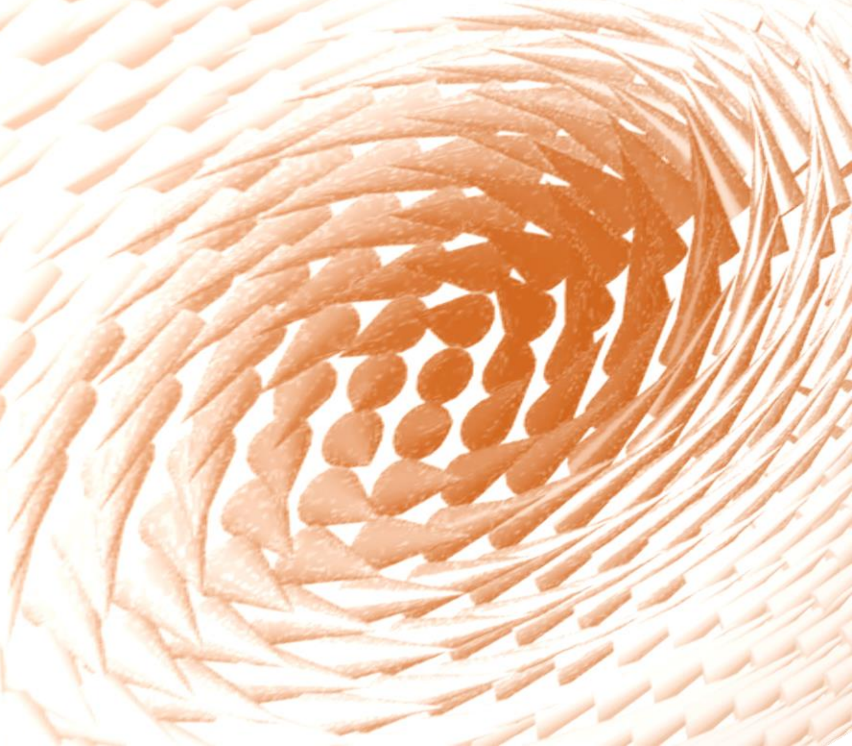
Magnetic vortices are coming…

We know how to count to two,
shall we learn to count to four?



Michal Urbánek

Introduction…

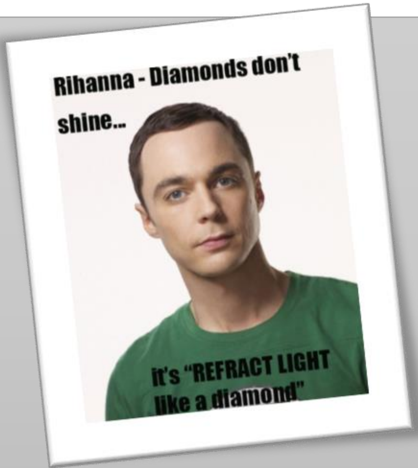
image: Apple

$$\nabla \cdot \boldsymbol{D} = \rho,$$

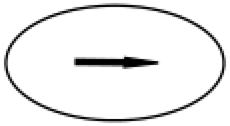
$$\nabla \cdot \boldsymbol{B} = 0,$$

$$\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t,$$

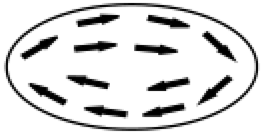
$$\nabla \times \boldsymbol{H} = \boldsymbol{j} + \partial \boldsymbol{D}/\partial t.$$



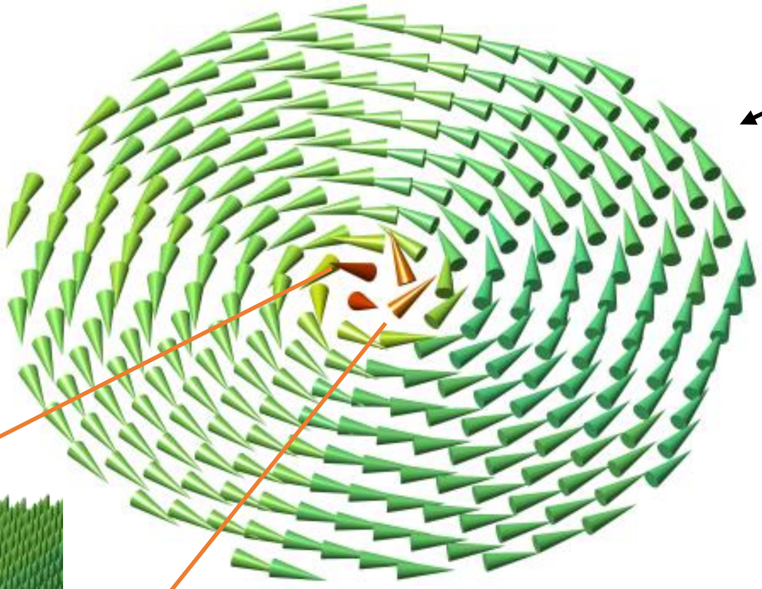
What is magnetic vortex?



