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Magnetization dynamics imaged with synchrotron-based magnetic microscopy

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Ultrafast Scientific Interest Group, Sept. 18, 2008

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UChicago Argonne LLC

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U.S. DEPARTMENT OF ENERGY

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  - *Vortex dynamics*
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  - *Magnetization Reversal*

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  - *Micromagnetic simulations, Lithography, PEEM measurements*
- Konstantin Guslienko, Argonne National Laboratory, now at Seoul National Univ.
  - *Analytical theory work*

Outline

- Introduction – Magnetization dynamics in nanostructures
- Microscopy techniques based on x-ray magnetic circular dichroism
- Recent results from the APS photoemission microscope
  - Magnetization reversal
  - Vortex dynamics
- Upgrades and future sources
- Summary

Time Scales in Magnetization Dynamics

Optical Processes

Field and Spin Current Driven Processes

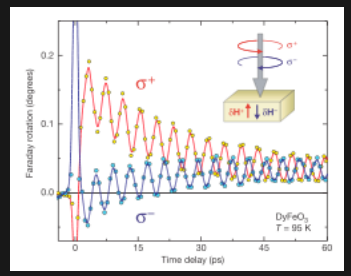
Magnetic Storage Stability Requirements

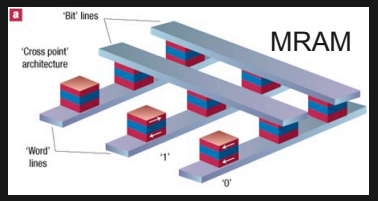
Thermal Processes

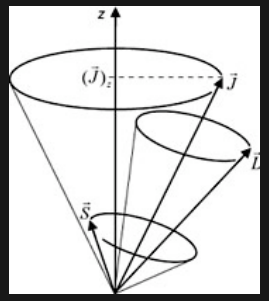
Earth's Dipole Field

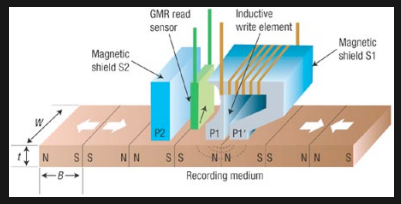
(s)

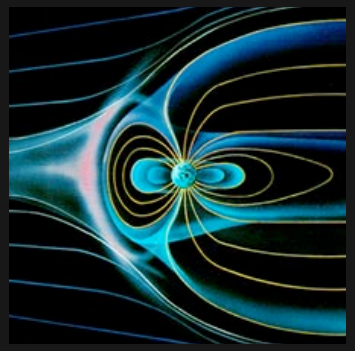
10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15}







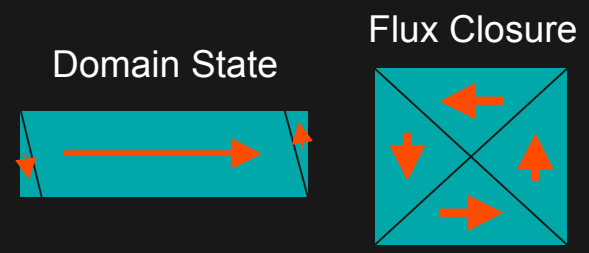




Finite size effects in magnetic nanostructures

Magnetostatics:

$E = E_{ext} + E_{exch} + E_{demag} + E_{anis}$



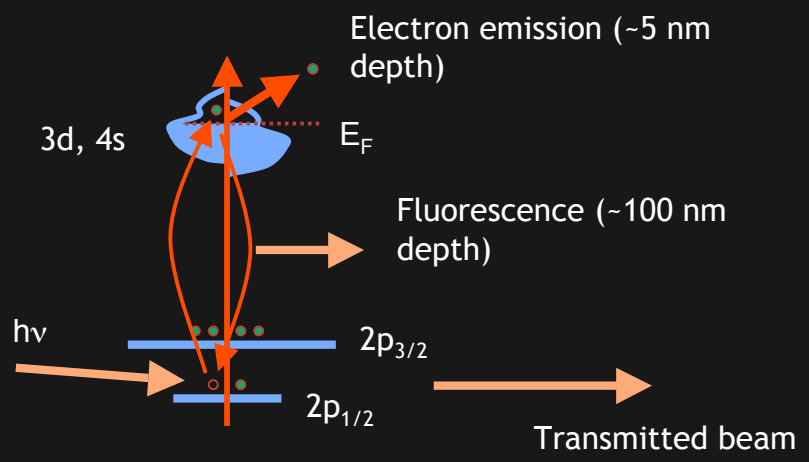
Dynamics (Landau-Lifshitz Eq.):

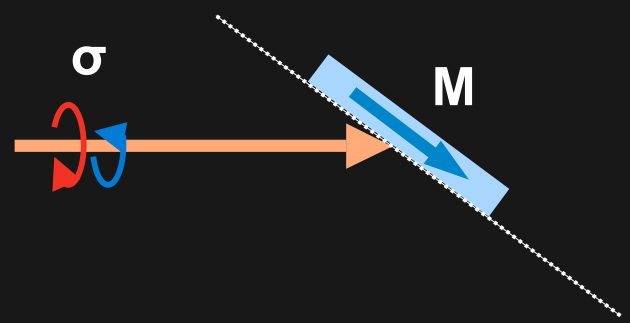
$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt},$$

