Spin Dynamics in Ferromagnetic Microstructures

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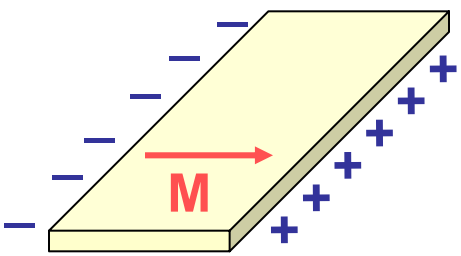
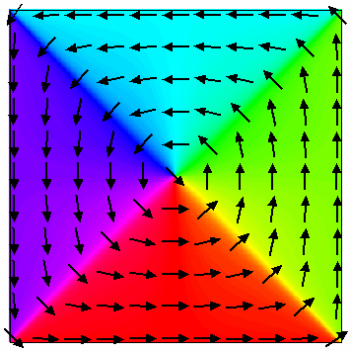
How are spin dynamics (frequency and time scales, mode structure) influenced by confinement?

1. What are the normal modes of an inhomogeneous magnetic system?





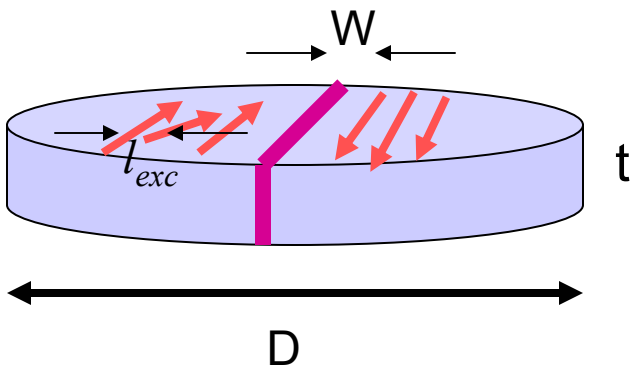
2. How is their “character” determined by length scale and/or magnetic microstructure?

Supported by NSF DMR99-83777 and the NSF MRSEC Program

Length Scales and Time Scales

1. Largest dimension of system (D)
   - magnetostatic modes for λ < D.

2. Domain wall thickness *W.*



3. Exchange length

$$l_{exc} = \frac{\sqrt{2\pi A}}{M_S}$$: Compare $E_{exc} = A(\nabla \mathbf{m})^2$ with $E_D = 2\pi M_S^2$.

   Spin waves for $l < l_{exc.}$

4. Smallest physical dimension of system (*t* for a thin film).

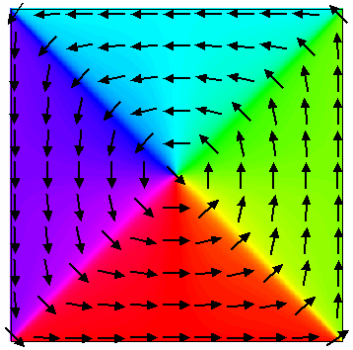
What happens when two or more of these length scales are close together?

1. Experiment: patterned structures: real time and real space

2. Modeling: semianalytical + simulation

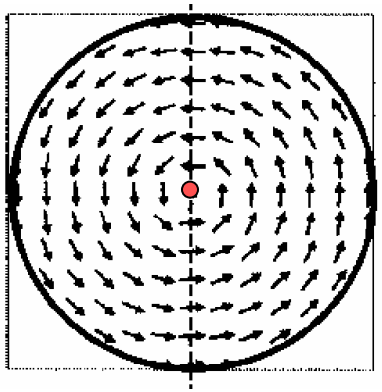
Length scales: 10 nm to 10 μm; Time scales: 50 psec to 10 nsec

Patterned Permalloy Films



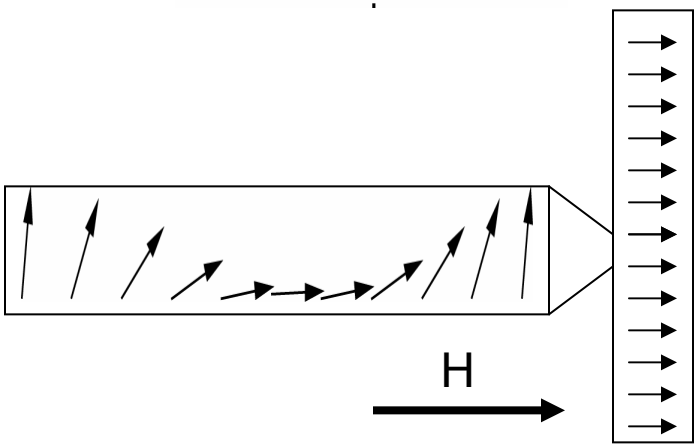
Closure Domains in Square Elements

- "Domain" and "wall" modes scale inversely with lateral size
- Damping time decreases with lateral size



