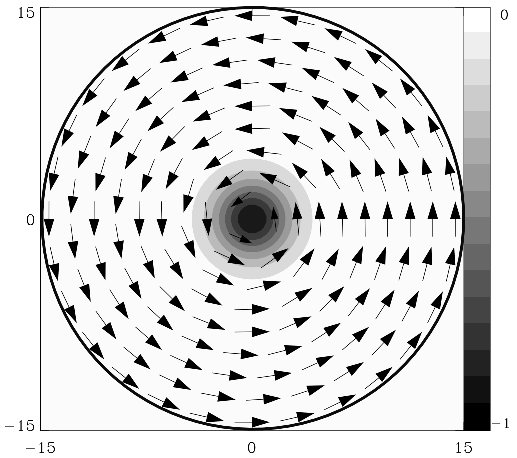
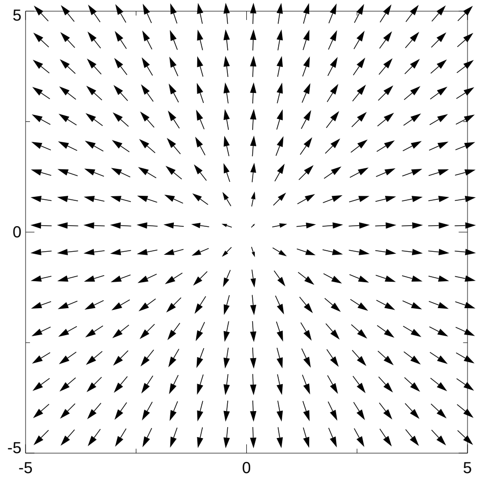
Dynamics of magnetic vortices

Outline

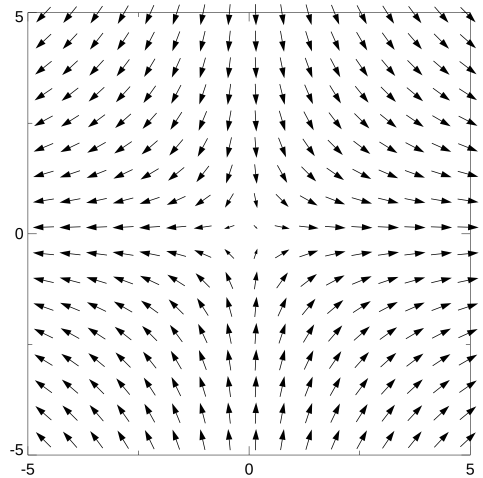
- A magnetic vortex
- Recent experiments
- Phenomenology: the Hall effect
- Topological charge of a vortex
- Vortex-antivortex pairs

A magnetic vortex





x



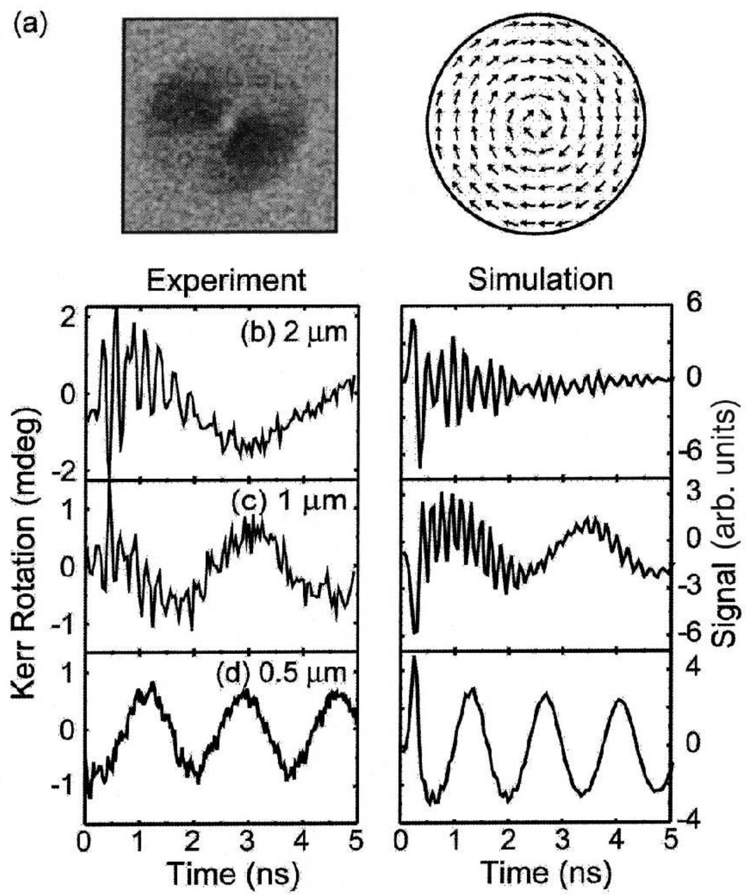
Vortex number (circulation): $\kappa = \pm 1(\pm 2 \ldots)$