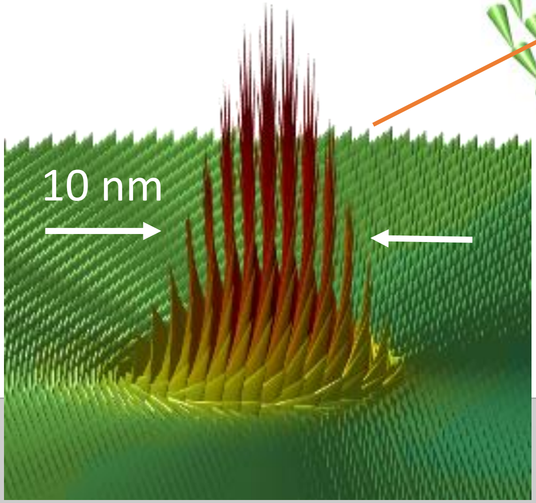
exchange interaction



demagnetizing field



diameter 100 nm – 3 μm



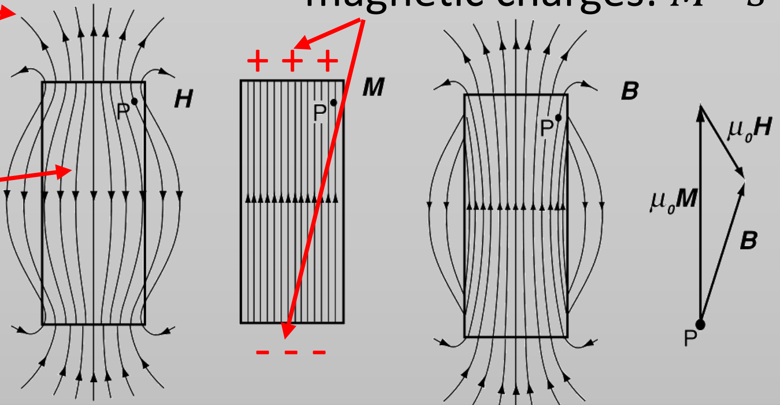
exchange length:
~ 3.5 nm

$$l_{ex} = \sqrt{\frac{A}{\mu_0 M_s^2}}.$$

stray field

demagnetizing field

magnetic charges: $\vec{M} \cdot \vec{s}$



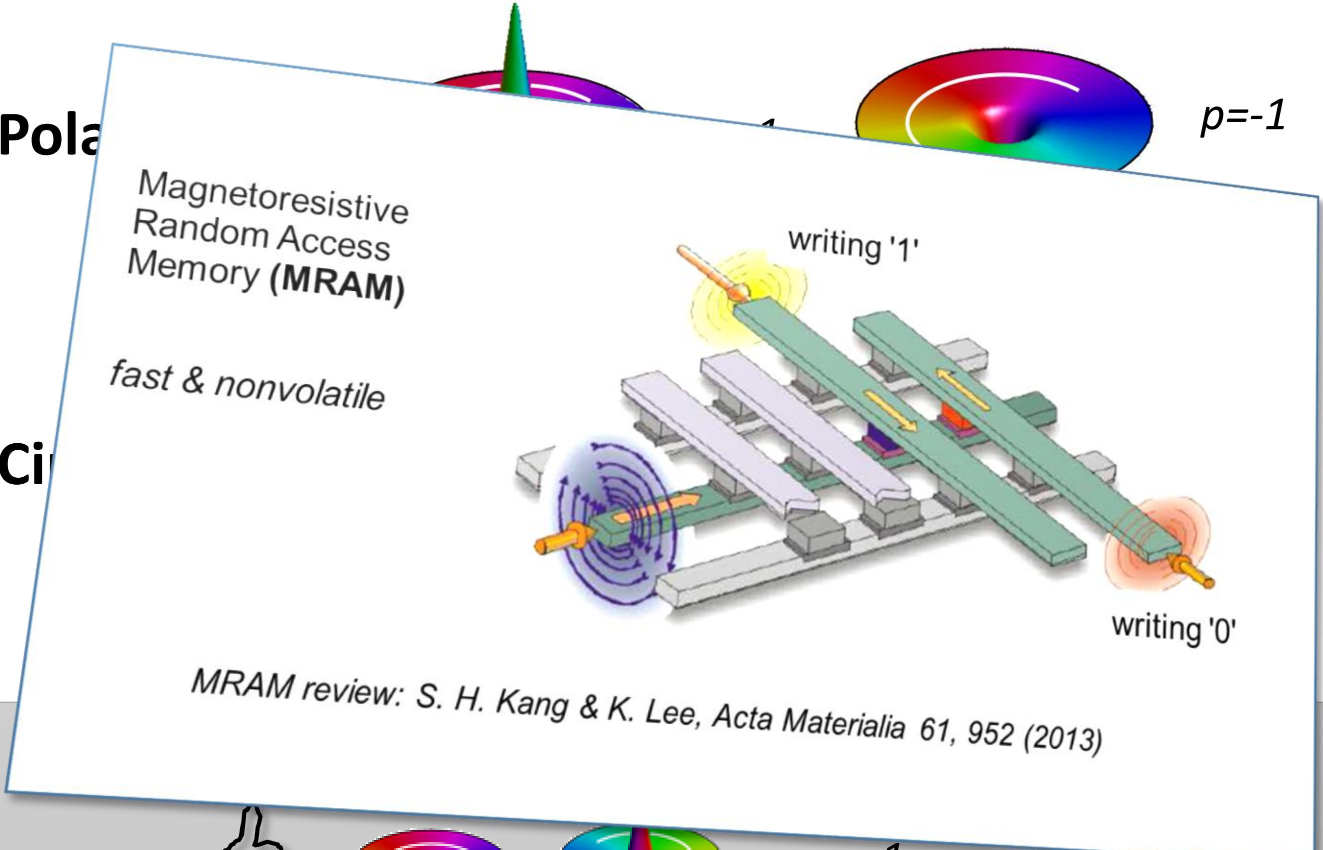
charge avoidance principle:
magnetic charges -> stray field = high energy cost
demagnetizing field reduces magnetic charges

Four vortex states

Pola

p=-1

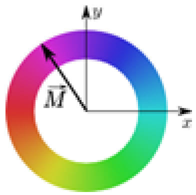
Ci



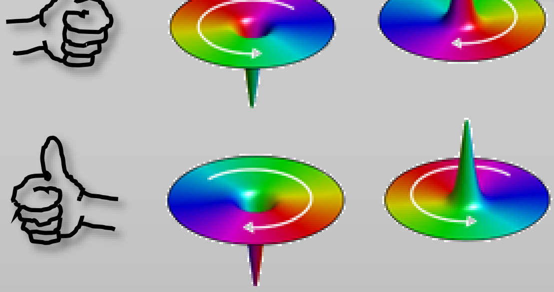
Magnetoresistive
Random Access
Memory **(MRAM)**

fast & nonvolatile

MRAM review: S. H. Kang & K. Lee, Acta Materialia 61, 952 (2013)



Chirality:
(=handedness)



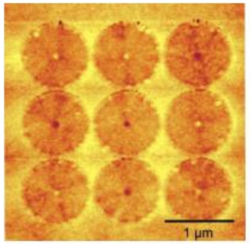
c·p=1

c·p=-1

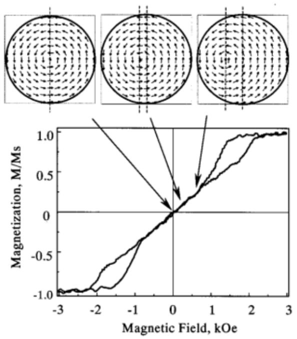
Symmetry breaking in formation of vortex states:

Im - Nature Commun 3 (2012)

