching of the **chirality and polarity** of the vortices! (**Irreversible**)

1. We have determined <u>the conditions for simultaneous stochastic and deterministic coding of the multivortex state</u> on the same wire.
2. These suggest that <u>for stochastic computing, each nanowire could be set as a sequence of bits.</u>

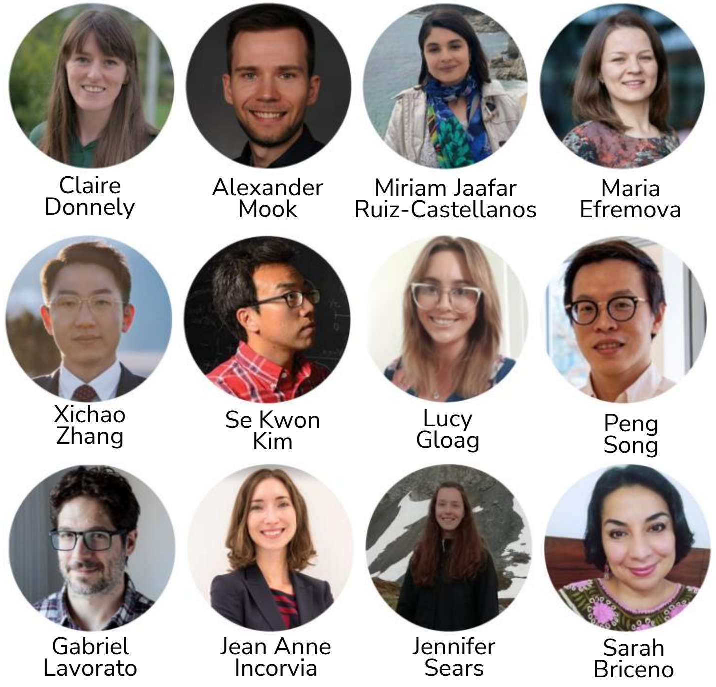
C. Bran et al., *Nanoscale* **13**,12587 (2021)

IEEE Around-the-Clock Around-the-Globe (AtC-AtG) 2022

AUGUST 31

24-hour non-stop virtual conference on magnetism

Invited Speakers



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- Covers all continents and time zones
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Thank you for your attention

Gracias por su atención

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