Polarity (magnetisation): $p = \pm 1$

Phase (orientation): $\phi_0 = [0, 2\pi]$

Imaging of spin dynamics in vortex structures

[Park, Eames, Engebretson, Berezovsky, Crowell, (Minnesota), Phys. Rev. B (2003)]



Sample

GaAs substrate

Disk elements: 60 nm thickness; 500 nm, 1 μm, 2 μm diameter

Time-resolved Kerr microscopy

150-psec field pulse

We observe a gyrotropic motion of the vortex around the enter of the particle.

"Vortex core-driven magnetization dynamics"

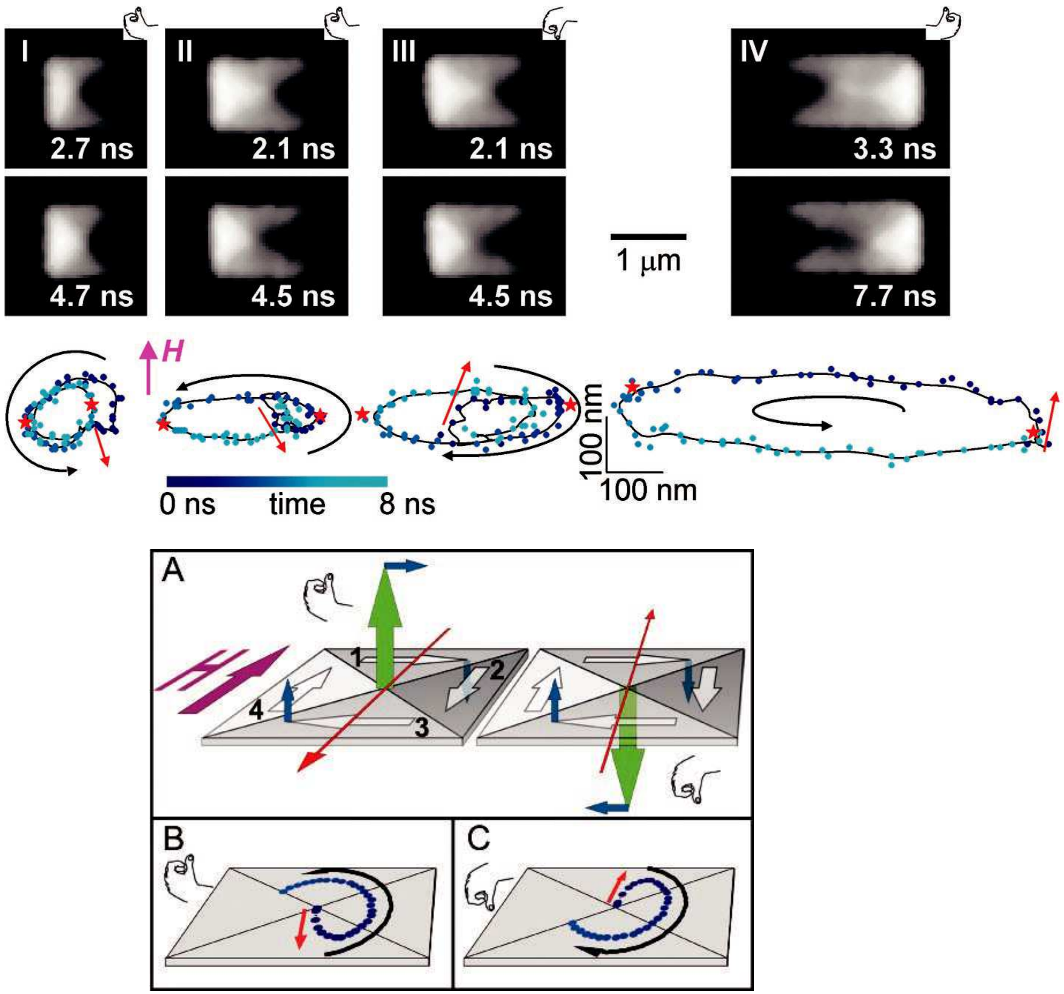
[Choe, Acremann, Scholl, Bauer, Doran, Stöhr, Padmore,

