Imprinting superconducting vortex trajectories in a magnetic layer

Gorky Shaw

Experimental physics of nanostructured materials
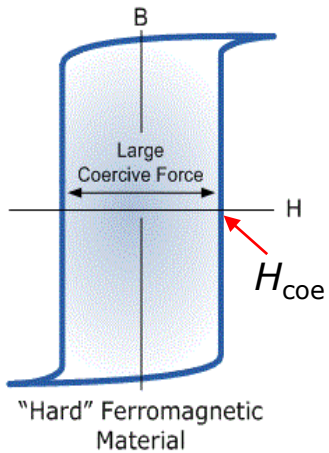*Physics Department, University of Liège*
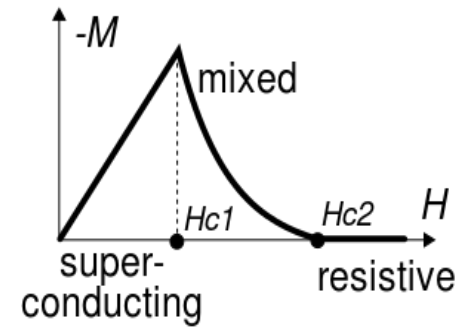*BELGIUM*

Supervisor: Alejandro V. Silhanek

Université de Liège
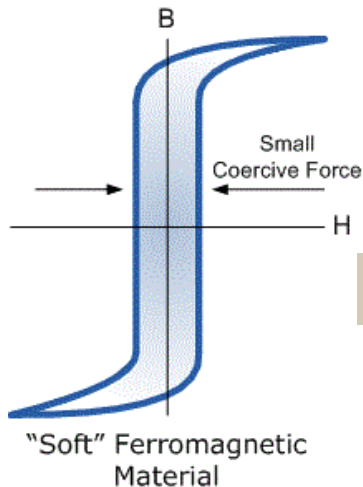
LABORATORY OF PHYSICS OF NANOSTRUCTURED MATERIALS

Superconductor-Ferromagnet hybrids

"Hard" Ferromagnetic Material

H_{coe}

Hard magnets: $H_{coe} \gg H_{c2}$

Modifications in F-layer ➡ modifications in S-layer

"Soft" Ferromagnetic Material

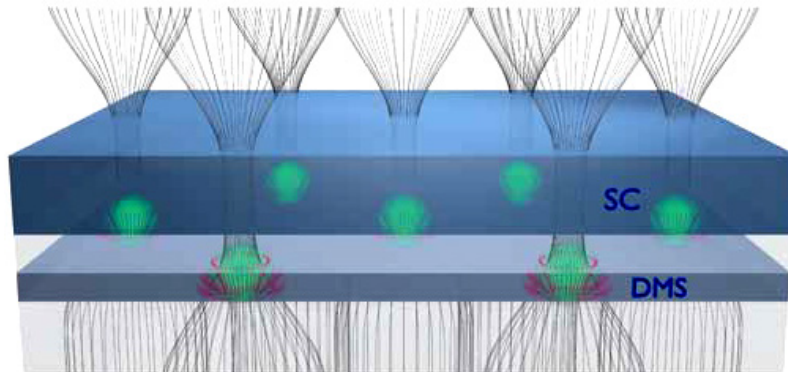**Soft magnets:** $H_{coe} \lesssim H_{c2}$

Modifications in F-layer ⬌ modifications in S-layer
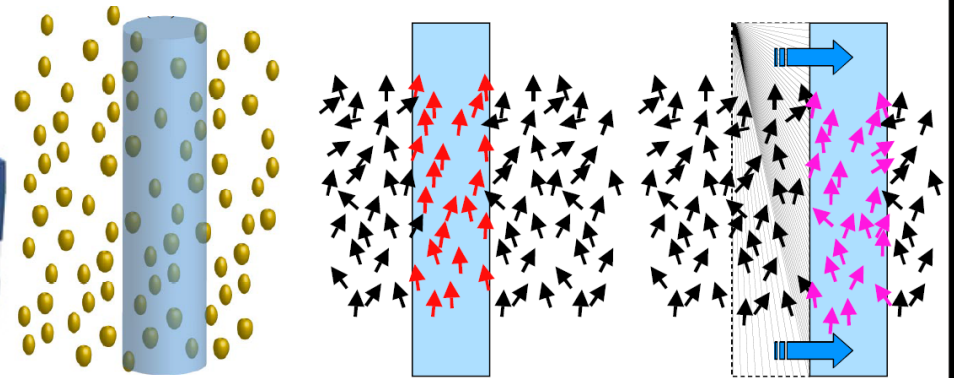
Superconductor+ Soft Ferromagnet

Local polarization of ferromagnetic material by stray field of a vortex

Superconductor +
Diluted magnetic semiconductor

Nb + Gd

Theoretical study.
(Berciu *et al* (2005) *Nature* **435**, 71-75).

Experimental evidence.
(Palau *et al* (2007) *Phys. Rev. Lett.* **98,** 117003).

Superconductor+ Soft Ferromagnet

Vortex as tiny magnetic scriber?