Important length scales: 1-10,000 nm

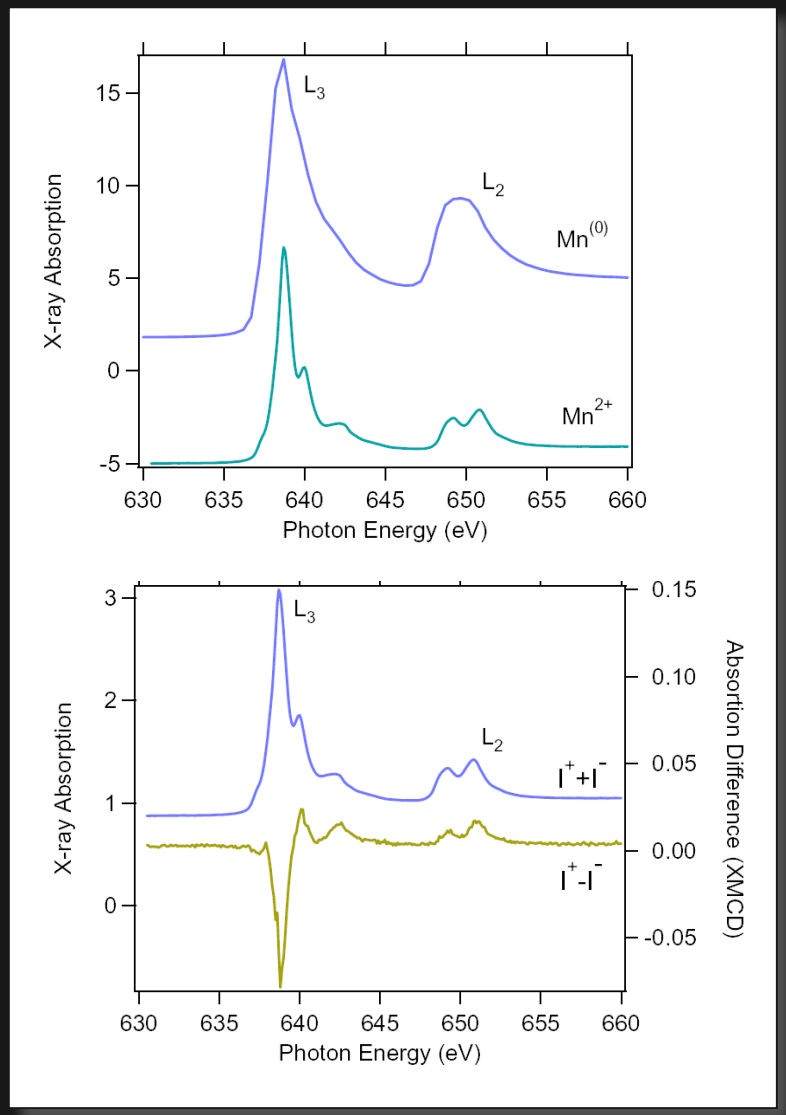
Important time scales: 1-10,000 ps

X-ray Absorption Spectroscopy and Circular Dichroism

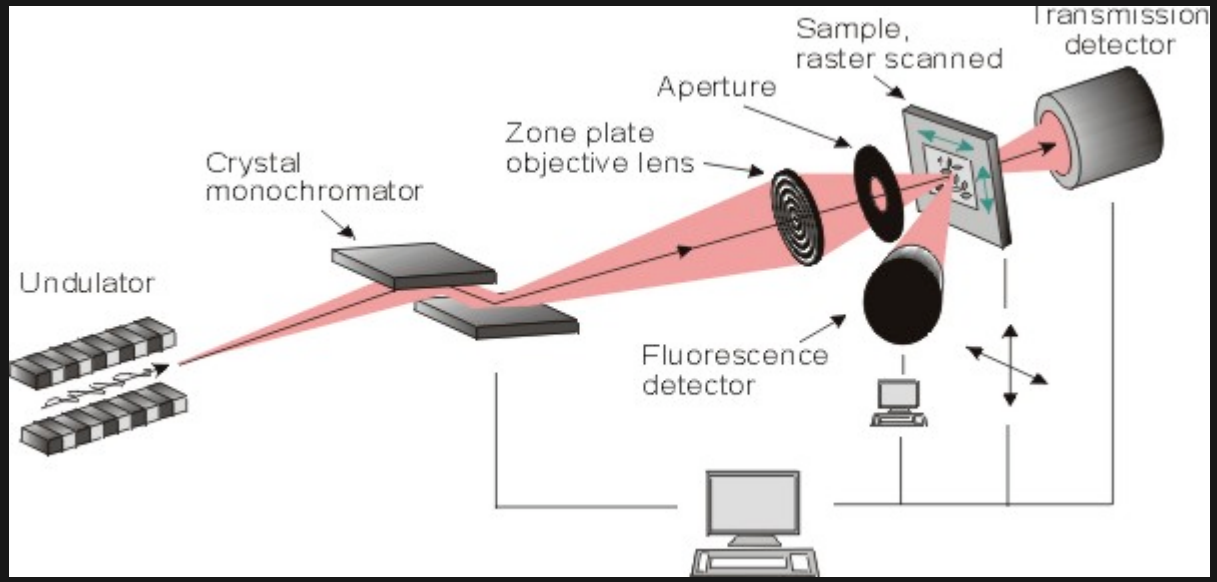


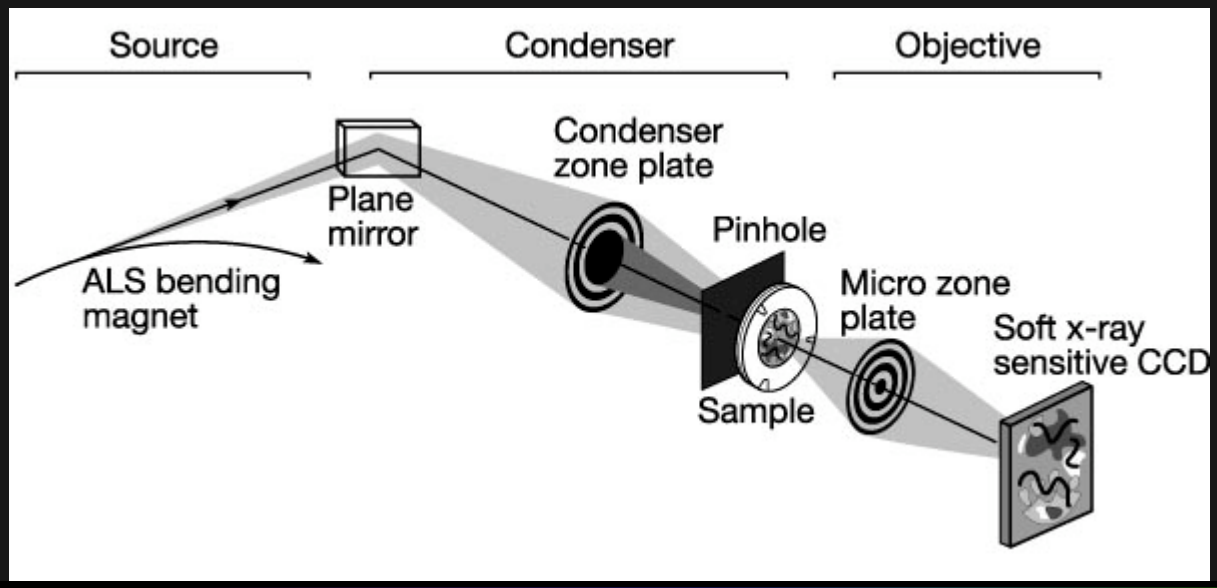


- XMCD ~ **σ•M**
  - Element and valence selective
  - High Sensitivity
  - Quantitative



Transmission X-ray Microscopy





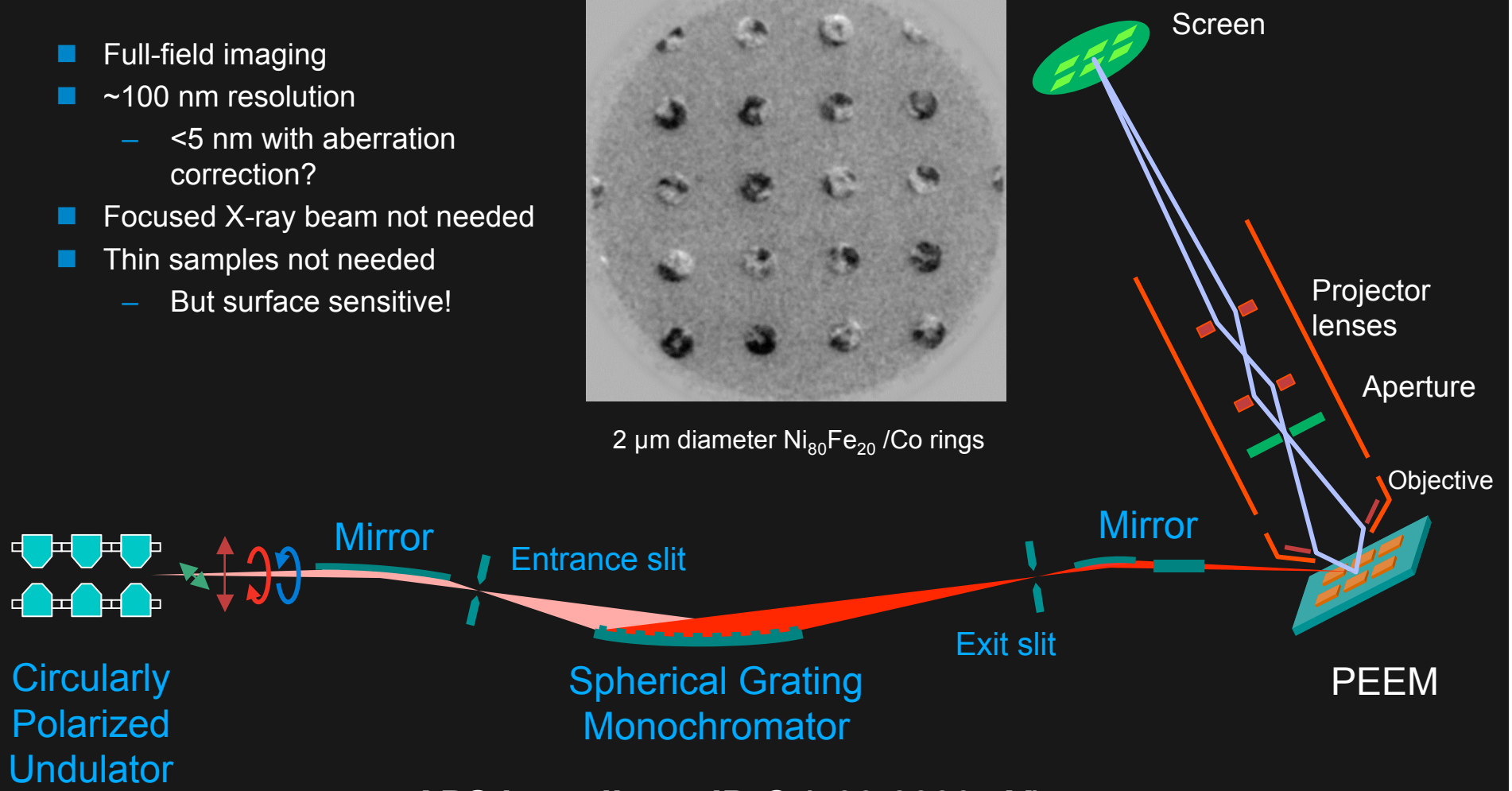
- Scanning or full-field modes
- Resolution limited by zone plate (~15 nm)
- Thin sample required

P. Fischer, et al., ALS

X-ray Photoemission Electron Microscopy (X-PEEM)

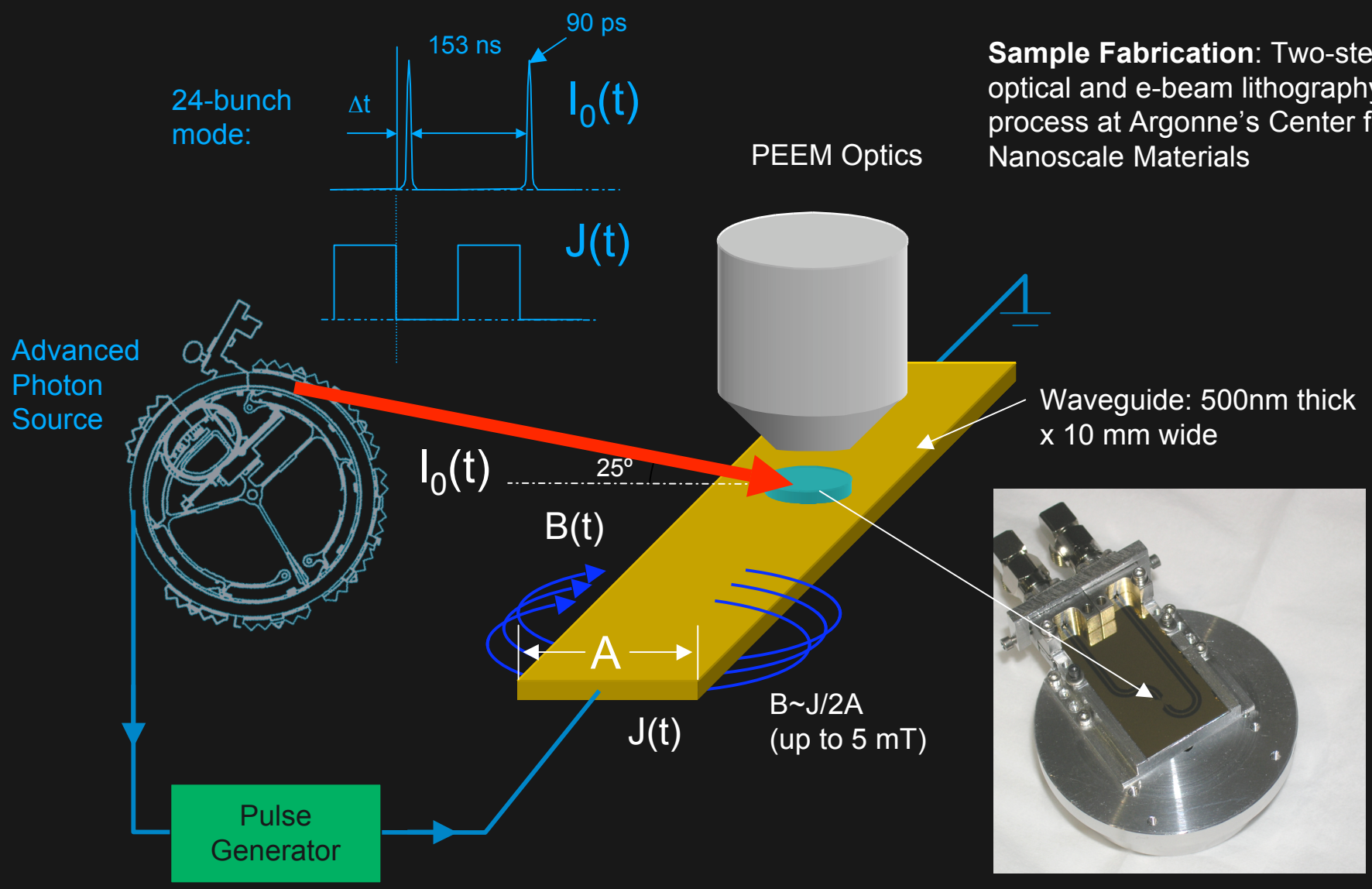
- Full-field imaging
- ~100 nm resolution
  - <5 nm with aberration correction?
- Focused X-ray beam not needed
- Thin samples not needed
  - But surface sensitive!