(Lawrence Berkeley National Lab, Stanford Synchrotron Radiation Lab.), Science (2004)]

Sample: Pattern 20 nm thick CoFe alloy film, by focused ion beam.
Rectangles: 1×1, 1.5×1, $2 \times 1 \mu\mathrm{m}^2$.

X-ray imaging: Fast (100 psec?) in-plane magnetic field pulses.
X-ray magnetic circular and linear dichroism (XMCD and XLCD). X-ray pulse ($\sim$ 70 ps) sets the time resolution.
Photoemission electron microscope (PEEM) spatial resolution $<$ 100 nm.

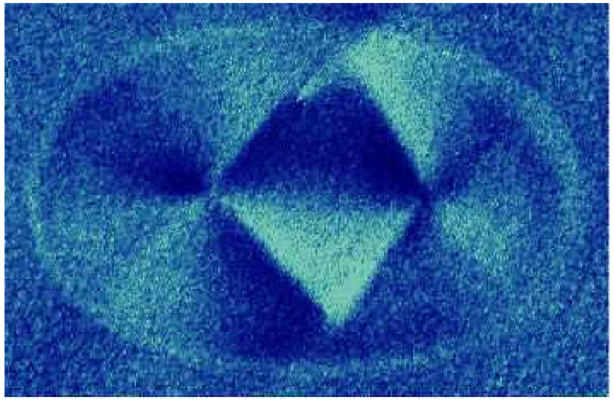
Effect of polarity ($\surd$), circulation ($\surd$), and orientation ($\times$), on vortex dynamics.

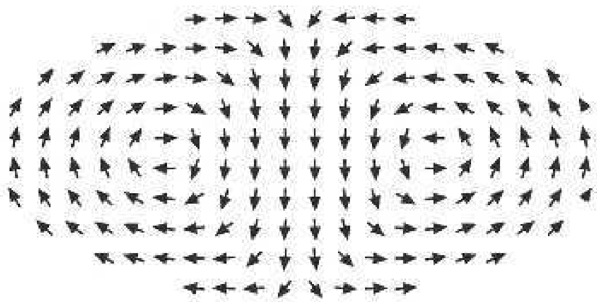


"Soliton-pair dynamics in patterned ferromagnetic ellipses"