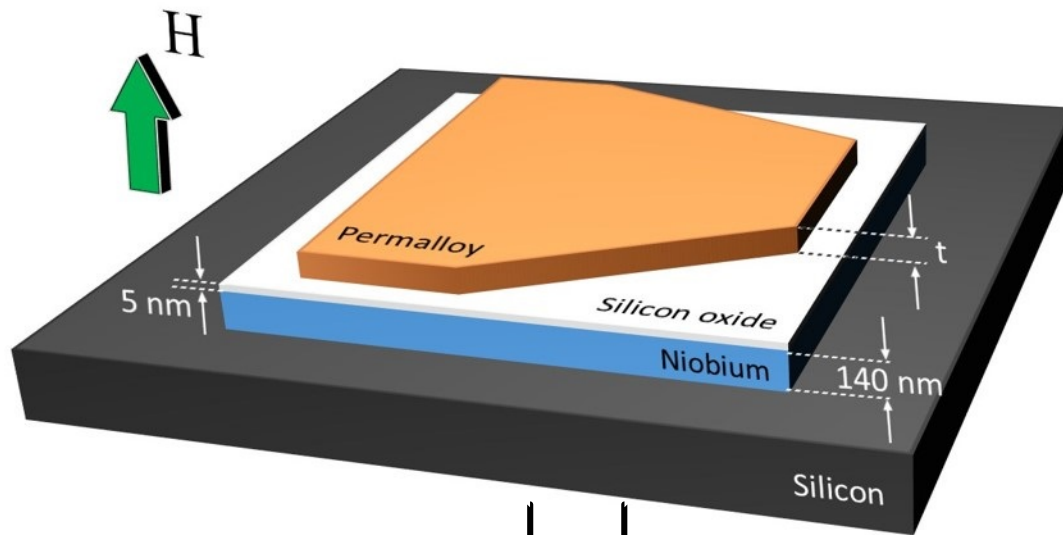Permalloy | 81% Ni and 19% Fe
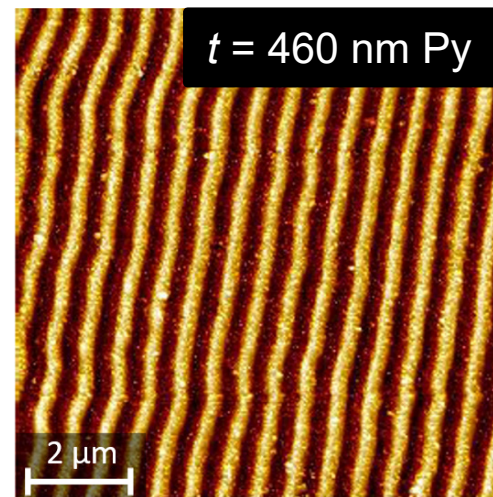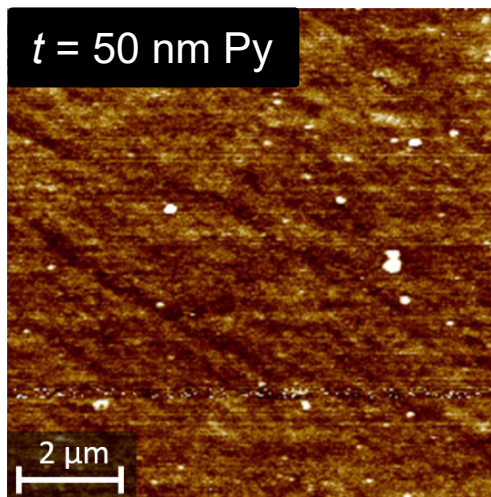
Low coercivity, high permeability | $H_{coe} \sim$ few mT

Easy-to-manipulate magnetic medium

Nb-Py hybrid system

H

5 nm

Permalloy

Silicon oxide

Niobium

t

140 nm

Silicon

Nb 2 mm × 2 mm
T_c = 9 K

t = 50 nm Py

2 μm

MFM images

Distinct magnetic
landscapes

t = 460 nm Py

2 μm

Imprinting superconducting vortex footsteps in a magnetic layer
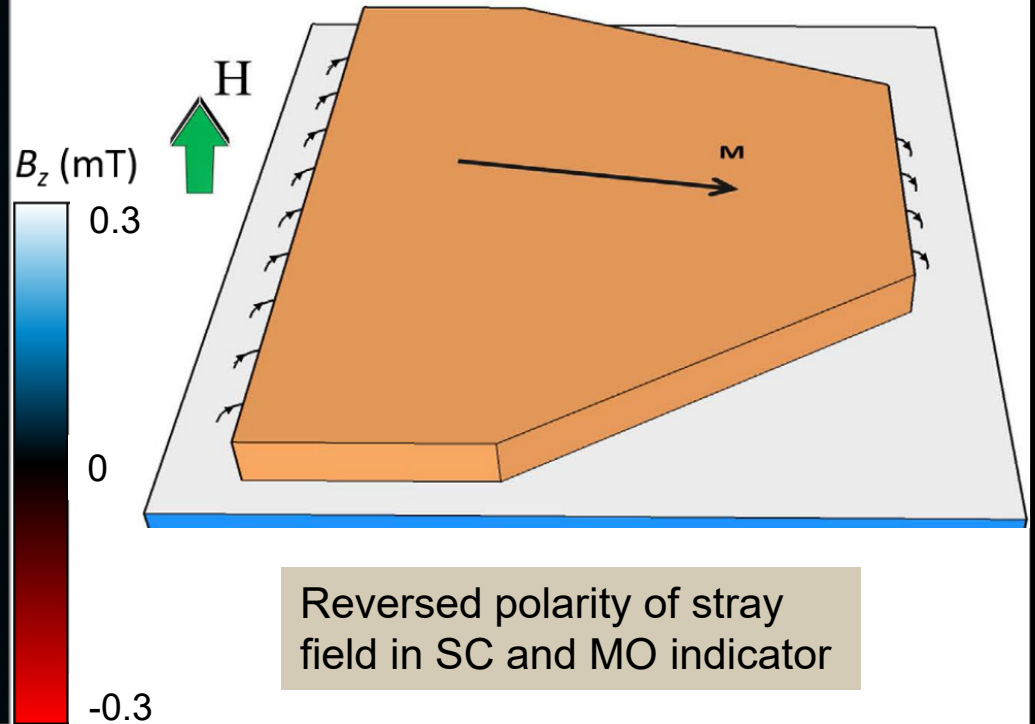J. Brisbois *et al* (2016), *Sci. Rep.* **6**, 27159.