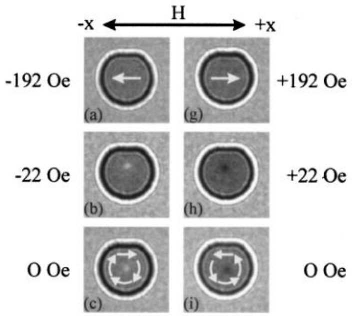
History



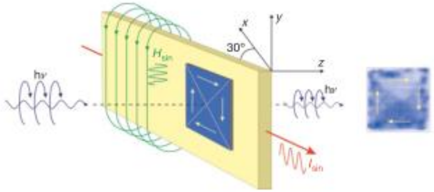
First observation of
the vortex core (by MFM)
*Shinjo Science **289** (2000)*



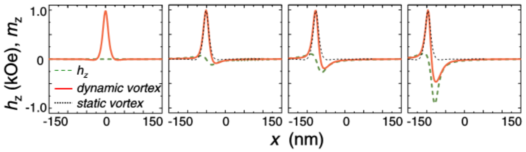
Rigid vortex model
*Guslienko APL **78** (2001)*



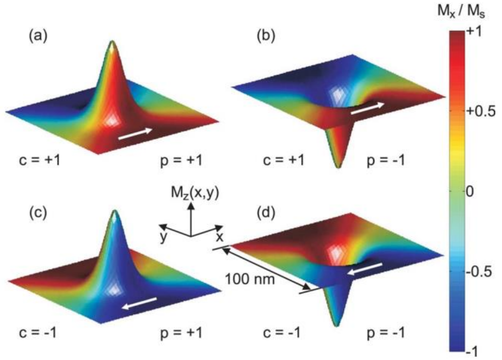
Circulation switching by
a static field
*Schneider APL **79** (2001)*



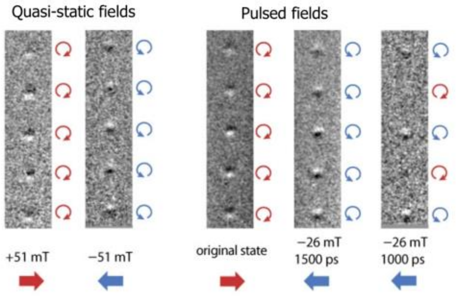
Fast core reversal
by in plane
alternating fields
Van Wayenberge
*Nature **444** (2006)*



Gyrotropic field, critical velocity
*Guslienko PRL **100** (2008)*

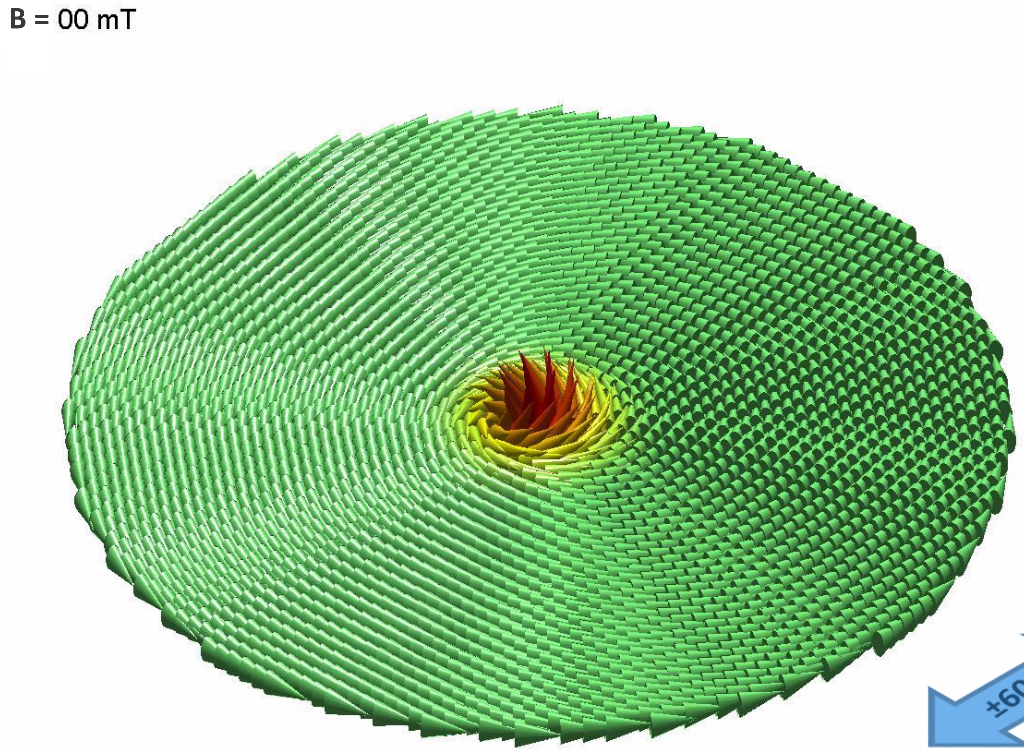


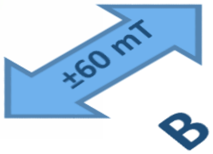
VRAM memory concept
Bohlens *APL **93** (2008)*