2 μm diameter $Ni_{80}Fe_{20}$ /Co rings



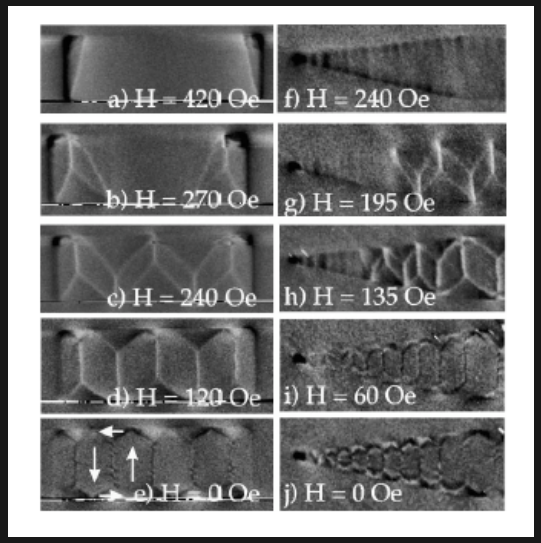
APS beamline 4-ID-C (500-3000 eV)

Pump-probe time-resolved X-PEEM

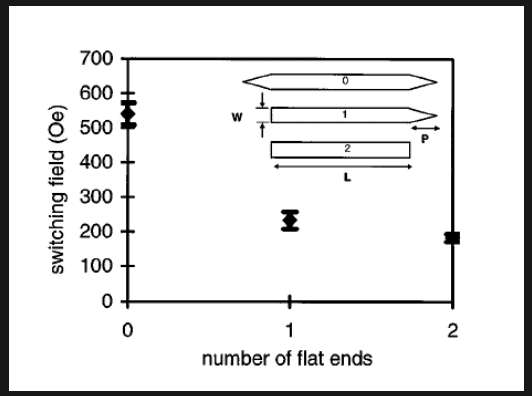


Sample Fabrication: Two-step optical and e-beam lithography process at Argonne's Center for Nanoscale Materials

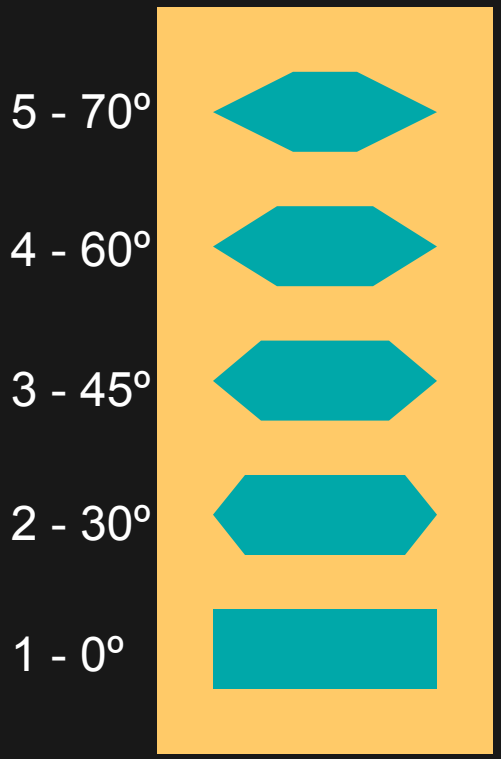
Influence of Shape on Magnetization Reversal



J. Yu, U. Rudiger, A.D. Kent, L. Thomas, S.S.P. Parkin, Phys. Rev. B **60**, 7352 (1999).



K. J. Kirk, J. N. Chapman, C. D. W. Wilkinson, Appl. Phys. Lett. **71**, 539 (1997).

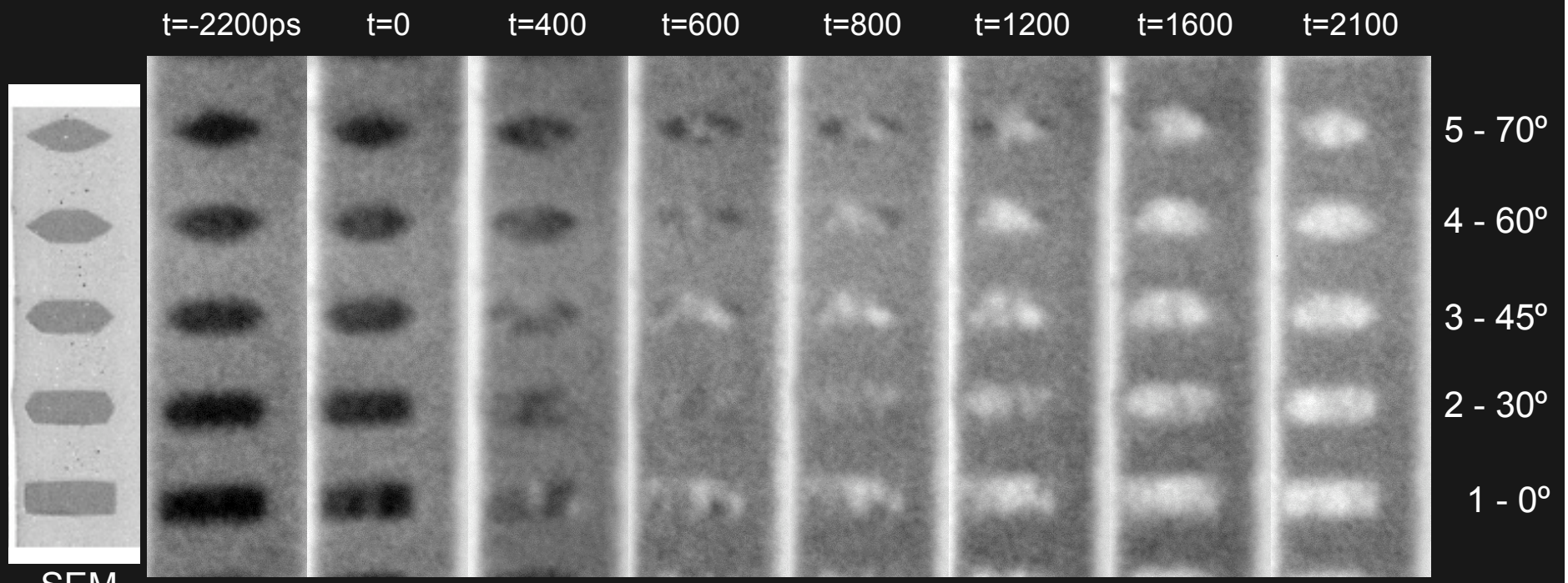


7x2 μm $Ni_{80}Fe_{20}$ needles

4 nm thick

Magnetization Reversal

Field transition



SEM

PEEM(XMCD)

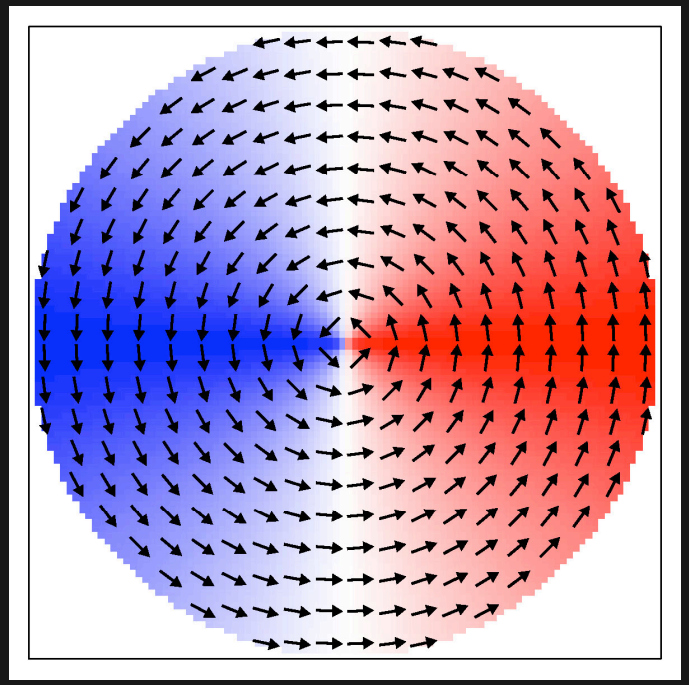
Beam direction

Applied field

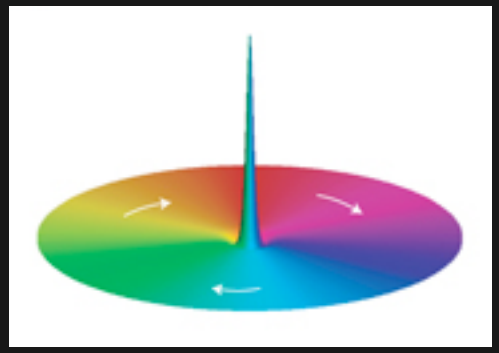
X. Han et al., PRL 98, 147202 (2007).