Nb-Py hybrid system

H

Permalloy
5 nm
Silicon oxide
Niobium
t
140 nm
Silicon

t = 50 nm Py

2 µm
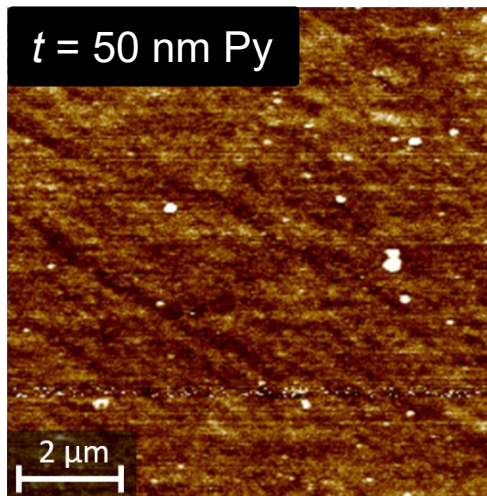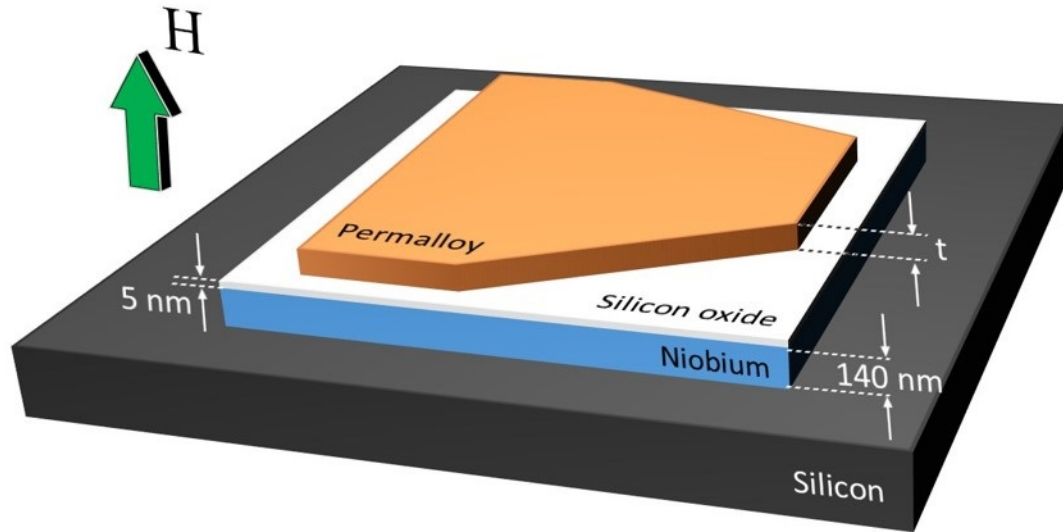
Thin Py:
Imprinting vortex trajectories in the permalloy

Magnetic properties of the permalloy layer
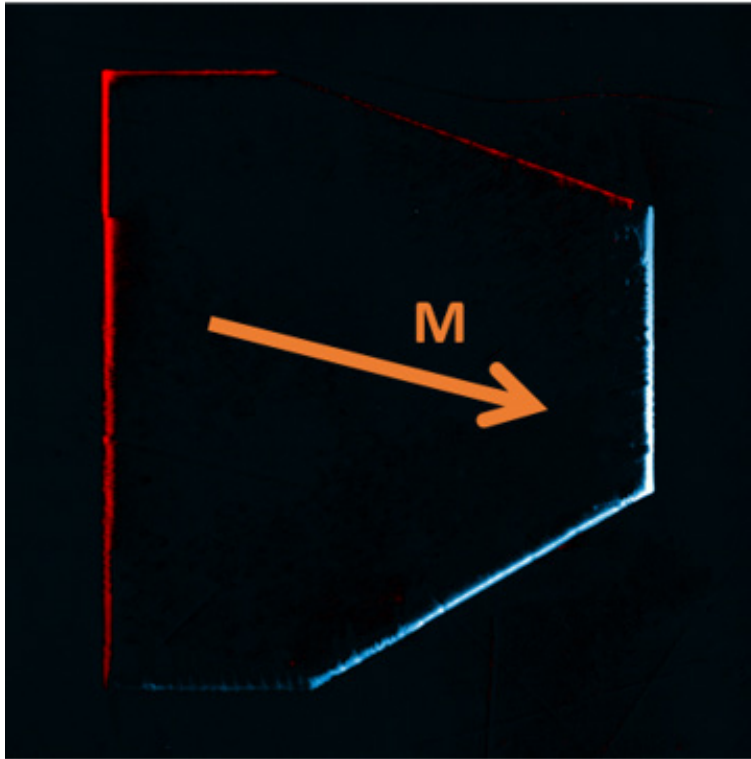
Magneto-optical image

B_z (mT)
0.3
0
-0.3

$\mu_0 H_{||,sat} \sim 2$ mT

H

M

Reversed polarity of stray field in SC and MO indicator

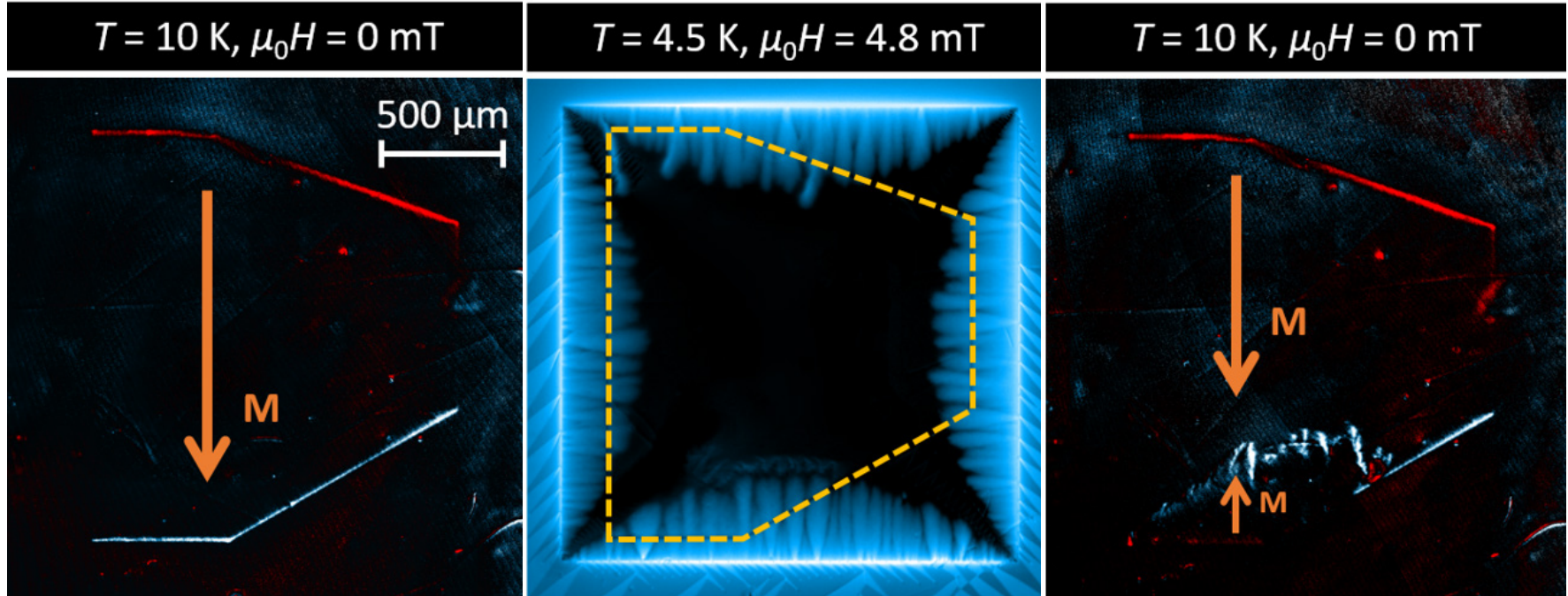Vortices of opposite polarity on red and blue-white edges