Vortex Structures

- Gyrotropic mode at low frequencies
- Higher modes with more magnetostatic character
- Weak dependence of dynamics on position of the vortex core

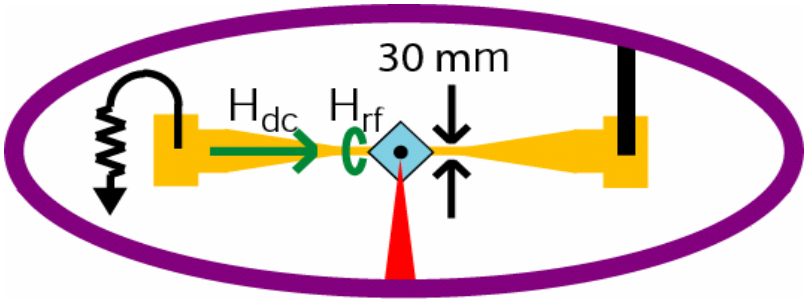


Inhomogeneous Magnetization in Wires

- Inhomogeneous internal field AND inhomogeneous magnetization
- Crossover modes

Experiment

Time-resolved Kerr microscopy

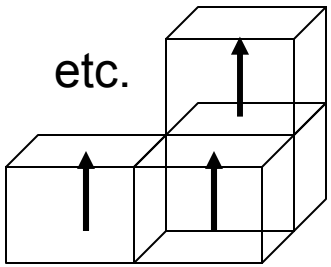


- Pulsed excitation: ~ 150 psec FWHM
- Spatial resolution: ~ 800 nm
- Measurement of ΔM_z: the change in the *z*-component of *M* due to the pump pulse

[Freeman *et al.,* J. Appl. Phys. **79**, 5898 (1996)]

Simulation

Landau-Lifshitz-Gilbert



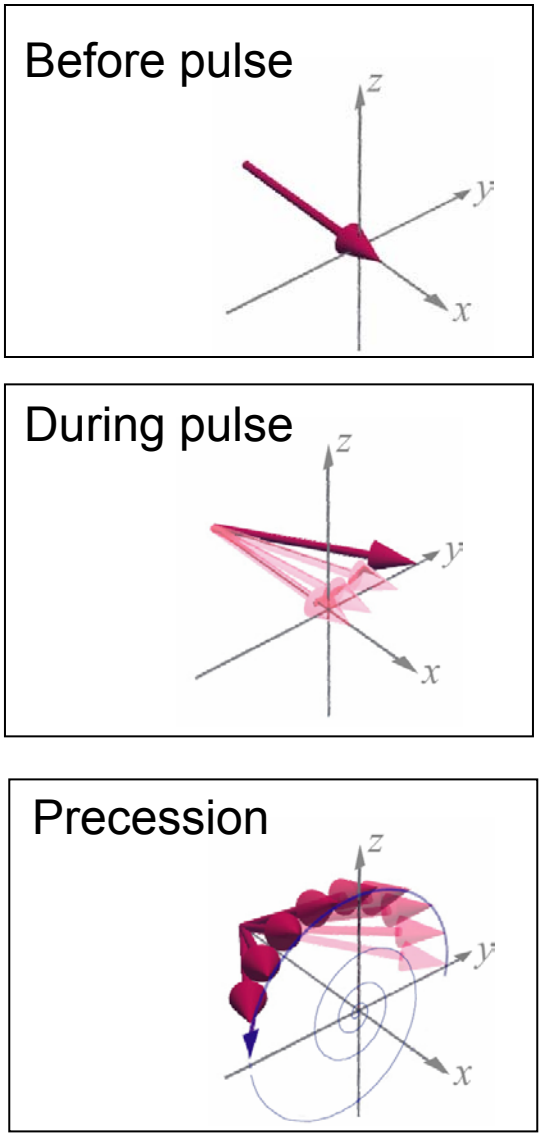
$$\frac{\partial \mathbf{M}_i}{\partial t} = -\gamma(\mathbf{M}_i \times \mathbf{H}_{eff,i}) - \frac{\gamma\alpha}{M_S}\mathbf{M}_i \times (\mathbf{M}_i \times \mathbf{H}_{eff,i})$$