Magnetic Vortices

- Flux closure state in circular structures

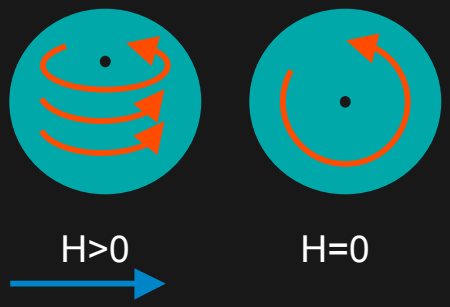


- Demagnetizing field drives in-plane circulating structure
- Exchange field forces local out-of-plane core (~10nm)



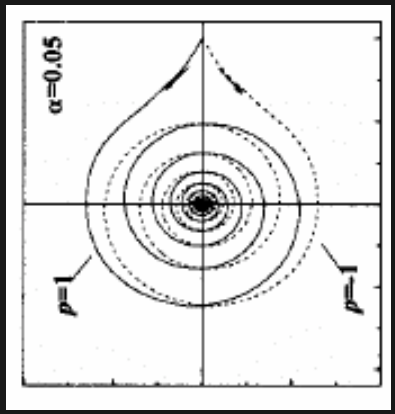
Vortex core dynamics

Vortex Core Eq. of Motion:



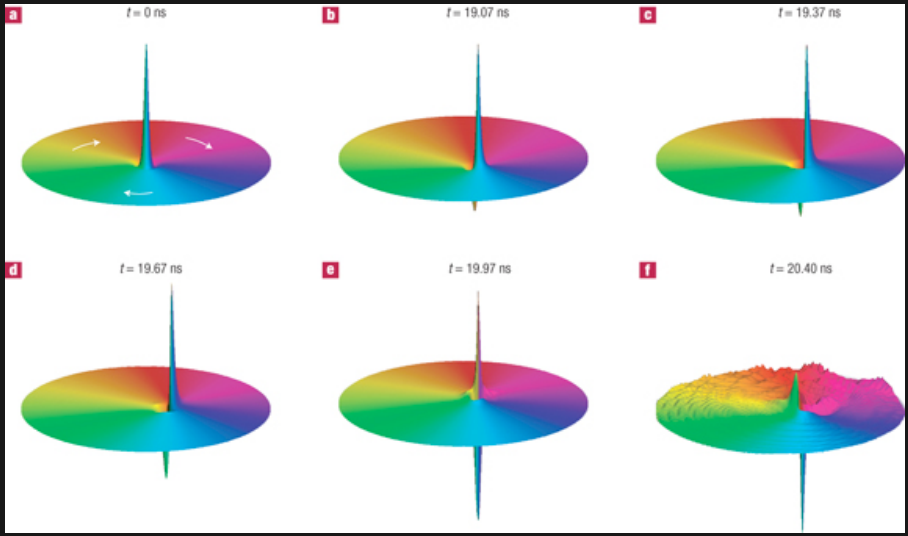
Landau-Lifshitz Eq.

$$\hat{M}\ddot{\mathbf{X}} - \mathbf{G} \times \dot{\mathbf{X}} + \frac{\partial W(\mathbf{X})}{\partial \mathbf{X}} = 0,$$



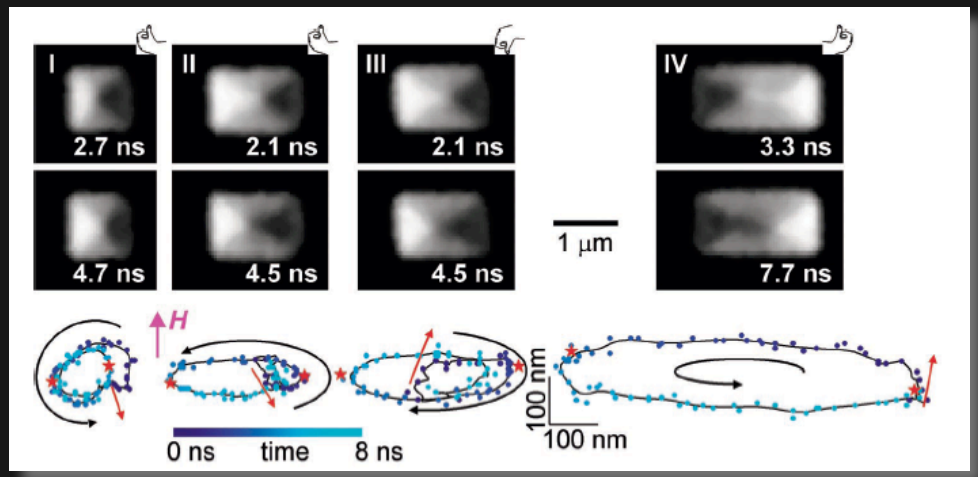
Fundamental or
“gyrotropic” mode

Vortex Core Polarity Reversal:



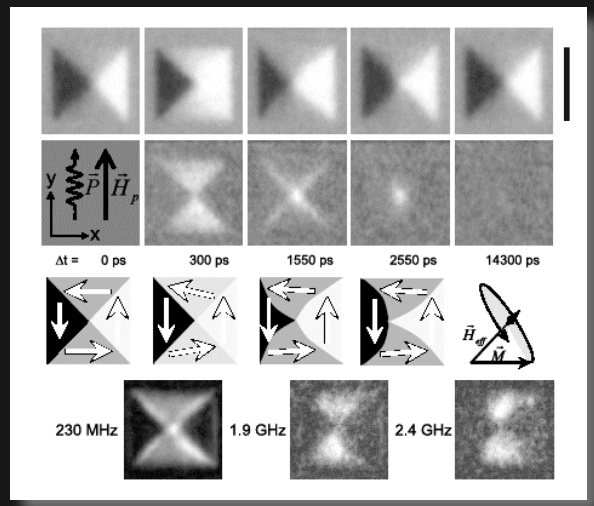
Yamada et al. Nature Materials 6, 270 (2007).

Vortex Dynamics



S.B.Choe et al., Science **304**, 420 (2004). (Advanced Light Source)

Observed gyrotropic mode in 1 μm Co squares



J. Raabe et al., PRL **94**, 217204 (2005). (Swiss Light Source)

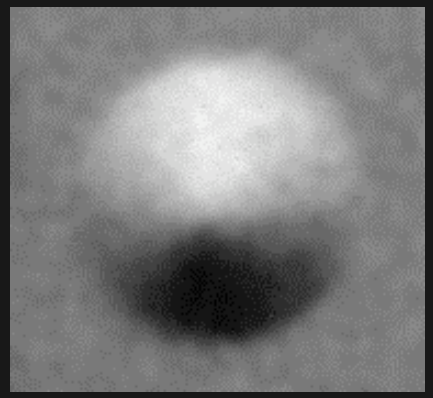
No gyrotropic mode in 6 μm permalloy squares

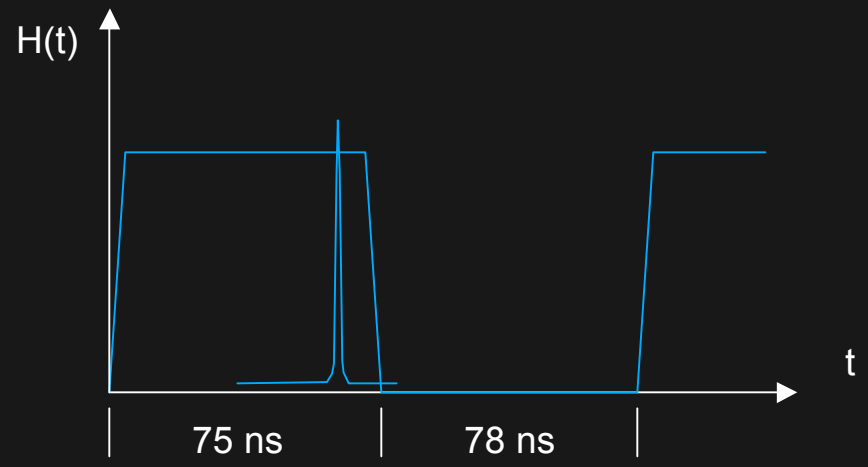
Many variable factors:

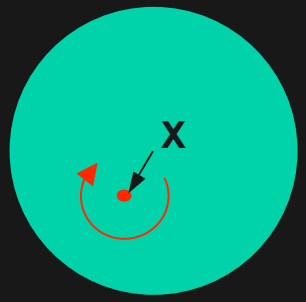
- Size of structures
- Shape (presence of domain walls)
- Material
- Excitation (amplitude, frequency)