Red edge

Blue-White edge

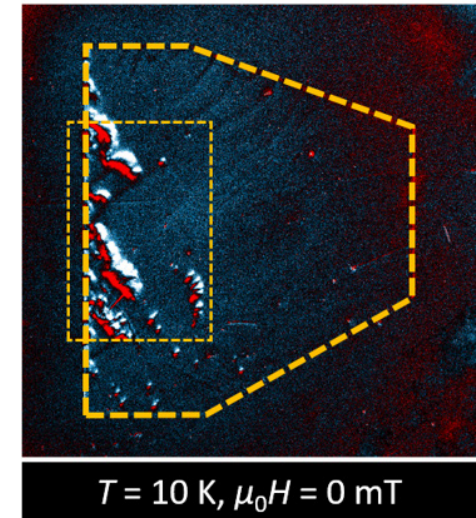# Imprinting vortex trajectories in the permalloy layer

$T = 10$ K, $\mu_0 H = 0$ mT | $T = 4.5$ K, $\mu_0 H = 4.8$ mT | $T = 10$ K, $\mu_0 H = 0$ mT
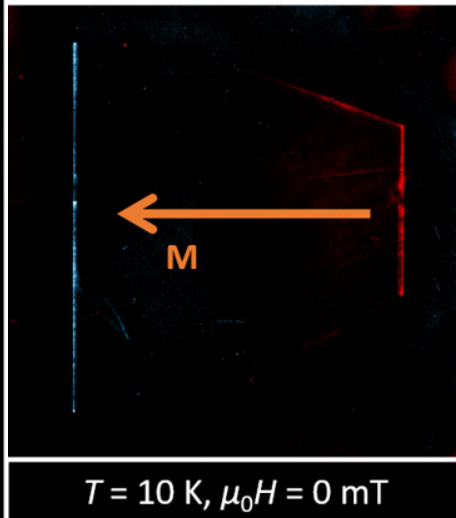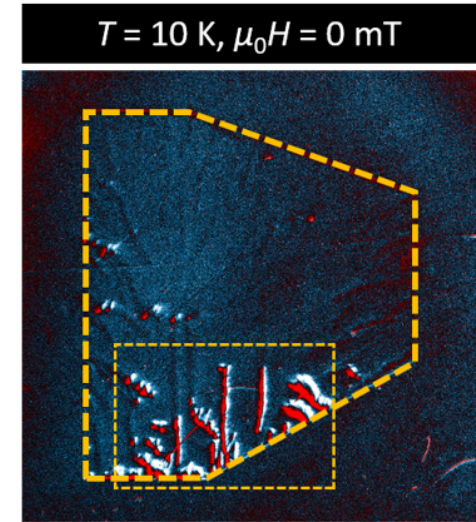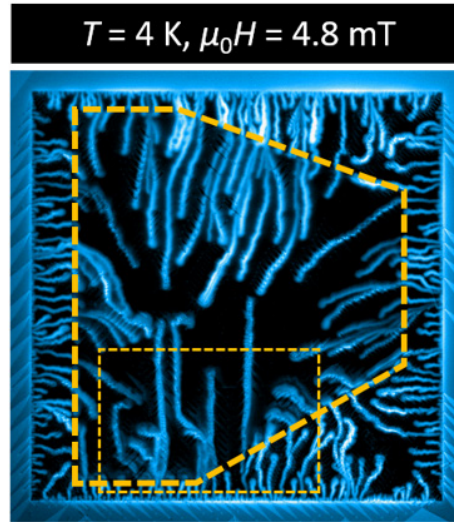
500 µm

M

- Smooth flux penetration into Py region.

- Clear imprint of flux penetration in the Py layer.
- Reversal of in-plane magnetization leaves head-to-head domain wall.