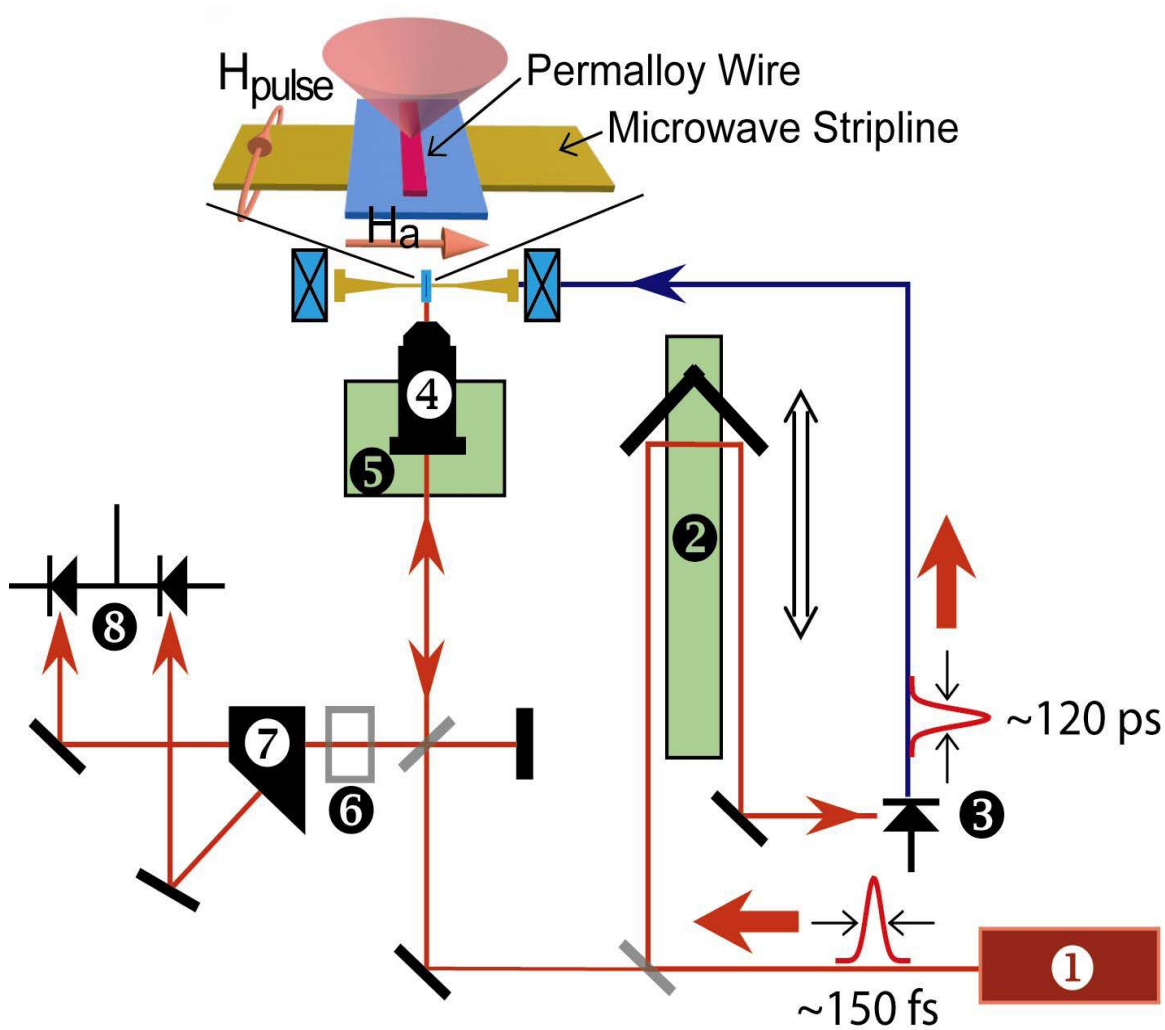
H_{eff} includes:

1) Static applied field
2) Exchange field
3) Time-dependent applied field
4) Demagnetization field