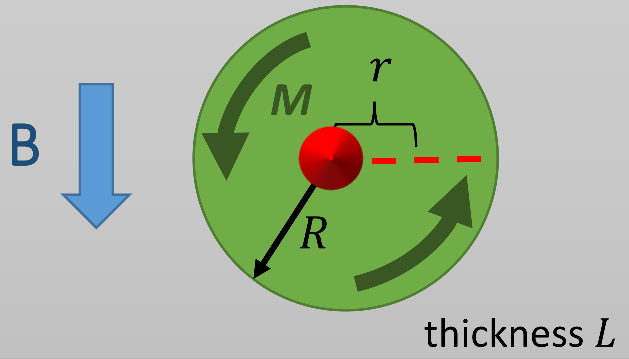


Dynamic circulation reversal
*Uhlíř Nature Nanotech **8** (2013)*

Magnetic vortex in slowly changing field







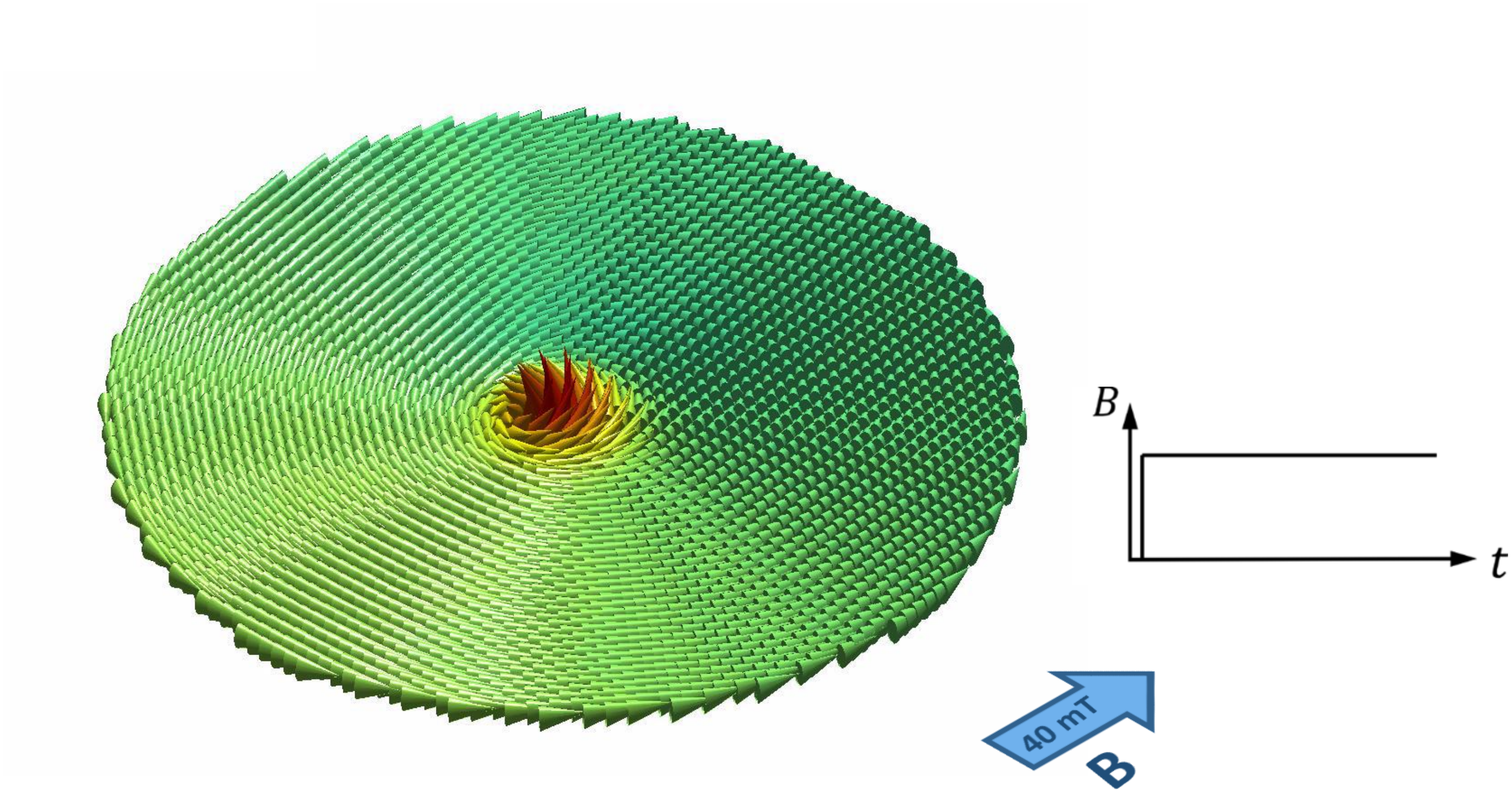
Rigid vortex model:

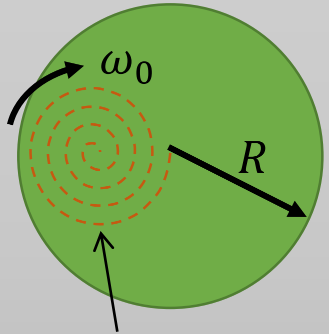
$$\chi_0 \sim \frac{R}{L}$$

$$r = \frac{\chi_0 B R}{M_s}$$

Guslienko APL 78 3848 (2001)

Magnetic vortex in fast rising field





equilibrium position at $B_{\mathbf{stat}}$

eigenfrequency $\omega_0 \sim \frac{1}{\chi_0}$

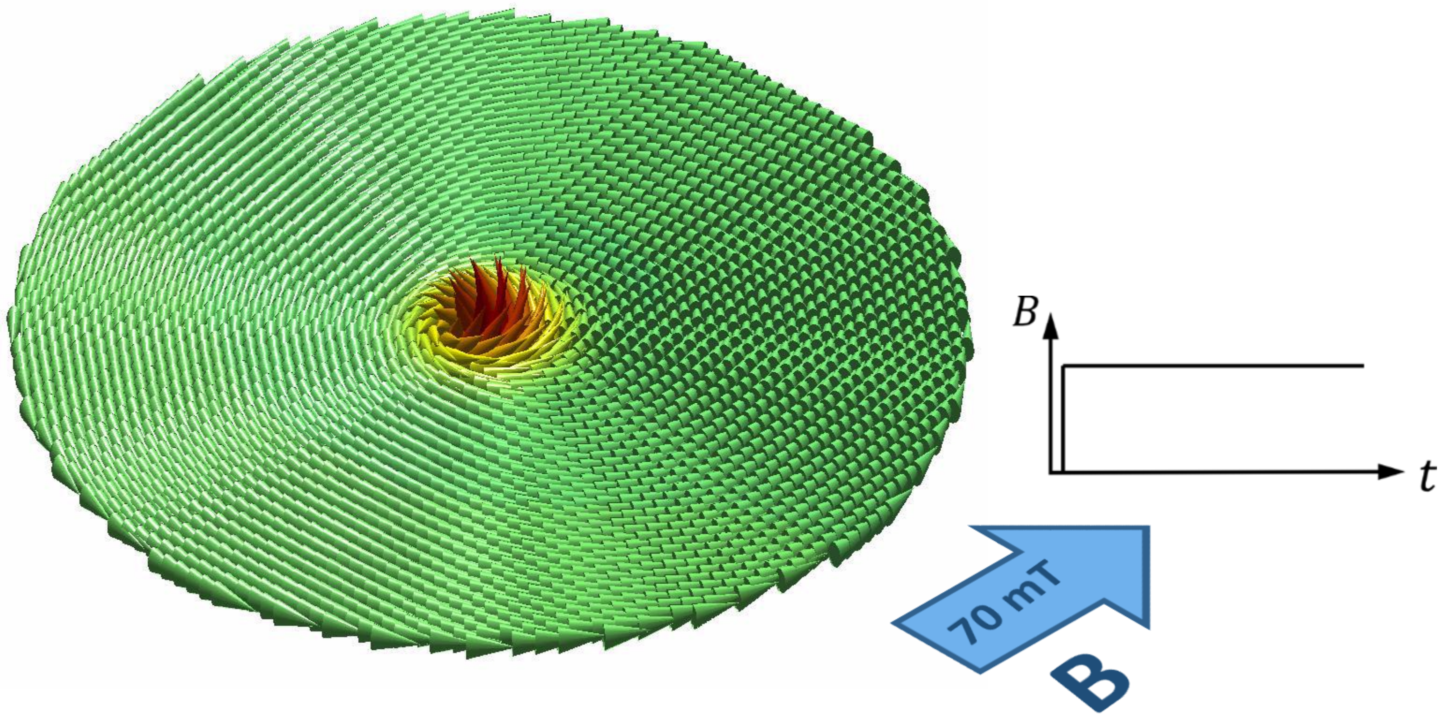
Thiele's equation of motion:

$$-\boldsymbol{G} \times \dot{\boldsymbol{X}} - \widehat{D}\dot{\boldsymbol{X}} + \frac{\partial W(\boldsymbol{X})}{\partial(\boldsymbol{X})} = \boldsymbol{0}$$

Thiele PRL 30 (1973)

Magnetic vortex in fast rising field

- core polarity switching



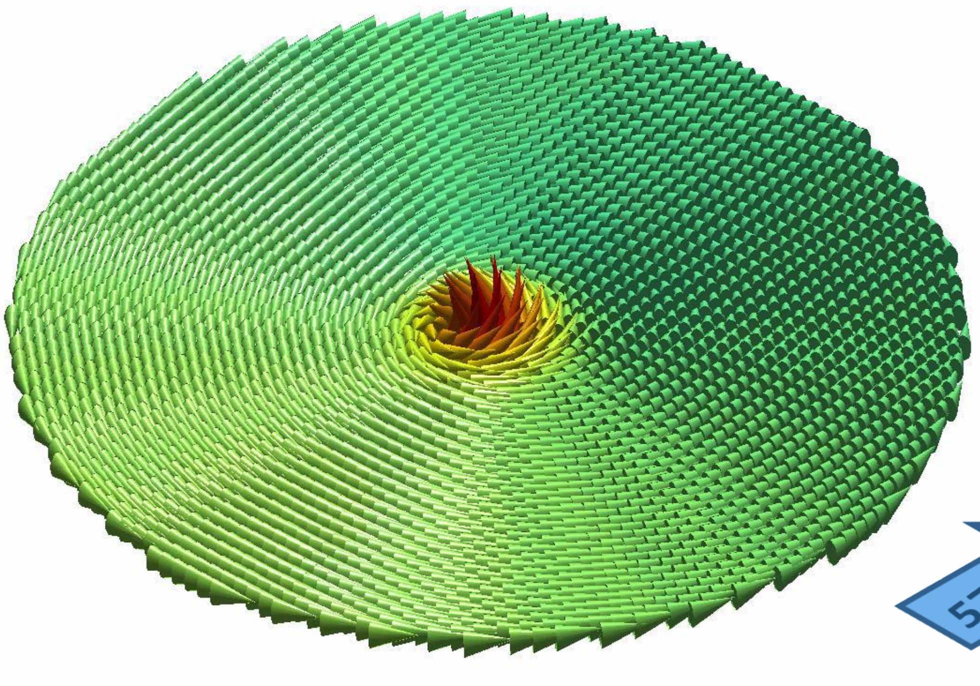
“gyrofield” $\vec{\boldsymbol{h}}$ created by the moving core, its magnitude is proportional to the core velocity $h_z \approx {}^{\omega_0}/_{r} = v_c$

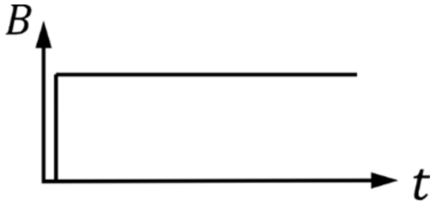
At certain value of v_c = v_{crit} the gyrofield becomes high enough to switch the core polarity
$v_{crit} \approx 320\ m/s$ (for Permalloy)

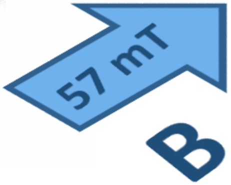
Van Vayenberge Nature 444 (2006)
Guslienko PRL 100 (2008)

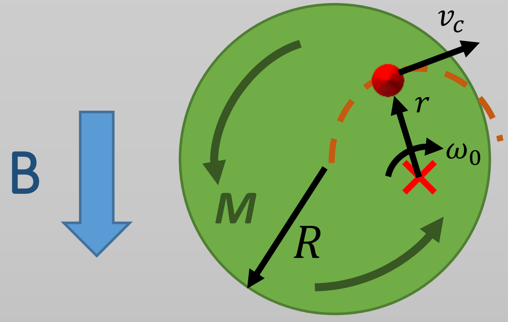
Magnetic vortex in fast rising field

- circulation switching









Thiele's equation, only half-period, neglecting damping => circular motion:

$$-\boldsymbol{G}\times\dot{\boldsymbol{X}}-\cancel{\hat{D}\dot{\boldsymbol{X}}}+\frac{\partial W(\boldsymbol{X})}{\partial(\boldsymbol{X})}=\boldsymbol{0}$$

$$r=\frac{\chi_0 B_{an-dyn}R}{M_s}$$

$$\omega_0=\frac{1}{2}\gamma M_s\frac{\xi^2}{\chi_0}$$

$$v_c=\omega_0 r \quad (<\boldsymbol{v}_{\boldsymbol{crit}}!!!)$$

dynamic annihilation field $B_{an-dyn}\approx\frac{1}{2}B_{an-stat}, r=\frac{1}{2}R$

Experiments: can we see them?