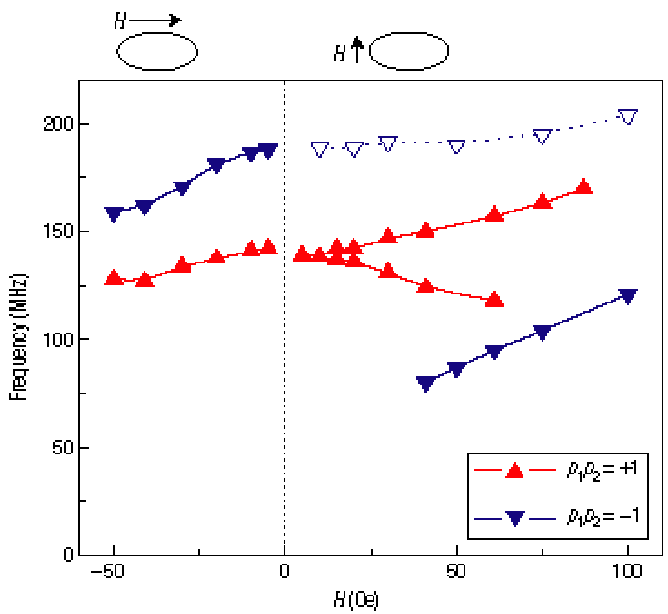
[Buchanan, Roy, Grimsditch, Fradin, Guslienko, Bader, Novosad, (Argonne National Laboratory), Nature Physics **1**, 172 (2005); Phys. Rev. B **72**, 024455 (2005).]

MFM image of 3μm $\times$ 1.5μm Permalloy ellipse.

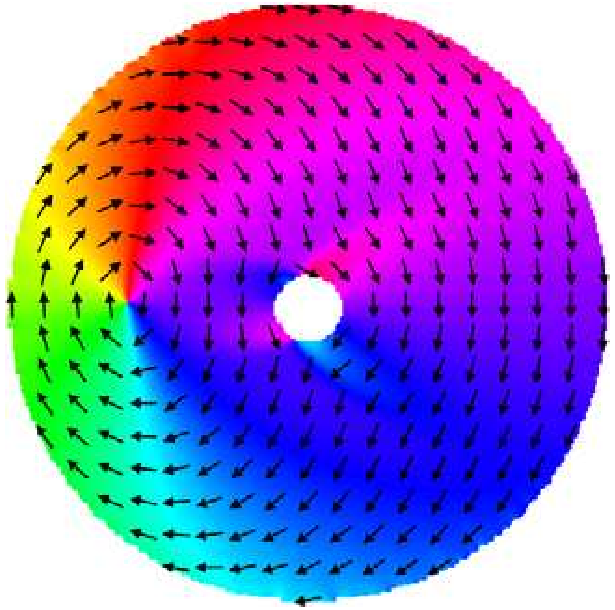




(i) Apply an in-plane field $\rightarrow$ change vortex positions. (ii) An rf current generates an oscillating magnetic field. (iii) Measure the impedence derivative spectra (resonances).



Vortex domain wall in a ring particle – Dynamics



Imagine an applied magnetic field in-plane and pointing azimuthally around the ring.

Vortex dynamics implies that the vortex wall would set in a circular motion around the ring!

Hall effect

2D charge motion perpendicular to a magnetic field

• Suppose electric field $\boldsymbol{E} = E\hat{\boldsymbol{x}}$:

$m\ddot{\boldsymbol{r}} = e\boldsymbol{E} \Rightarrow m\ddot{x} = eE \rightarrow$

acceleration along x-axis.

• Suppose magnetic field $\boldsymbol{B} = B\hat{\boldsymbol{z}}$:

$m\ddot{\boldsymbol{r}} = e(\dot{\boldsymbol{r}} \times \boldsymbol{B}) \Rightarrow v_x \sim \cos(\omega t)$,