- NIST OOMMF code (single-layer)
- LLG (Scheinfein) - multilayer

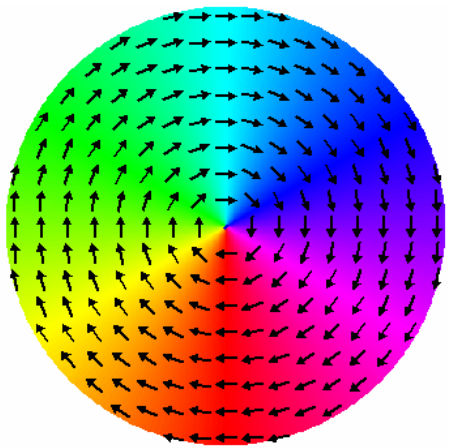
Time-Resolved Kerr Microscopy





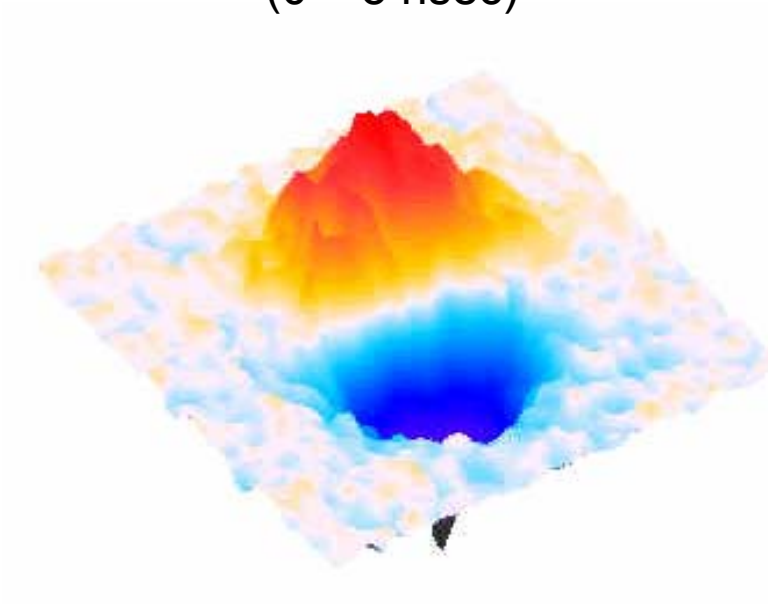
[Freeman *et al.*, J. Appl. Phys. 79, 5898 (1996)]

Full Time-Resolved Images (Movies)

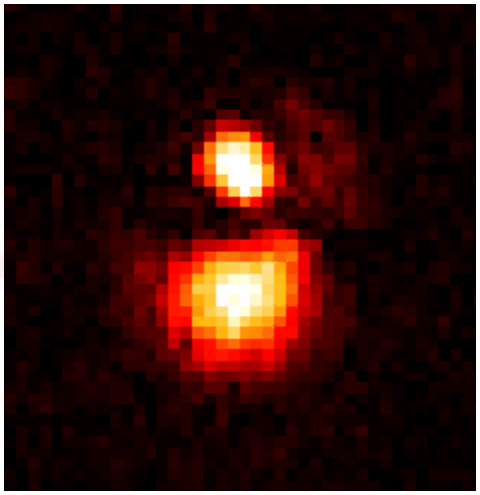


D = 1 μm

Real Time Movie
(0 – 5 nsec)