Magnetic Force Microscopy (MFM)

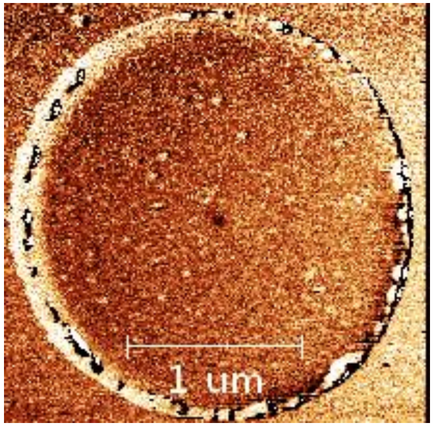
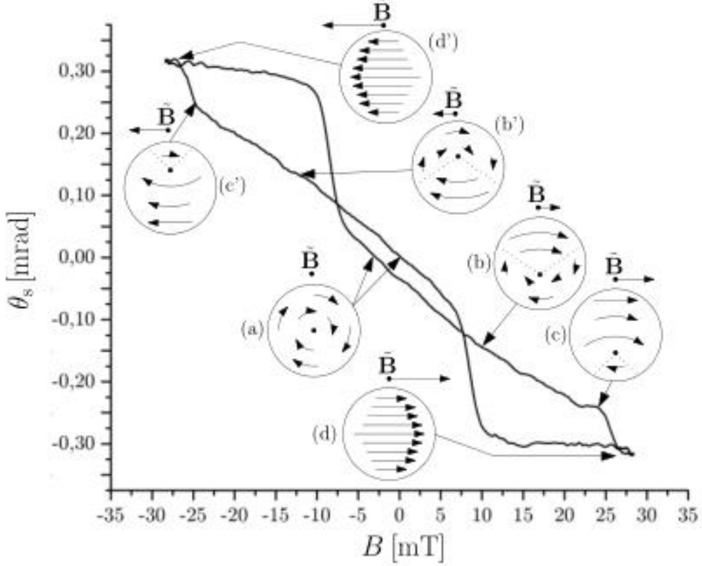
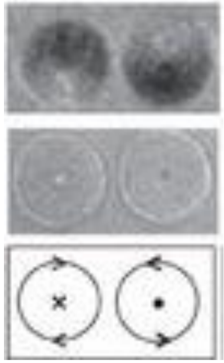


image: Michal Staňo

Magneto Optical Kerr Effect (MOKE)