Imaging of free vortex motion in circular structures

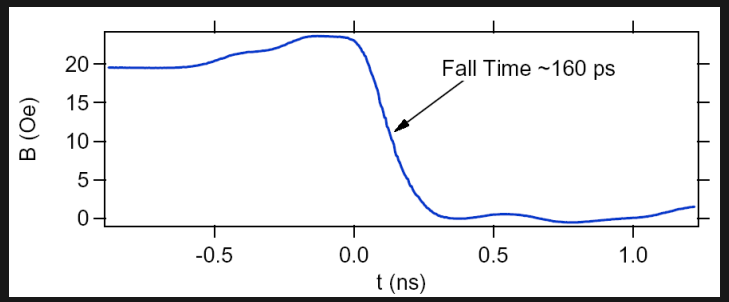
6 μm diameter, 30 nm thick permalloy disks:







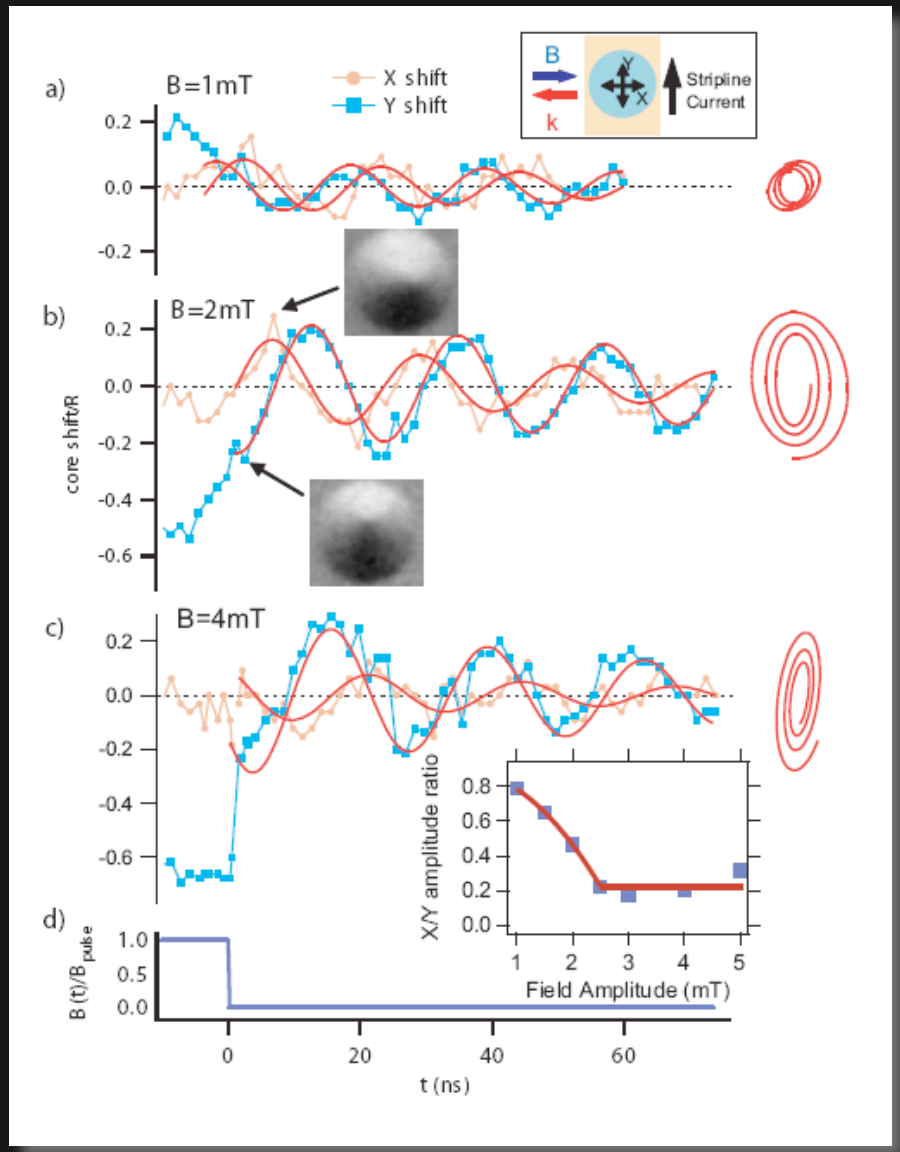
Core Position **X**=(*X*, *Y*)