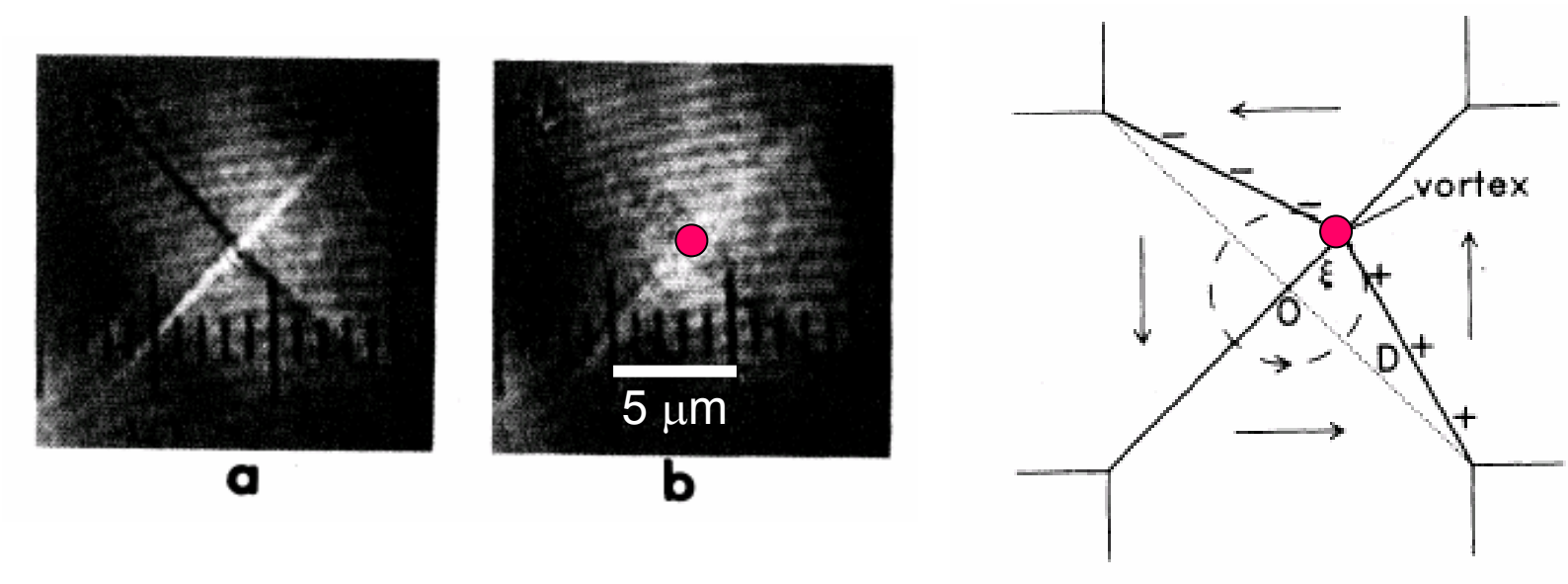
Spectral Power
Movie (0 – 8 GHz)



J. P. Park *et al.,* Phys. Rev. B **67**, 020403R (2003)

Phase images: see M. Buess *et al.,* Phys. Rev. Lett. **93**, 077207 (2004)

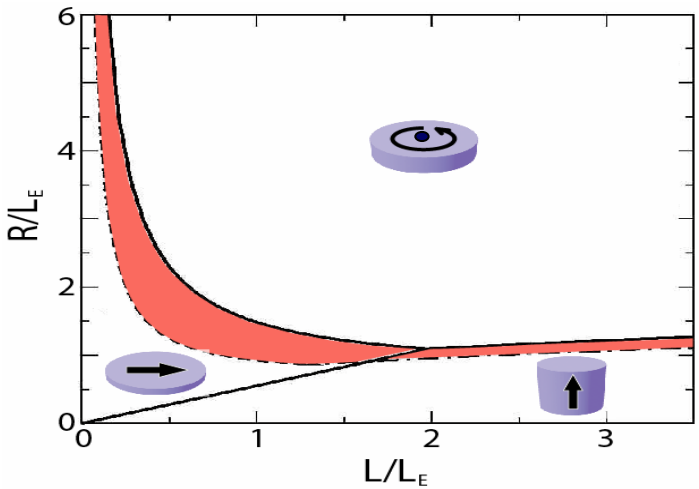
Low-frequency Dynamics: A Magnetic Vortex



- B. E. Argyle, E. Terrenzio, and J. C. Slonczewski, Phys. Rev. Lett. **53**, 190 (1984)
- A. A. Thiele, Phys. Rev. Lett. **30**, 230 (1973) (Bubble domain dynamics)