$v_y \sim \sin(\omega t), \quad \omega = e/m \rightarrow$

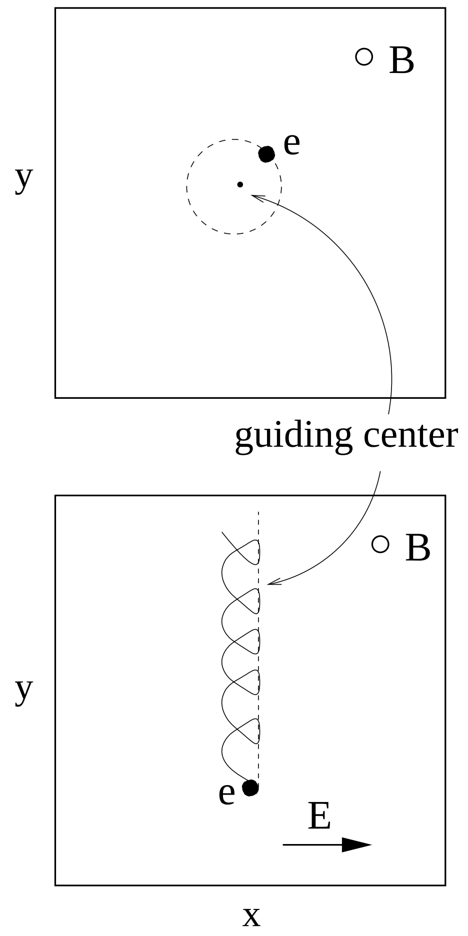
circular motion (charge is pinned).

• Electric and magnetic field:

$m\ddot{\boldsymbol{r}} = e\boldsymbol{E} + e(\dot{\boldsymbol{r}} \times \boldsymbol{B}) \Rightarrow$

$v_x = 0, \; v_y = -E/B \rightarrow$

motion perpendicular to $\boldsymbol{E}$.



Topological numbers

On a circle

Suppose a thin film (two-dimensional material). Run around a circle, at spatial infinity, and follow the vector $\boldsymbol{M}$ as it rotates.

If the vector rotates by 2π (e.g., for a vortex) then the topological number is $\kappa = 1$. (Also possible are $\kappa = 0, \pm 1, \pm 2 \ldots$.)

On a sphere

Run over the whole plane and follow $\boldsymbol{M}$ (a 3D vector) as it points on the sphere.

E.g., the vectors ($\boldsymbol{M}$) in a vortex cover one half of a sphere.
We say that the vortex has topological charge (number) $\mathcal{N} = \pm 1/2$.
(Also possible are $\mathcal{N} = 0, \pm 1, \pm 2 \ldots$.)
We can see that for a vortex:

$$\mathcal{N} = \frac{1}{2} p\, \kappa, \qquad p : \text{polarity.}$$

Topological charge

A measure of the complexity of the structure is an invariant of the motion:

$$\mathcal{N} = \frac{1}{4\pi} \int q \, d^2x, \quad q = \frac{1}{2} \epsilon_{\mu\nu} \left(\partial_\nu \boldsymbol{m} \times \partial_\mu \boldsymbol{m} \right) \cdot \boldsymbol{m}, \quad (\mathcal{N} = 0, \pm 1, \pm 2, \ldots)$$

Conservation law

A measure of the soliton position is a conserved quantity!

$$I_x = \int xq \, d^2x, \qquad I_y = \int yq \, d^2x,$$

Hall analogy

$$B \leftrightarrow \mathcal{N}$$

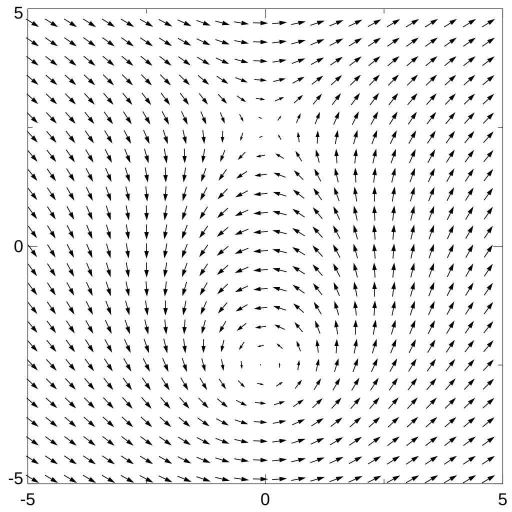
Guiding center $\leftrightarrow (I_x, I_y)$