Imprinting vortex trajectories in the permalloy layer

Blue-White edge: Antivortices

Red edge: Vortices

$T = 10 \text{ K}, \mu_0 H = 0 \text{ mT}$
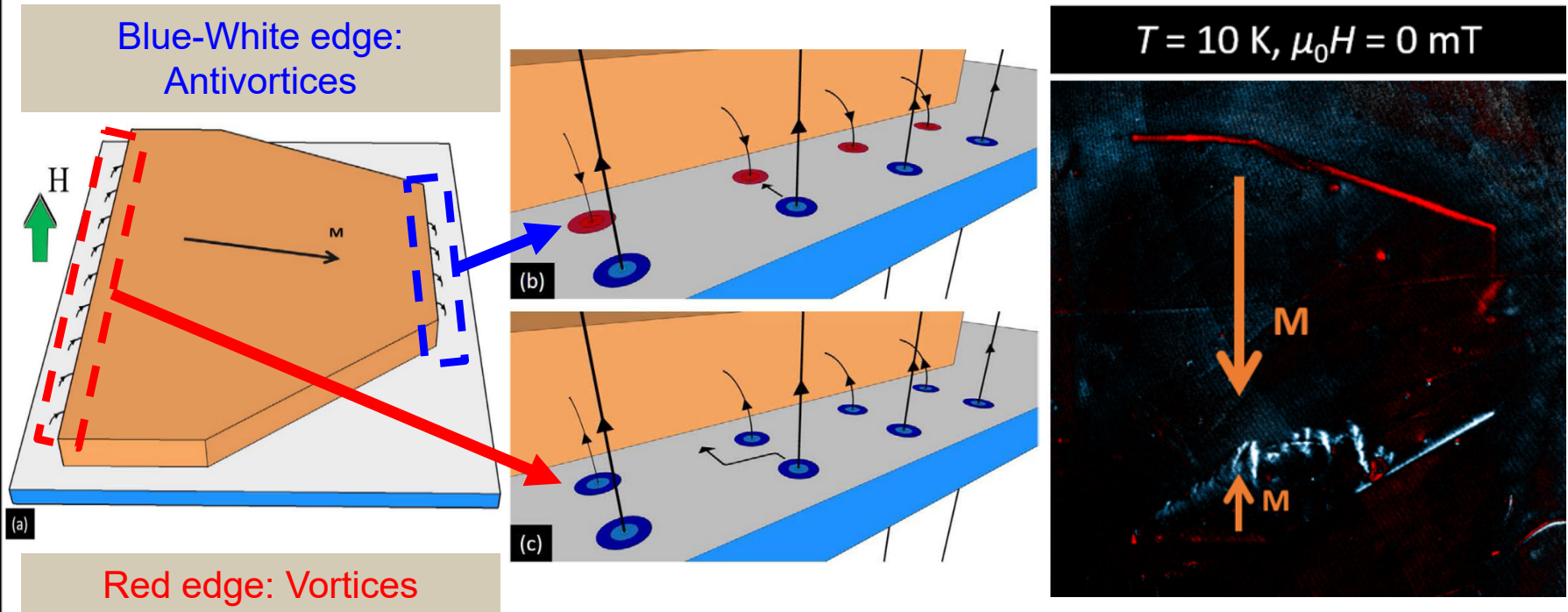
- Flux front progressing against **M** impeded upon encounter with antivortices.

- Advancing flux front generates large enough $\mathbf{B}_\parallel$ to switch **M** in Py layer.

- Vortex trajectories imprinted.

Imprinting flux avalanches

$T = 10$ K, $\mu_0 H = 0$ mT

500 μm

M

$T = 10$ K, $\mu_0 H = 0$ mT

M

$T = 10$ K, $\mu_0 H = 0$ mT

$T = 4$ K, $\mu_0 H = 4.8$ mT

$T = 4$ K, $\mu_0 H = 4.8$ mT

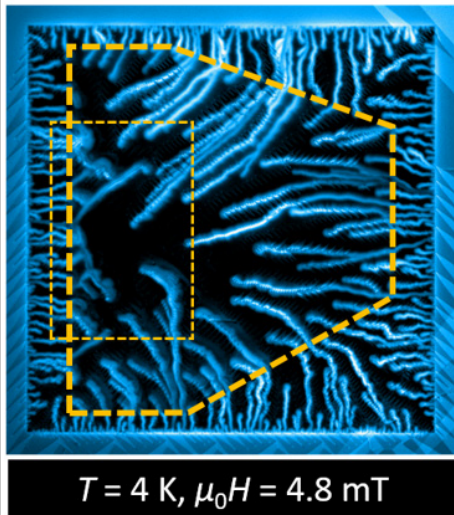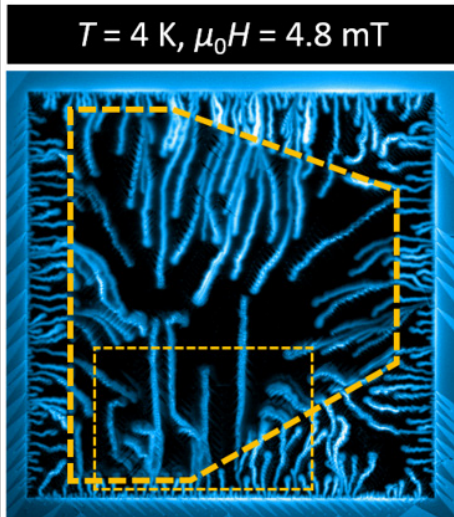$T = 10$ K, $\mu_0 H = 0$ mT