Vortices in Permalloy Disks

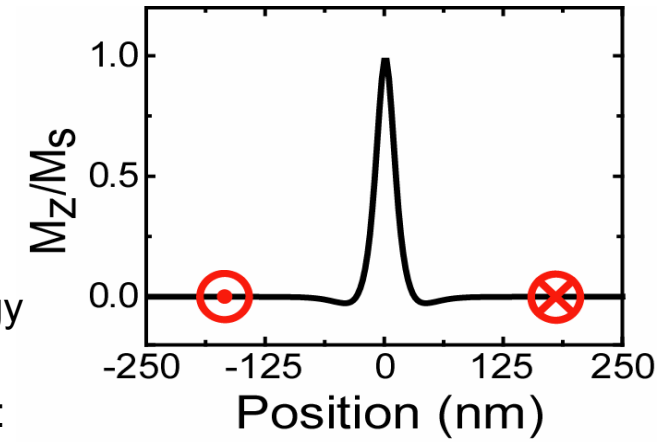
- Phase diagram of nanoscale cylinders



Exchange energy

⇕

Magnetostatic energy

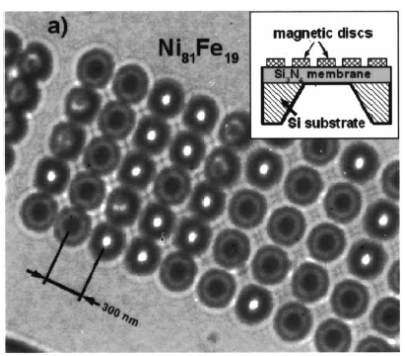


Size of vortex core:

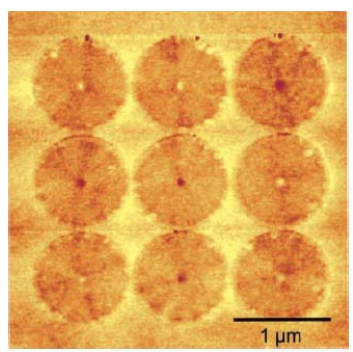
$$2\sqrt{A/2\pi M_S^{\,2}} = 10nm$$ for $Ni_{0.81}Fe_{0.19}$