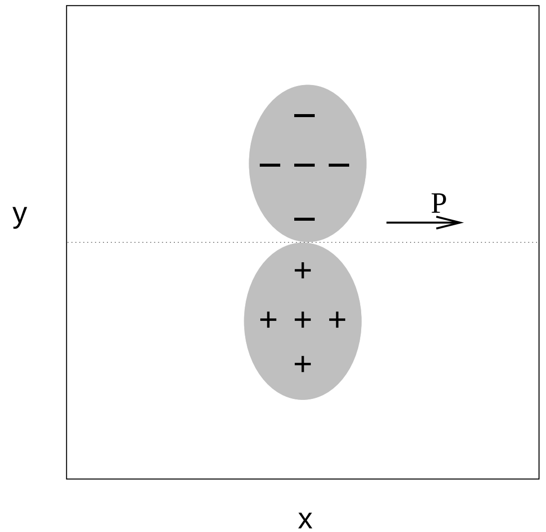
Vortex-Antivortex pairs

Consider two vortices with opposite circulation (same polarity) which we call a vortex-antivortex pair.

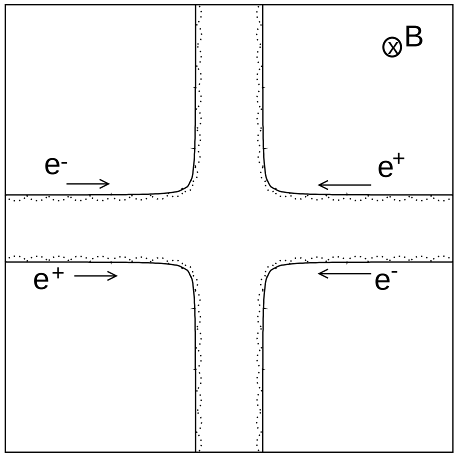
- Vanishing topological charge ($\mathcal{N} = 0$) $\Rightarrow$ not pinned.
- Propagating.
- Velocity $v \simeq \frac{1}{L}$, L: size of the pair.
- Analogies with vortex pairs in fluids.

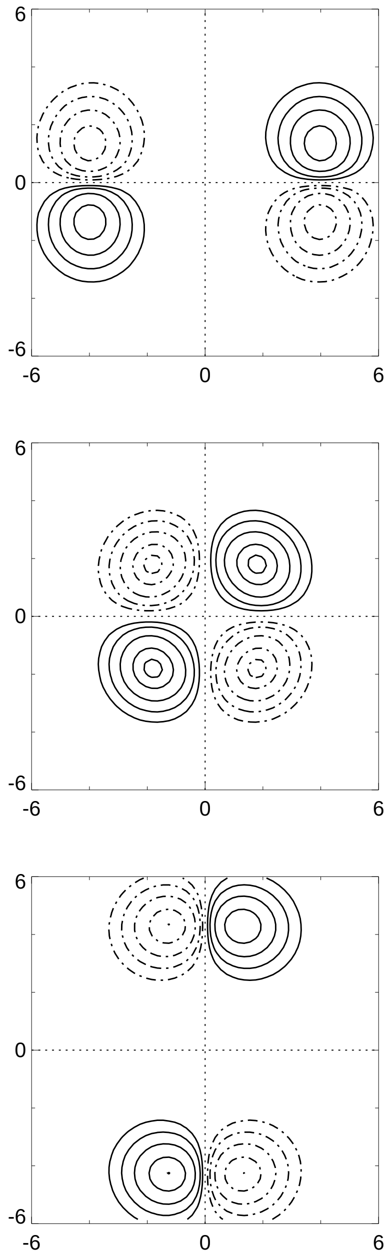
Now, consider two vortices with opposite circulation and opposite polarity! (?)