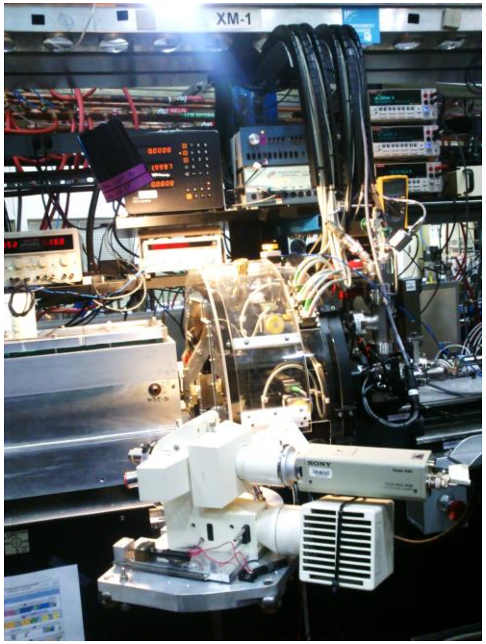


measurement:
Lukáš Flajšman & Jan Balajka

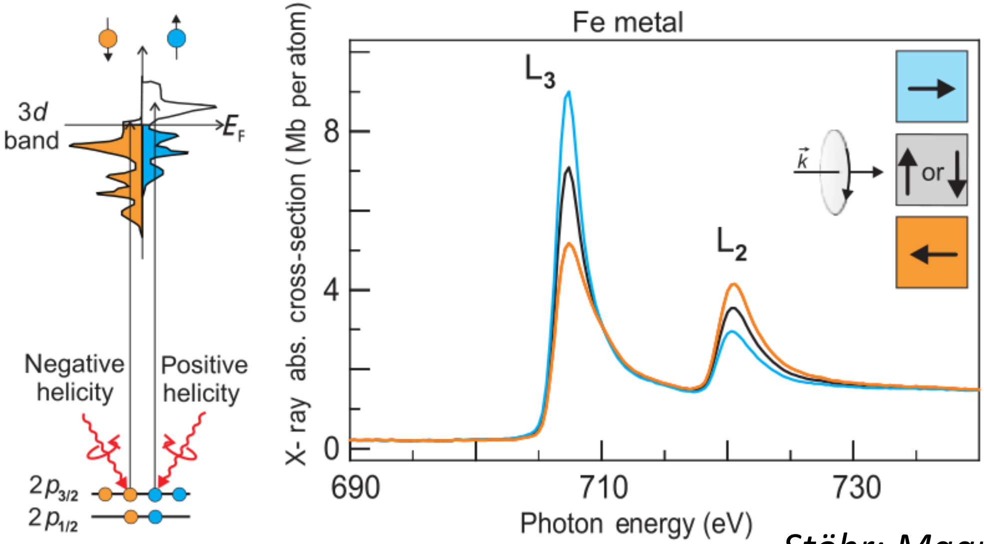


Magnetic Transmission X-ray Microscopy (MTXM)
image: Mi-Young Im

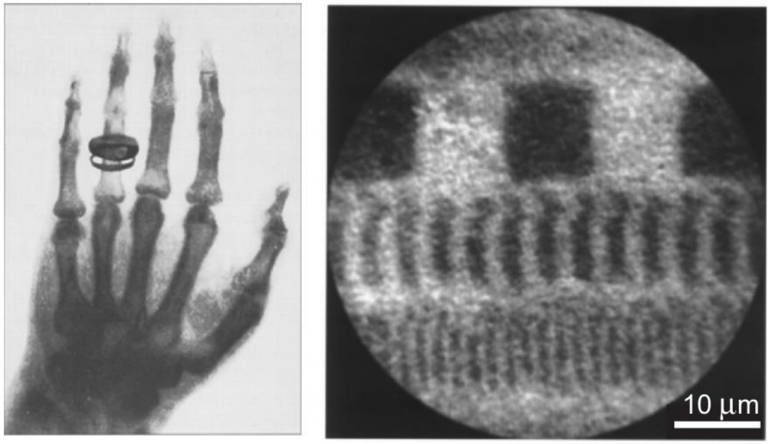
Magnetic Transmission X-ray Microscopy



X-ray Magnetic Circular Dichroism



Stöhr: Magnetism



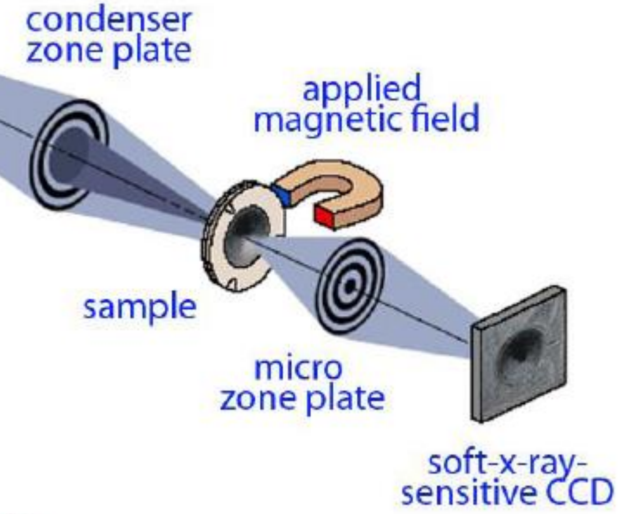
Stöhr: Magnetism

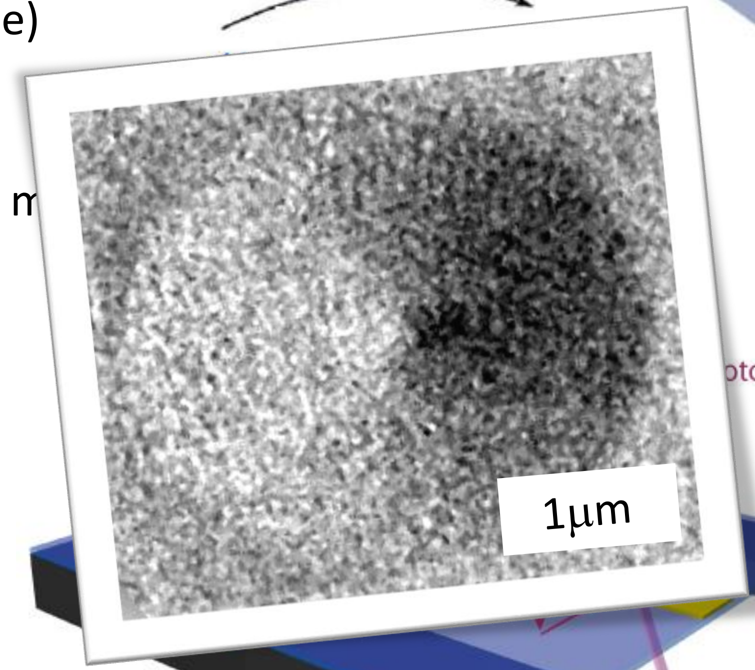
Image by ALS

Experiments

MTXM - Magnetic Transmission X-ray Microscopy

XM-1 Microscope
BL 6.1.2, ALS, Berkeley USA
Energy: 707 eV (Fe L3 Edge)
Spatial resolution: 25 nm
Field of view: 15 µm
Sample tilt 30° - in plane m





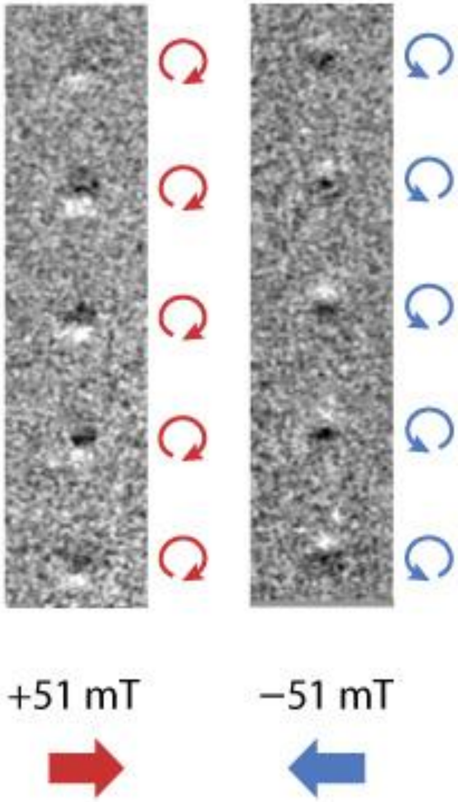
pulse generator

sample:
SiN membrane, 200 nm thick
Au waveguide, 50 nm thick
NiFe nanodisks, 200-1000 nm wide, 20-30 nm thick