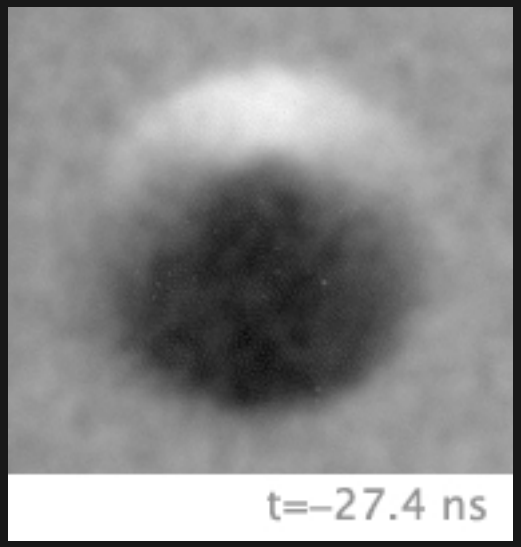
Resonance Frequency > 40 MHz

Bunch Frequency = 6.5 MHz

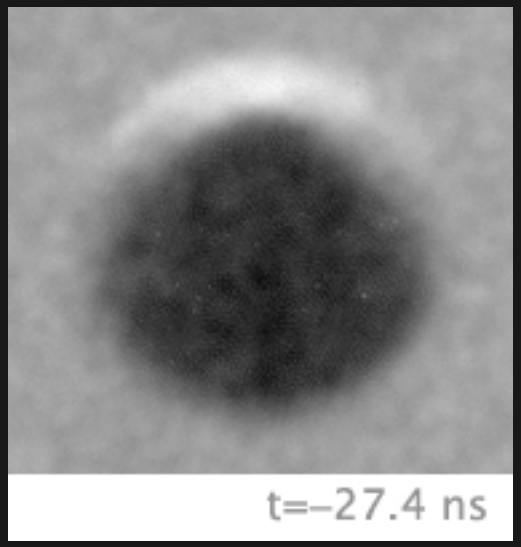
Vortex core positions D=6 μm



2 mT

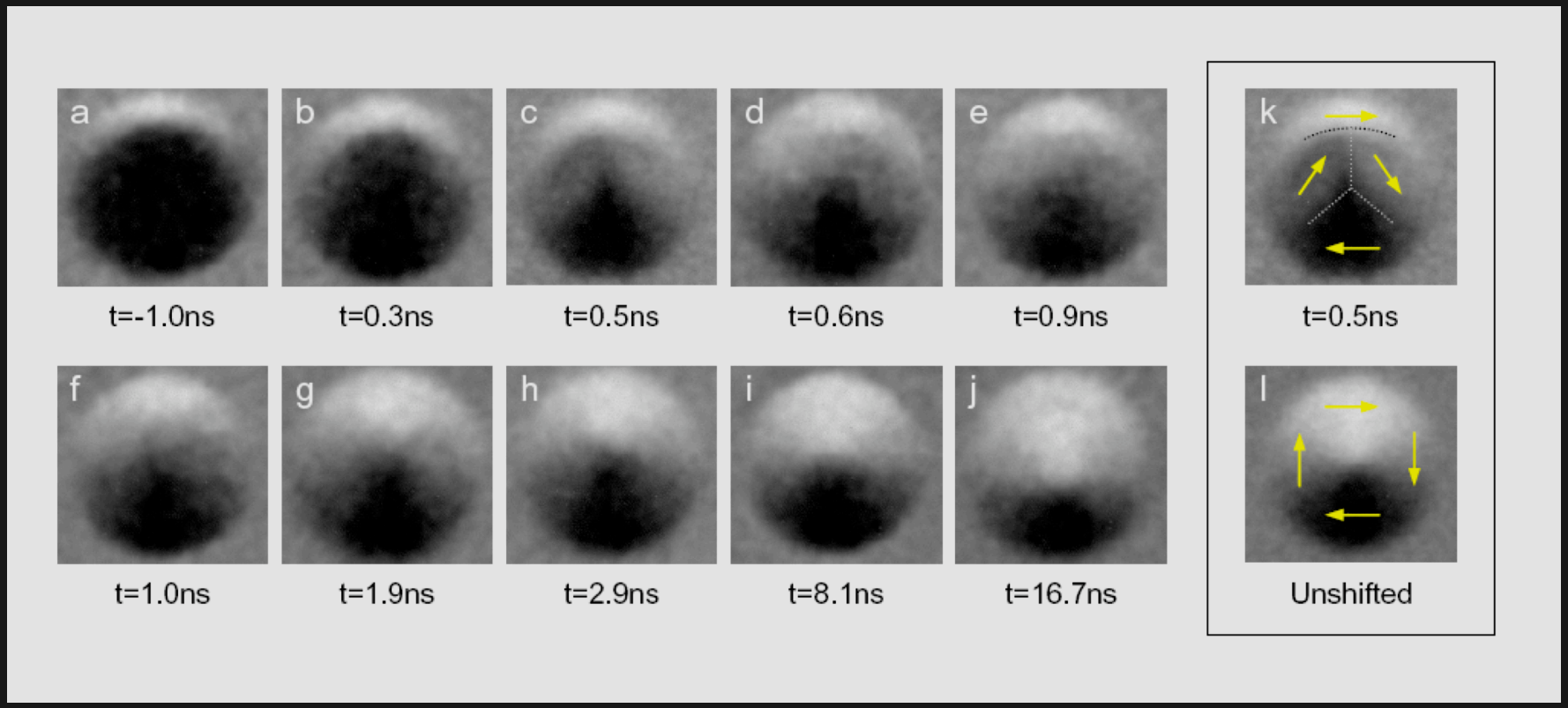


4 mT

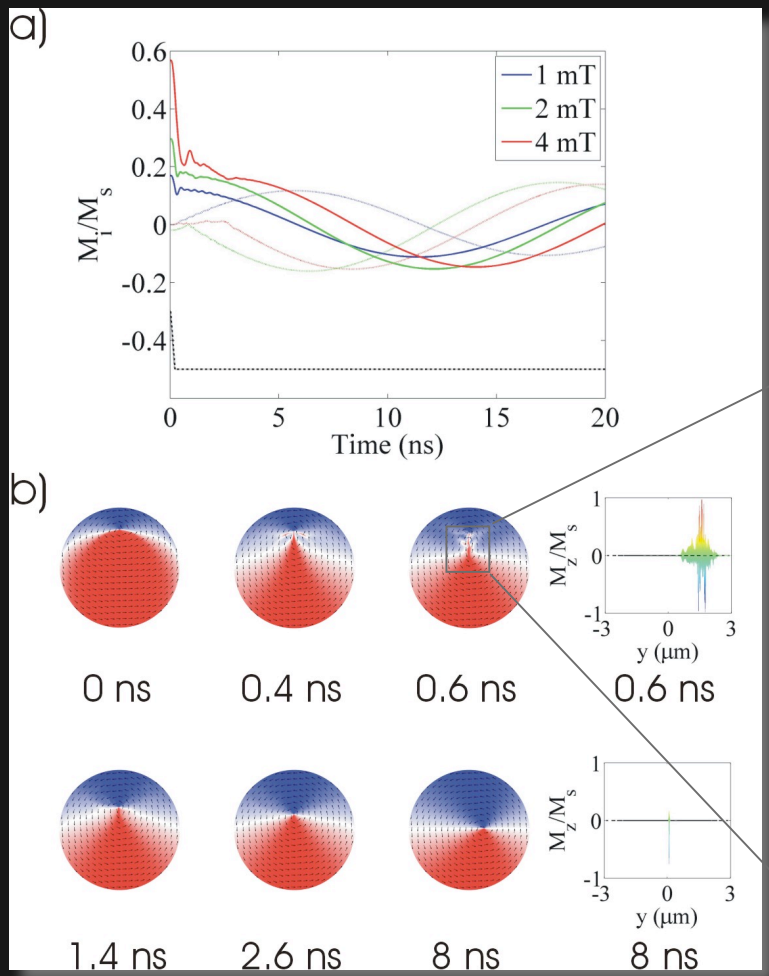


Transient States in first 1 ns

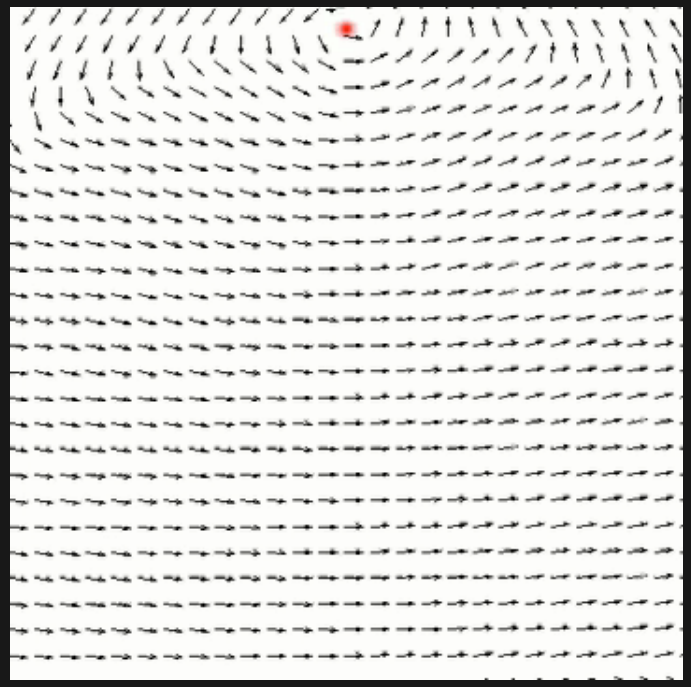
Transient Domain States seen at t=0 – 1 ns



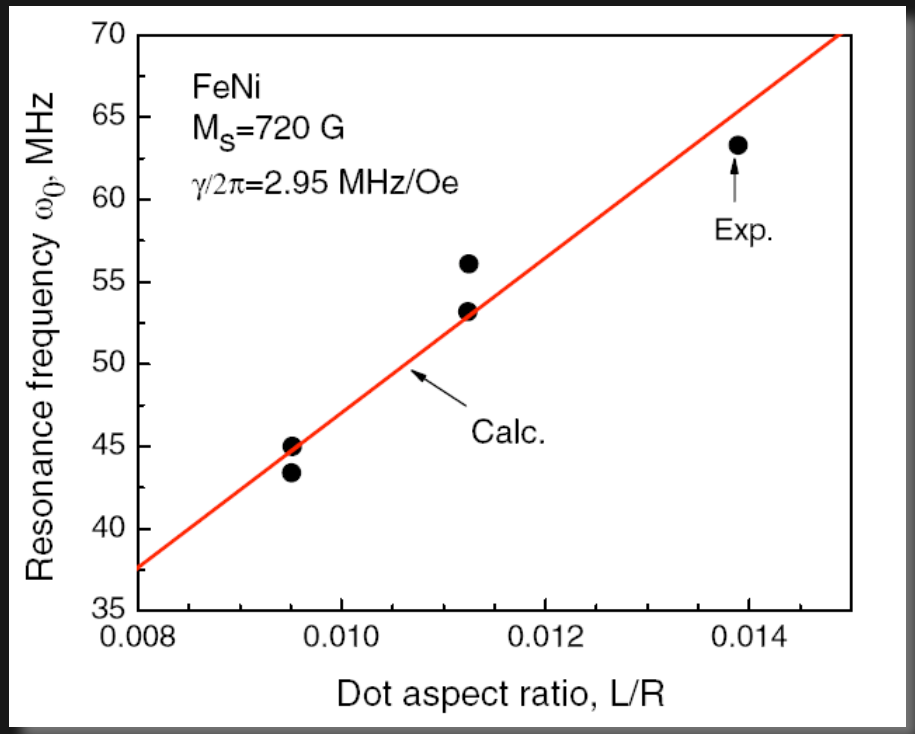
Micromagnetic Simulations: Transient States



- Simulations begin with equilibrium state for H_x = 1, 2, and 4 mT and with positive core polarization
  - Field is removed abruptly
- Trajectory appears circular for diameters from 100 nm to 6 microns



Analytical Theory: Oscillation frequencies and critical field



Vortex Core resonance frequency:

$$\omega = \omega_m \frac{5}{9\pi} \frac{L}{R}$$

where $\omega_m = \gamma 4\pi M_s$

Critical Field, Displacement:

H_{cr}/H_{an}~0.28

$H_{an}=c^{-1}M_s$~9.6 mT

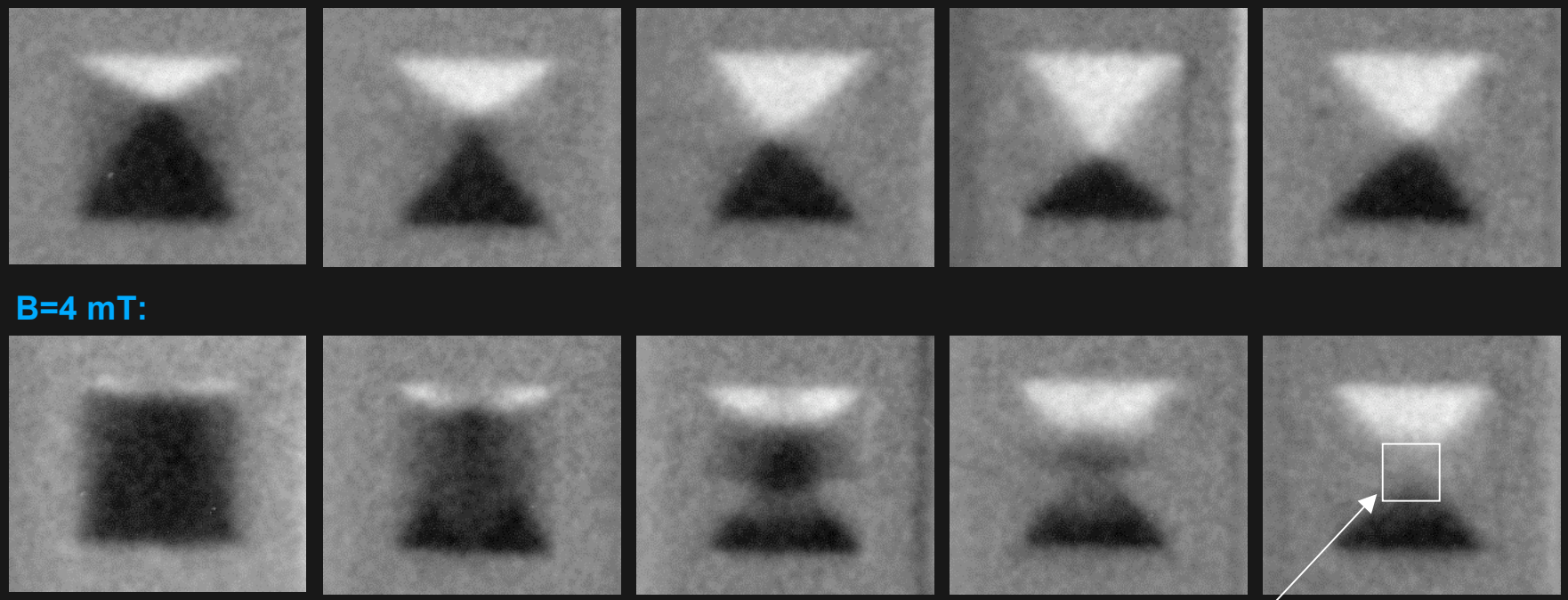
H_{cr}~2.7 mT

X_{cr}/R~0.28

Stochasticity in non-linear motion

Relaxation of 6 µm squares after field pulse

B=2 mT:



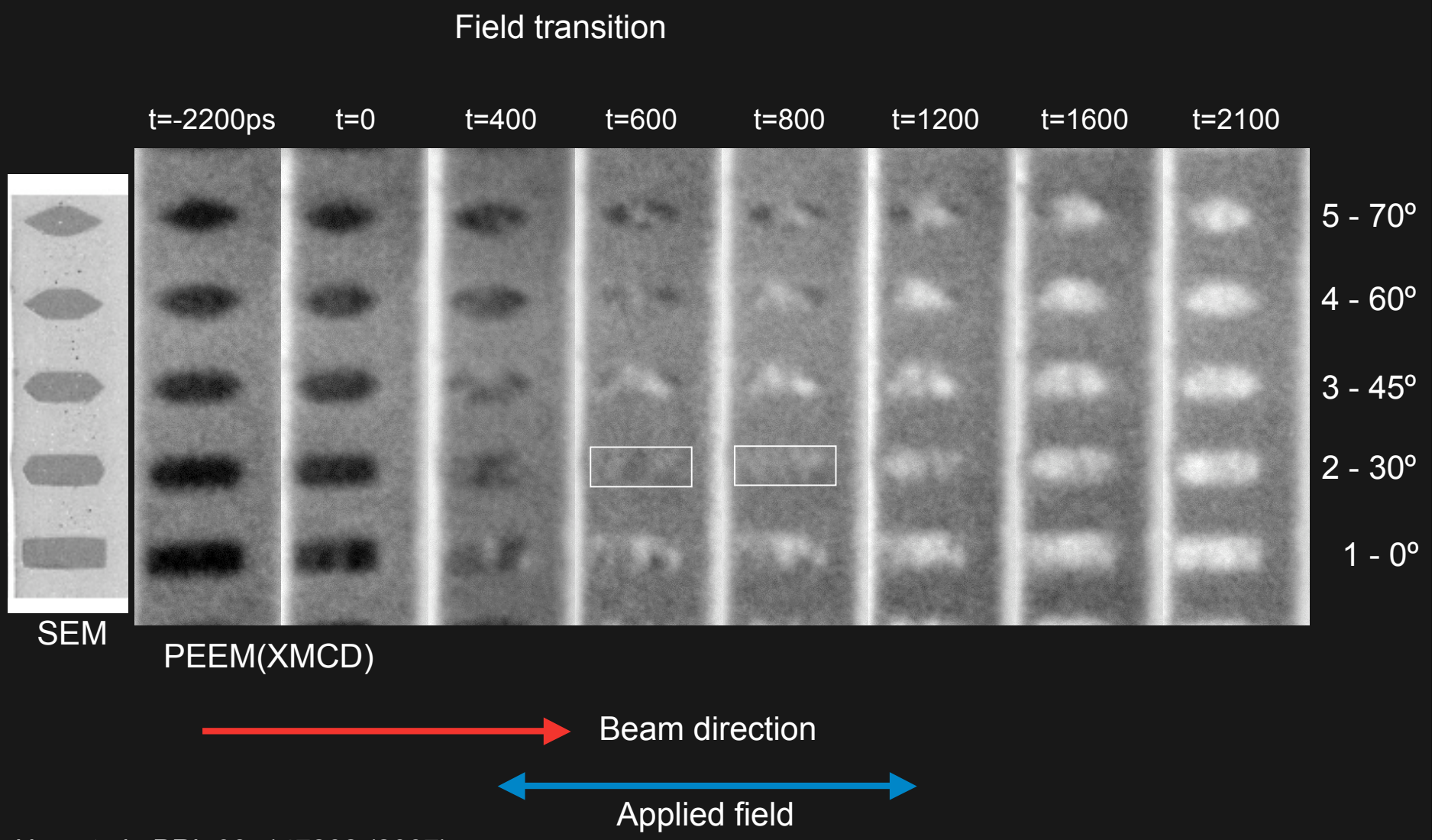
t=0 ns | t=+1.4 ns | t=+9.8 ns | t=+16.8 ns | t=+23.8 ns

B=4 mT:

Beam direction

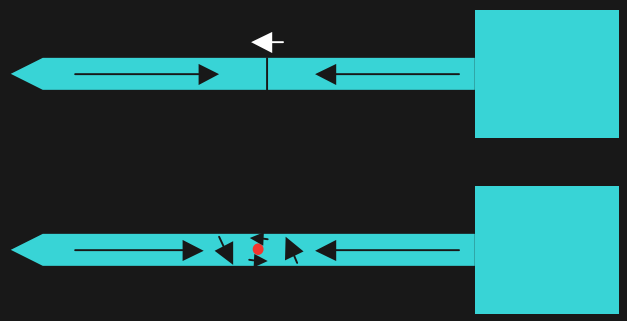
Random motion

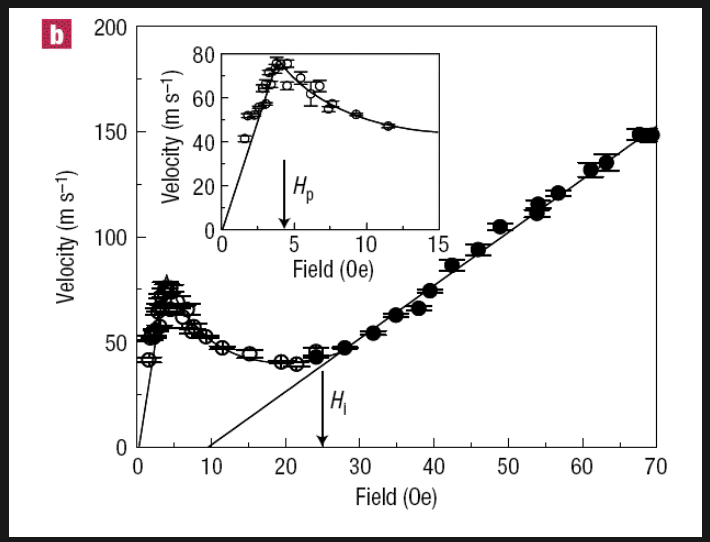
Magnetization Reversal



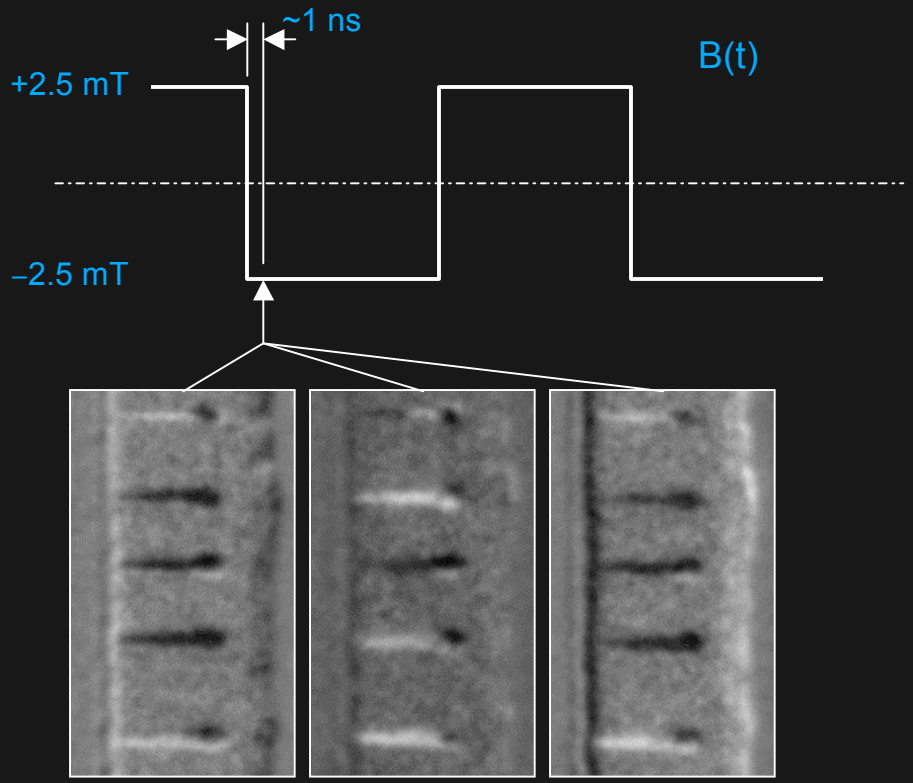
X. Han et al., PRL 98, 147202 (2007).