Scattering of Vortex-Antivortex pairs





$$\ddot{\boldsymbol{r}}_i = q(\boldsymbol{E}_i + \dot{\boldsymbol{r}}_i \times \boldsymbol{B}), \quad \boldsymbol{r}_i \equiv (x_1, x_2)$$

$$q = \pm e, \ i = 1, 2, 3, 4$$

$$\boldsymbol{E}_i = -\sum_j \frac{\partial U(\boldsymbol{r}_i - \boldsymbol{r}_j)}{\partial \boldsymbol{r}_i}$$

Vortex core reversal

[Waeyenberge, Puzic, Stoll, Chou, Tyliszczak, Hertel, Fähnle, Brückl, Rott, Reiss, Neudecker, Weiss, Back, Schütz, (Stuttgart, Regensburg), Nature (2006)]

Sample

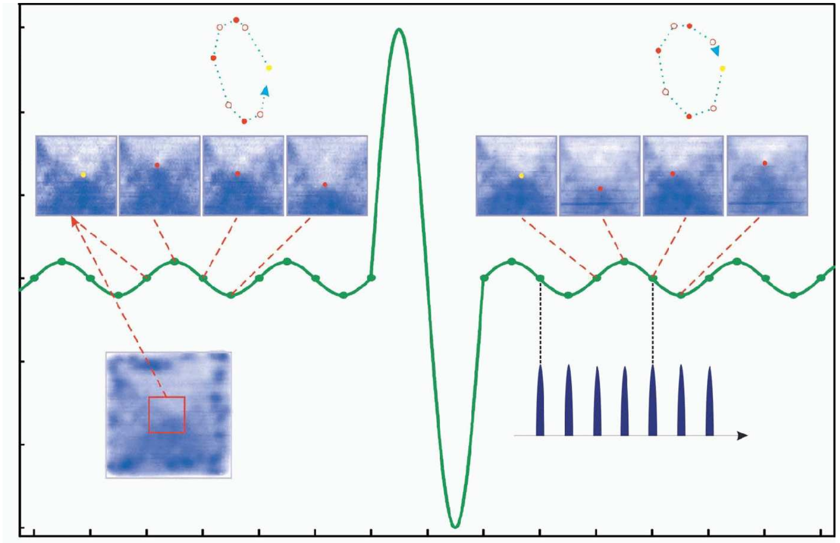
Square NiFe elements: $1.5\mu m \times 1.5\mu m \times 50 nm$ (Si_3N_4 substrate)

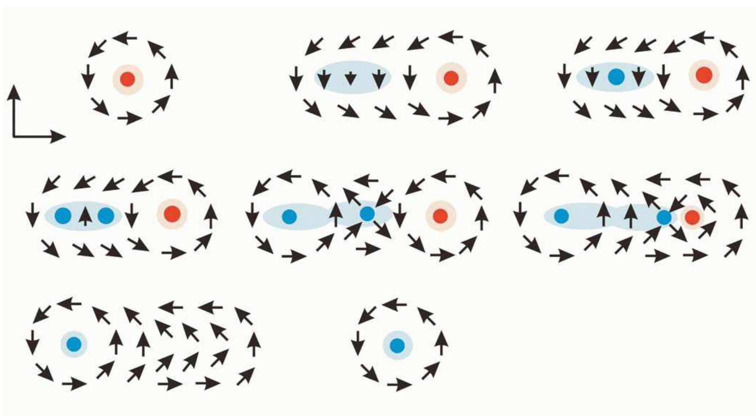
Methods

XMCD, resolution 30nm, 150ps.

Process

Alternating field (250 MHz, 0.1 mT).
Add a "burst" of 1.5 mT, for one period.
Check that you obtained vortex core switching!





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