$T = 10$ K, $\mu_0 H = 0$ mT
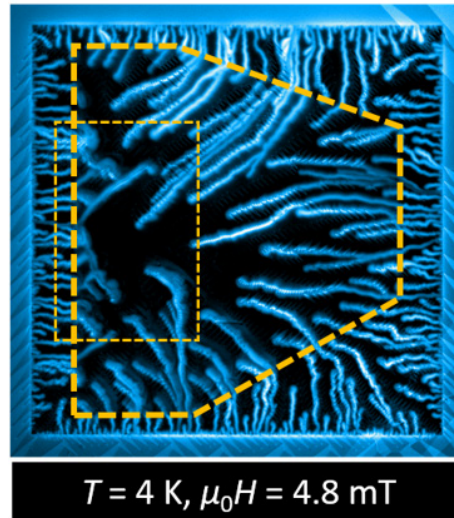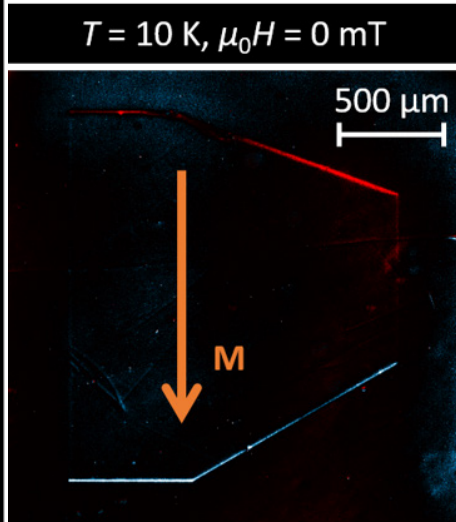
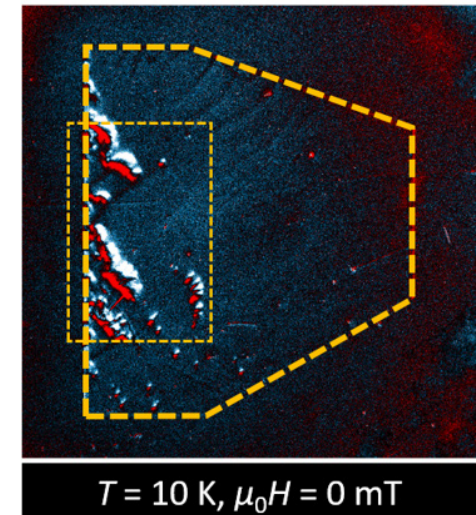- Flux avalanches undergo deflection of trajectories.
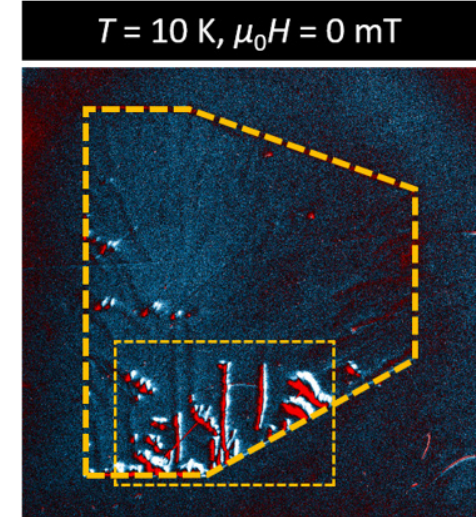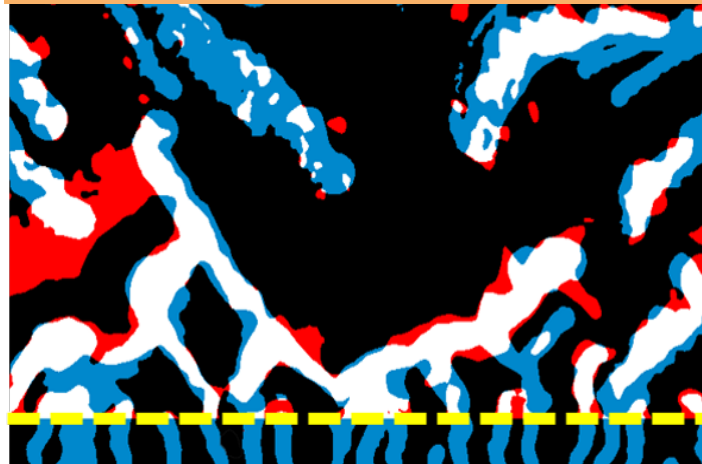- Avalanches imprinted.
- Excellent correlation between position of avalanches and their imprints.

Imprinting flux avalanches

$T = 4\,K,\ \mu_0 H = 4.8\ \text{mT}$

$T = 10\,K,\ \mu_0 H = 0\ \text{mT}$

Imprinting is stable, even up to **room temperature**!

$T = 4\,K,\ \mu_0 H = 4.8\ \text{mT}$

$T = 10\,K,\ \mu_0 H = 0\ \text{mT}$

- Superposition of binary images: (low **B** black, avalanches blue, imprints red).

- White: Avalanches and imprints overlap → Excellent correlation.
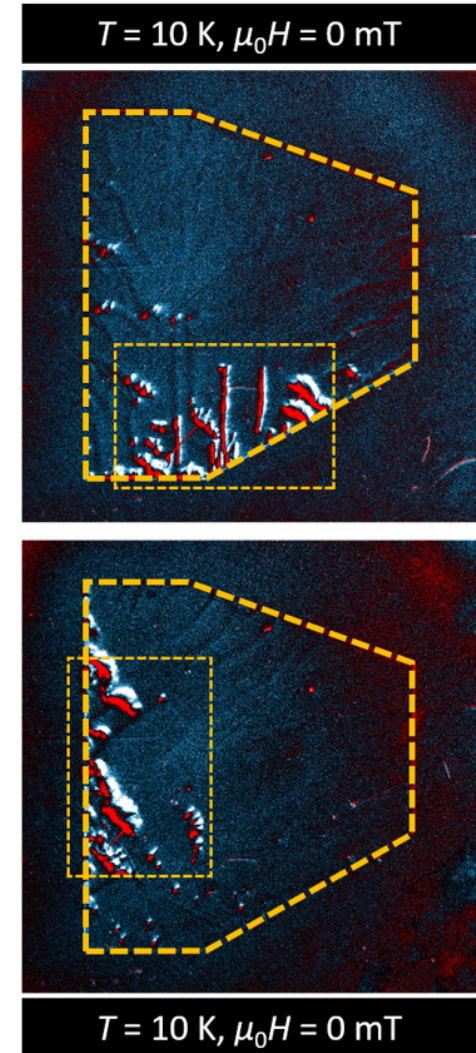
11

Nature of imprints

- Imprints seem to correspond to head-to-head domain walls pointing up and down, and delimiting interfaces between regions of different **M**.

- Also weak traces on whole surface of the Py layer.

- Similar to Bloch and Néel domain walls identified by Uspenskaya *et al*.