Random domain wall motion in nanowires





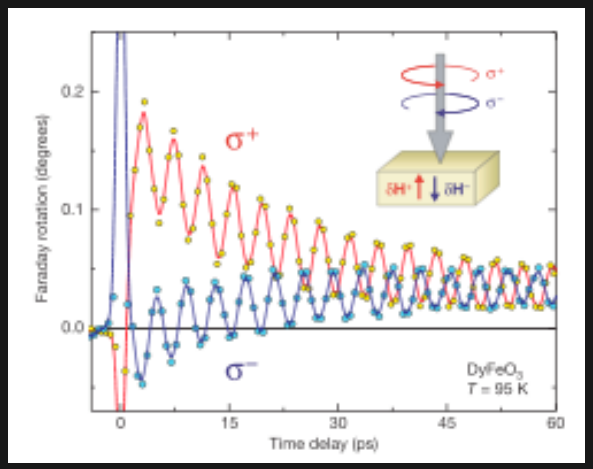
Beach et al., Nat. Mater. 4, 741 (2005).



Domain walls can be stable for ~10 min,
Long term they are not

Future experiments

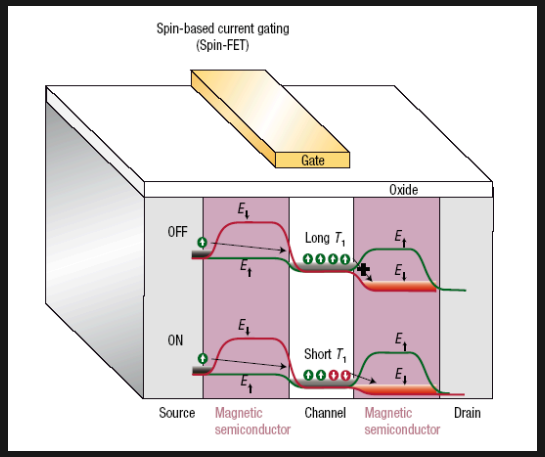
Optically induced magnetization processes



A.V. Kimel et al., Nature 435, 655 (2005).

Improved time resolution!

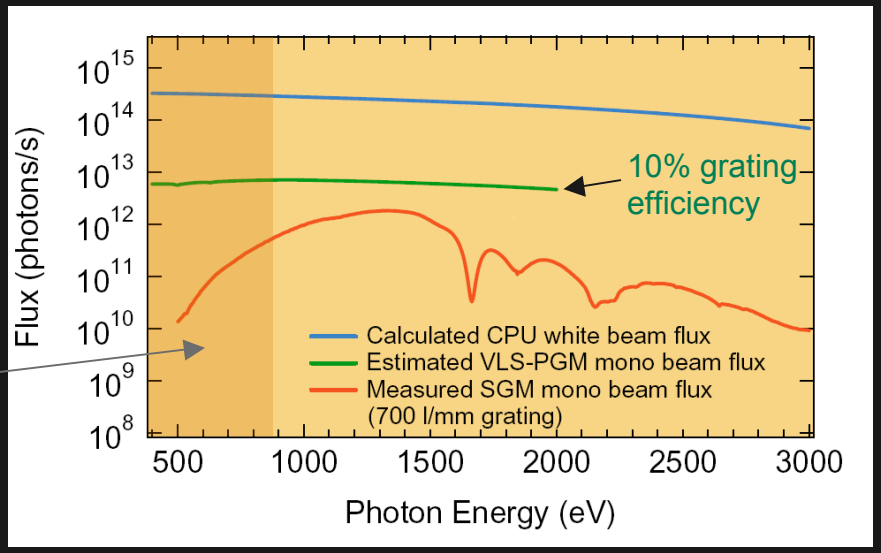
Spin transport



Spin-FET

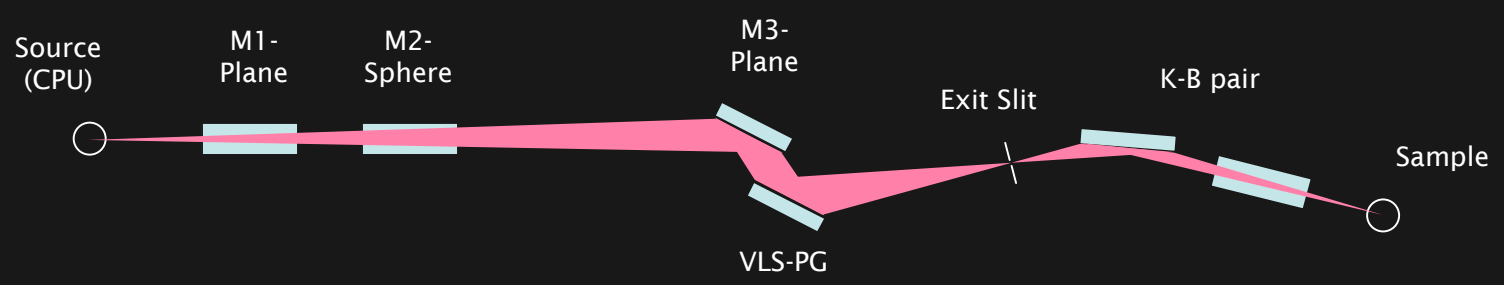
Improved sensitivity!

Proposed Upgrade to 4-ID-C



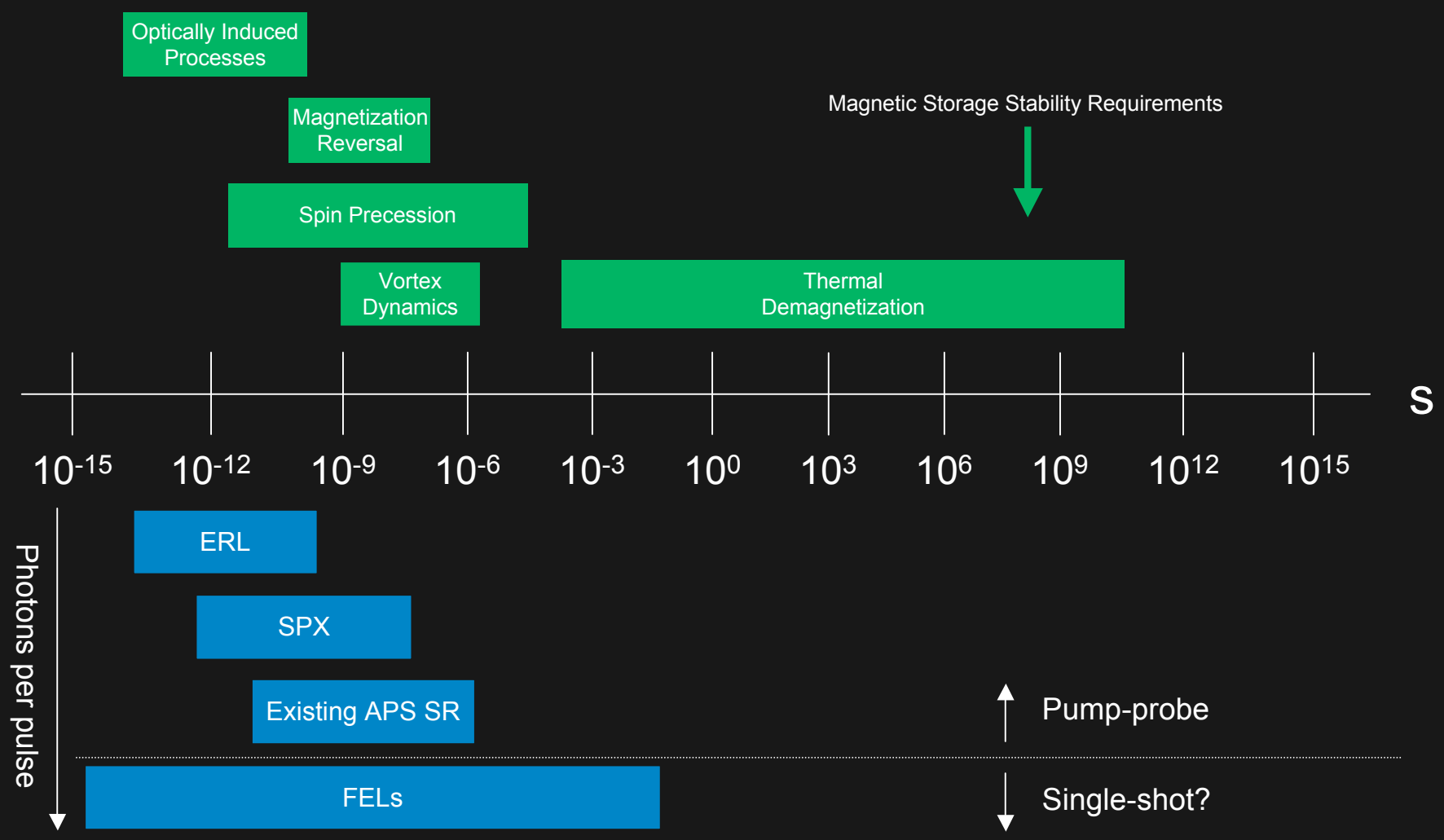
95% of beamtime requests

Proposed: varied line-spacing plane grating design
Energy range: 400-2000eV
Peak efficiency @ 1000eV
Resolution: 5000-10000



Improved flux by 1-2 orders of magnitude between 500 and 1000 eV.
~3 orders with new undulator

Future Sources



Summary

- Influence of Shape on Magnetization Reversal
  - Rectangular structures – end domains
  - Tapered structures – center domains
- Bias field dependence of vortex core trajectory
- Initial motion at high fields motion is complex
  - transient states
  - vortex-antivortex pairs
  - multiple core polarization reversal events
- Experimental critical field H_c~2.5 mT, core displacement X_c~0.2R agree well with simulations and analytical predictions
- Beware of stochasticity
  - may be induced by choice of shape and driving field