K.L. Metlov *et. al.*, J. Magn. Magn. Mater. 242-245 (2002) 1015

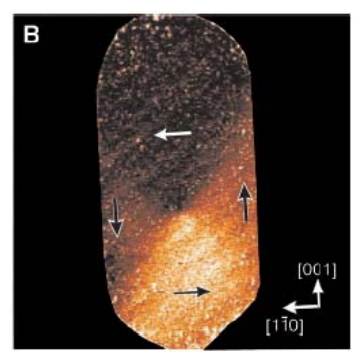
- Observation of magnetic vortices



1) Lorentz Microscopy on 200 nm Co disk



2) MFM on 1 µm Permalloy disk

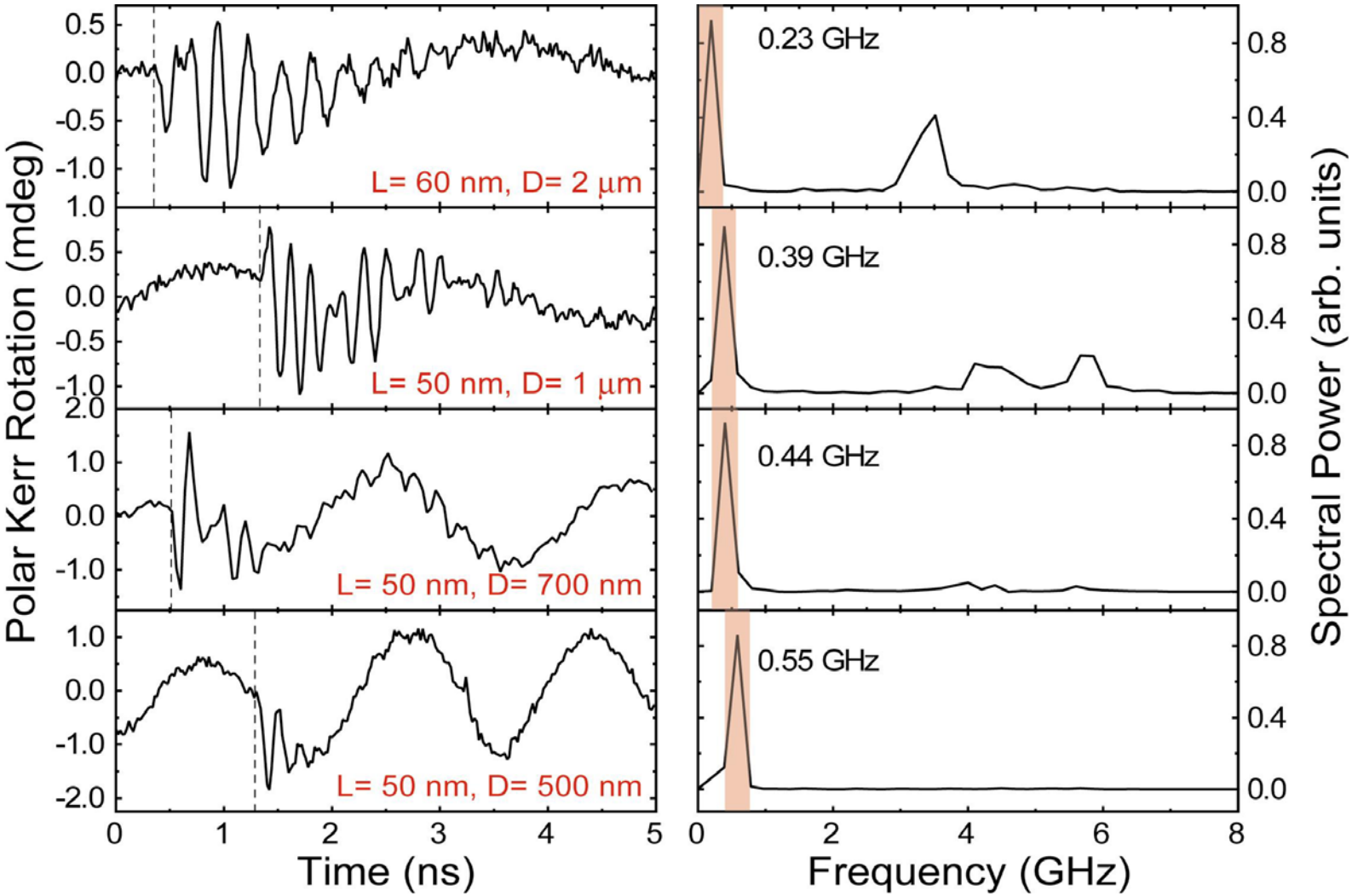


3) SP-STM on 200 nm wide and 500 nm long Fe island

1) J. Raabe *et al*. J. Appl. Phys. 88, 4437 (2000)
2) T.Shinjo *et al*. Science 289, 930 (2000)
3) A. Wachowiak *et al.* Science 298, 577 (2002)

Time Scans on Vortex Structures at Fixed Position

In 0 Oe Applied Field (L= thickness, D= diameter)



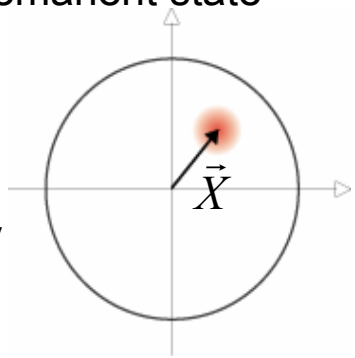
Vortex Dynamics

- Analytical solution for vortex eigenfrequencies in the remanent state

  K. Yu. Guslienko *et al.* J. Appl. Phys. 91, 8037 (2002)

$$\vec{G}\times\frac{d\vec{X}}{dt}-\frac{\partial W(\vec{X})}{\partial\vec{X}}=0,\quad \begin{cases}\vec{V}=\dfrac{d\vec{X}}{dt}=\vec{\omega}\times\vec{X} \quad where\ \vec{\omega}=\omega\hat{z}\\ W(\vec{X})\end{cases}$$

: total magnetic energy of a shifted vortex

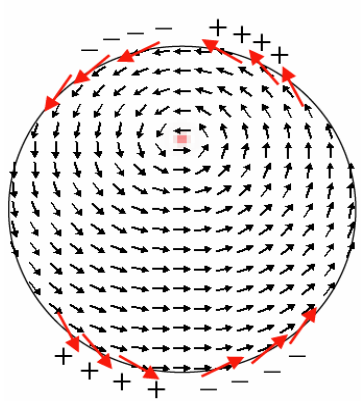


$$\omega=\frac{1}{2}\gamma M_S\frac{\xi^2}{\chi(0)}\quad ,<\vec{m}>_{in-plane}\times\hat{h}\equiv\xi\cdot a$$