$T = 10\ \text{K},\ \mu_0 H = 0\ \text{mT}$

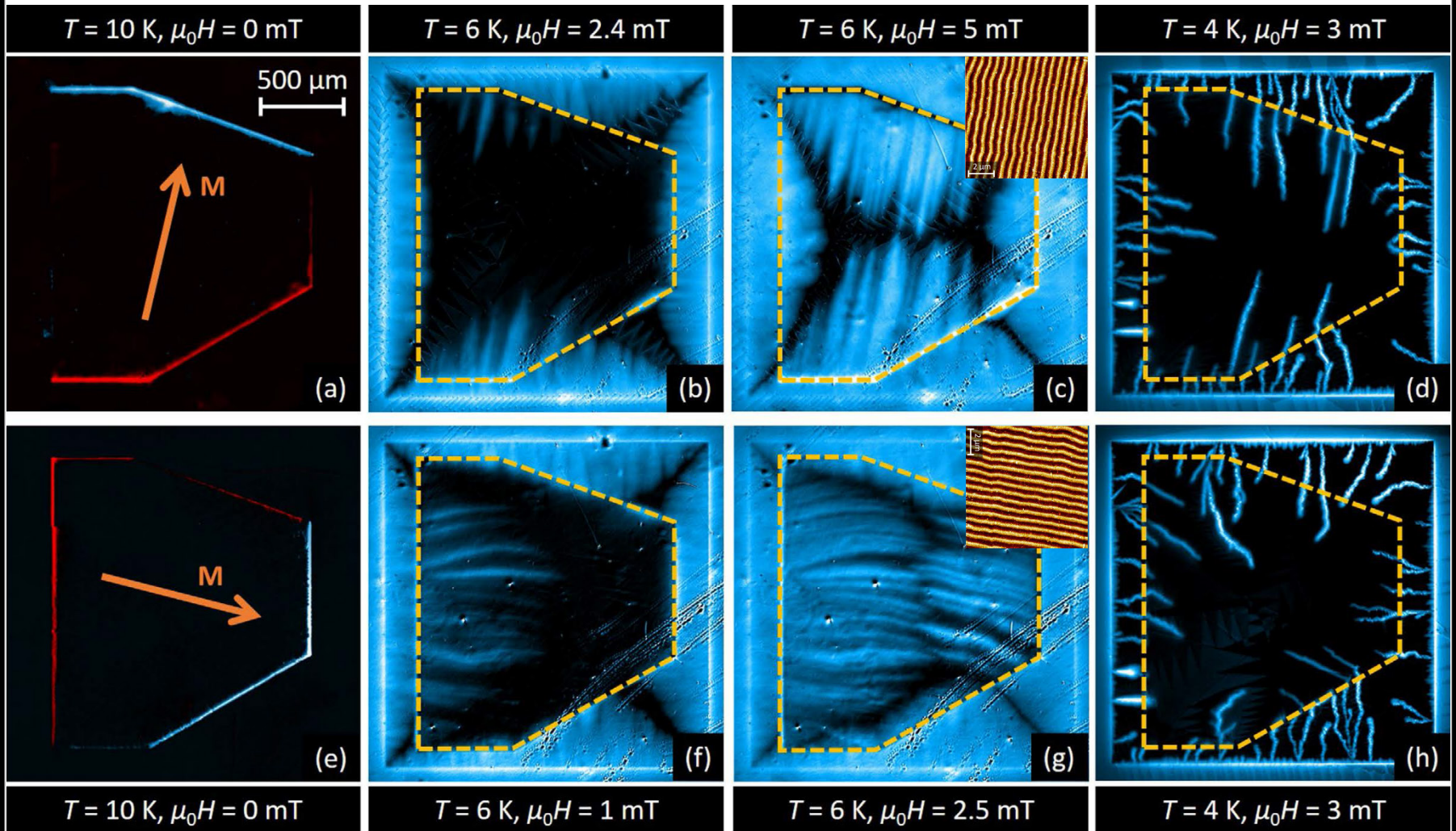$T = 10\ \text{K},\ \mu_0 H = 0\ \text{mT}$
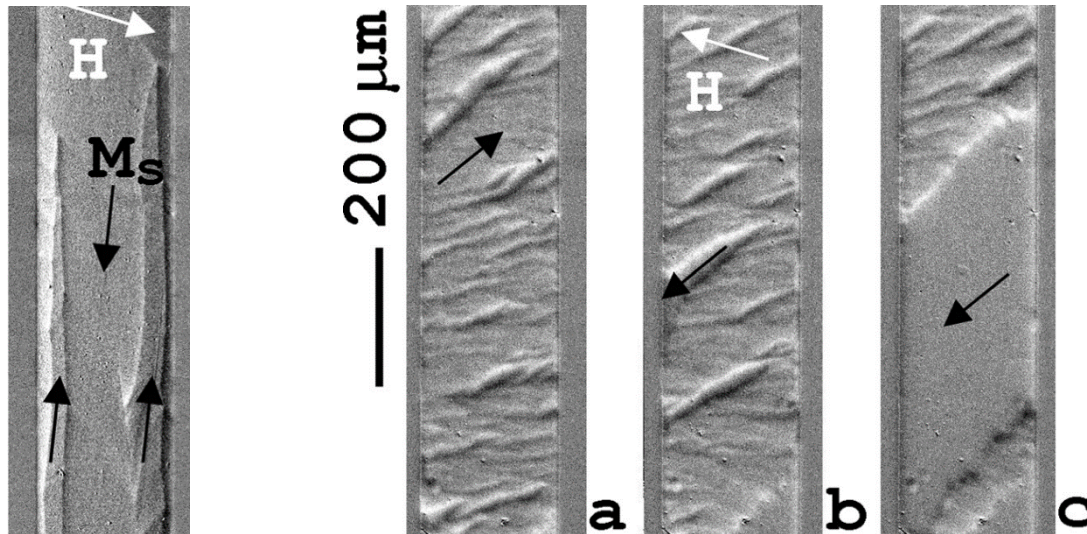
Domain structure of a Py 30 nm/Nb 60 nm bilayer under magnetic field.

Domain structure of a Py 20 nm/Nb 100 nm bilayer formed during the magnetization reversal under magnetic field.