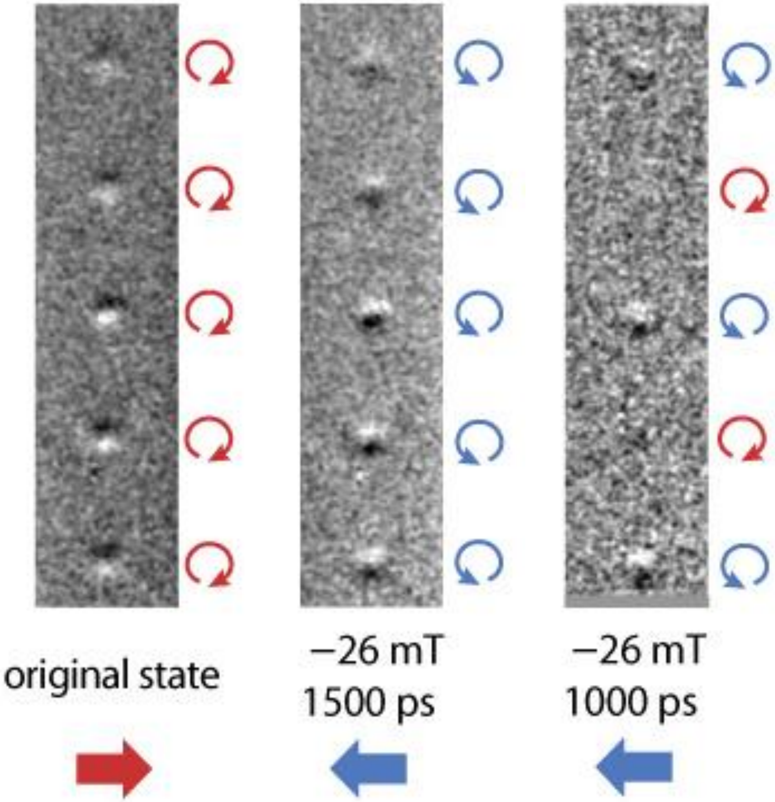
oscilloscope

Experiments

Quasi-static fields



Pulsed fields



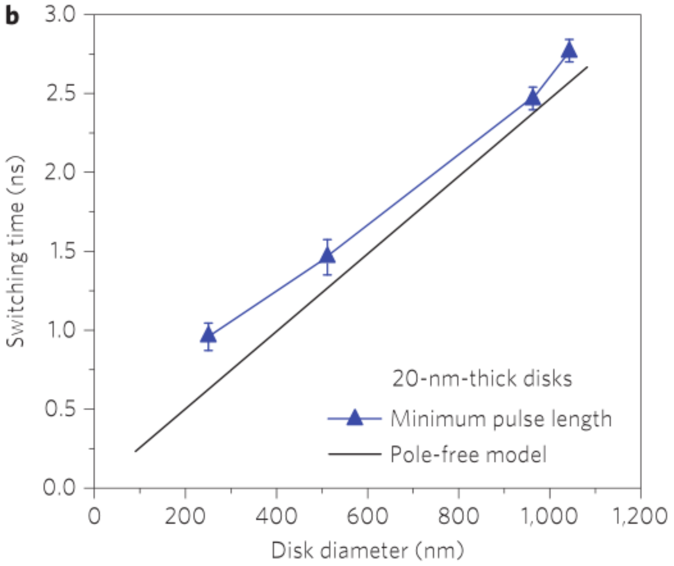
Disks **250** nm wide, **20** nm thick

Uhlíř Nature Nanotech. ***8*** *(2013).*

Experiments

Disk size (nm) (diameter/thickness)	$B_{an\text{-}stat}$ (mT)	$B_{an\text{-}dyn}$ (mT)	$B_{an\text{-}dyn}/B_{an\text{-}stat}$	t_s (ns)
250/20	51	26	0.51	1
510/20	32	14	0.44	1.5
960/20	27	13	0.48	2.5
1000/20	29	17	0.59	2.5
1040/20	23	11	0.48	2.8

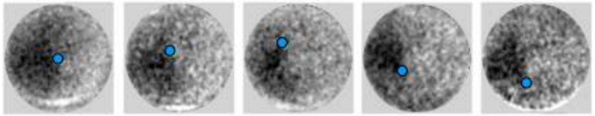
Average ratio
0.50 ± 0.05

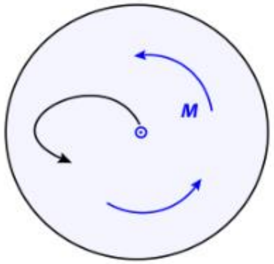


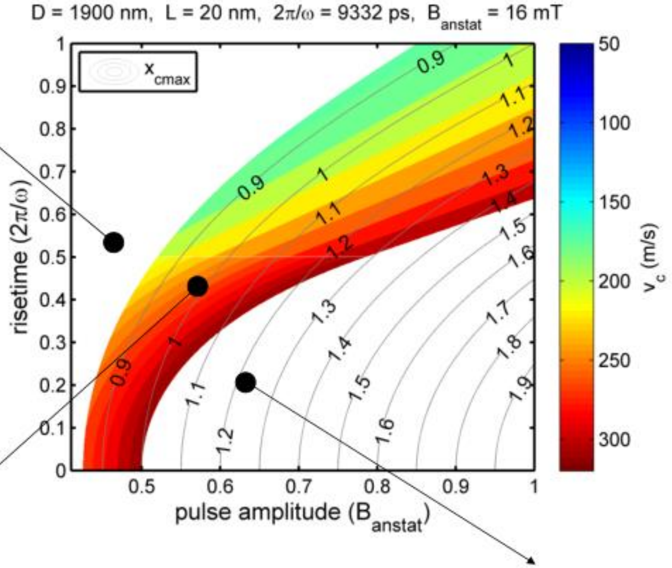
- Fast and effective circulation switching
- Sub-nanosecond switching times
- ½ of the amplitude compared to static switching

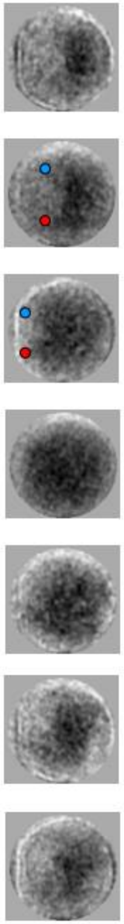
Experiments

Free gyration
(example with a 1000/20 disk)

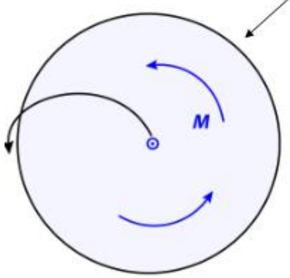








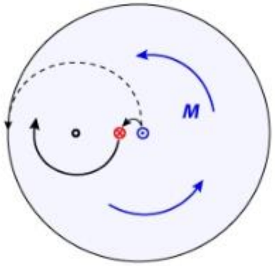
Core expulsion
(1900/20 disk)

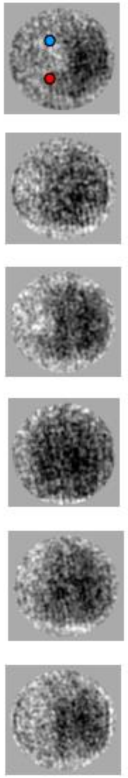


Amplitude 8.9 mT
rise time 4 ns

Polarity switching
(1900/20 disk)

Amplitude 9.8 mT
rise time 1.5-1.9 ns





The symmetric contrast associated with a combination of two trajectories for a core polarity "up" and "down" follows from:
1) random nucleation of the core polarity after core expulsion,
2) switching of the core polarity when pulses with a short rise time are applied.

Conclusion

Yes
(magnetic recording industry)

Yes
(it’s obvious)

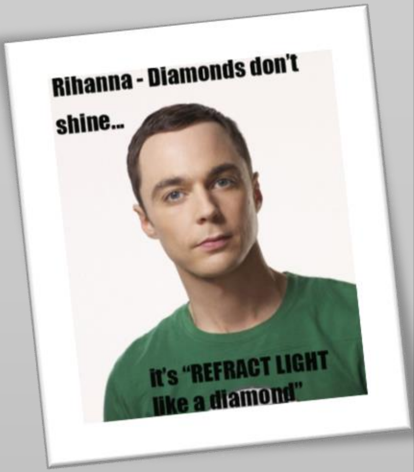
Yes
(nonvolatile memory =
less energy consumption)

Drawbacks:

- So far only separate polarity and circulation control
- Random polarity after circulation switching
- Difficult readout (synchrotron, MFM)

Plans for the future:

- Control of all four vortex states by a single magnetic pulse
- Electric readout



Credits

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BERKELEY LAB
Lawrence Berkeley National Laboratory

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CXRO
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ALS
ADVANCED LIGHT SOURCE