Uspenskaya *et al* (2013) *J. Appl. Phys.* **113**, 163907.
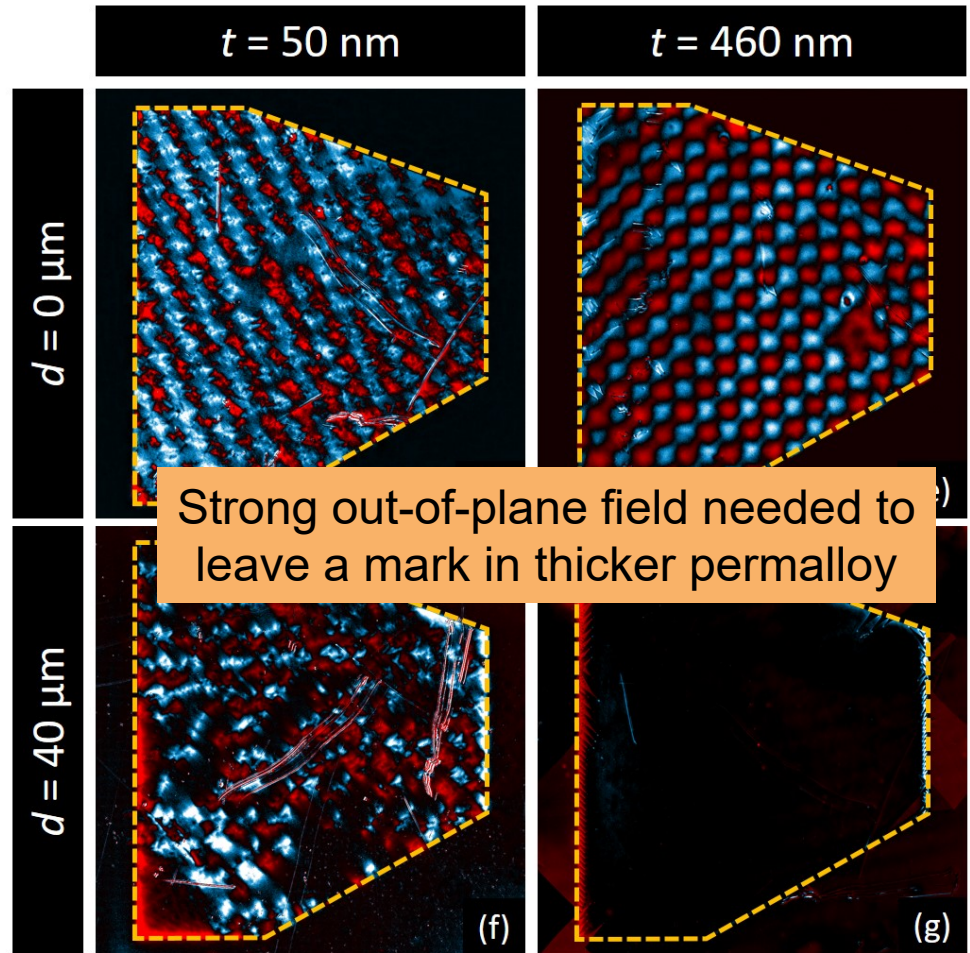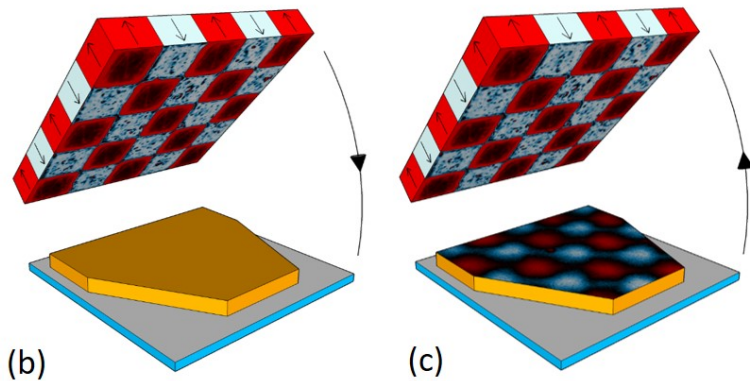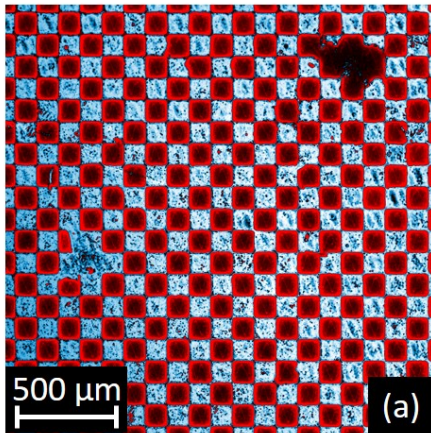
Flux guidance in thick permalloy

$T = 10$ K, $\mu_0 H = 0$ mT	$T = 6$ K, $\mu_0 H = 2.4$ mT	$T = 6$ K, $\mu_0 H = 5$ mT	$T = 4$ K, $\mu_0 H = 3$ mT

500 μm

M

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

(e) (f) (g) (h)

M

$T = 10$ K, $\mu_0 H = 0$ mT	$T = 6$ K, $\mu_0 H = 1$ mT	$T = 6$ K, $\mu_0 H = 2.5$ mT	$T = 4$ K, $\mu_0 H = 3$ mT

- Asymmetry in flux penetration.
- Flux guidance along magnetic domains.
- **NO Imprinting.**

Room temperature imprinting

Transferring a pattern from a hard magnet (NdFeB) to the permalloy

500 µm

(a)

(b)

(c)

$t = 50$ nm

$t = 460$ nm

$d = 0$ µm

$d = 40$ µm

Strong out-of-plane field needed to leave a mark in thicker permalloy
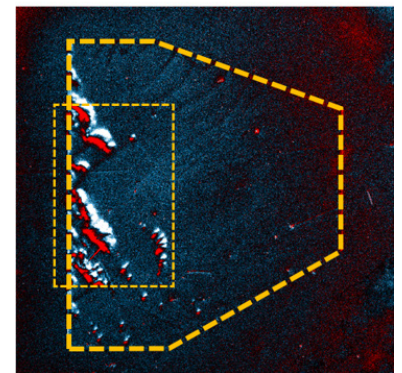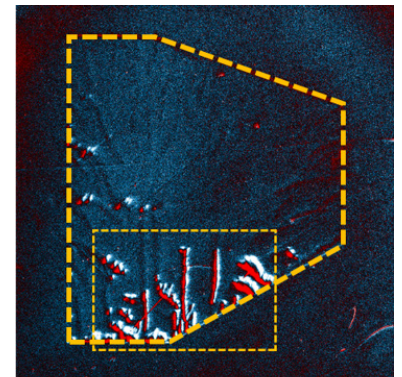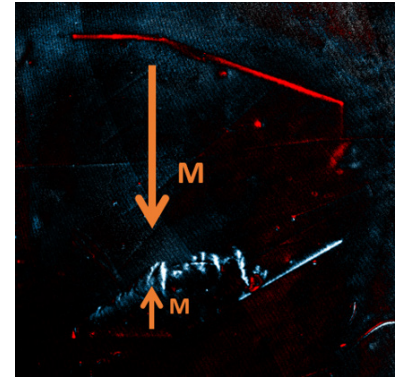
(f)

(g)

Conclusions

- Imprinting of vortex trajectories observed in Nb-Py hybrids.

- Excellent correlation between flux avalanches and their imprints.

- Possibility to visualise imprinting *ex situ*.

- Thickness of Py layer critical parameter.

Next: single vortex imprints?

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Pierre Colson, Benoît Vanderheyden, Philippe Vanderbemden (*Liège*)

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Thank You