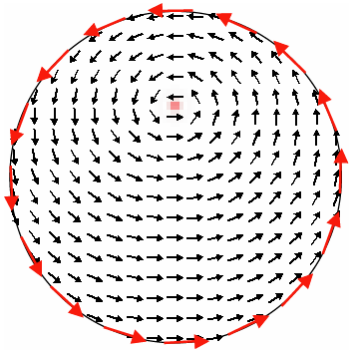
$\dfrac{\omega_0}{2\pi}\approx$ 1 GHz for β = L/R ~ 0.2

- Two different models used to calculate the total magnetic energy $W(\vec{X})$

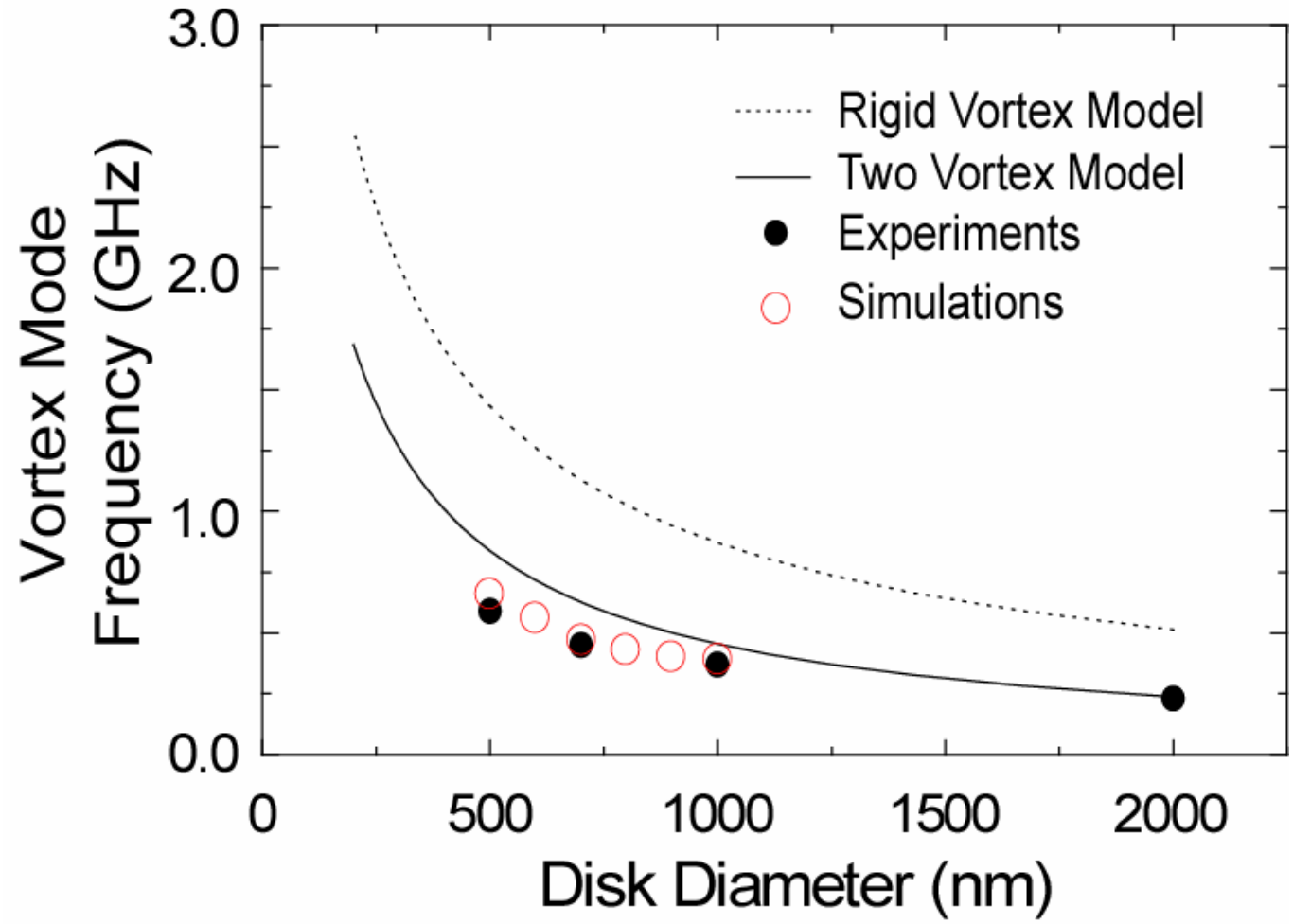
[Rigid vortex model]



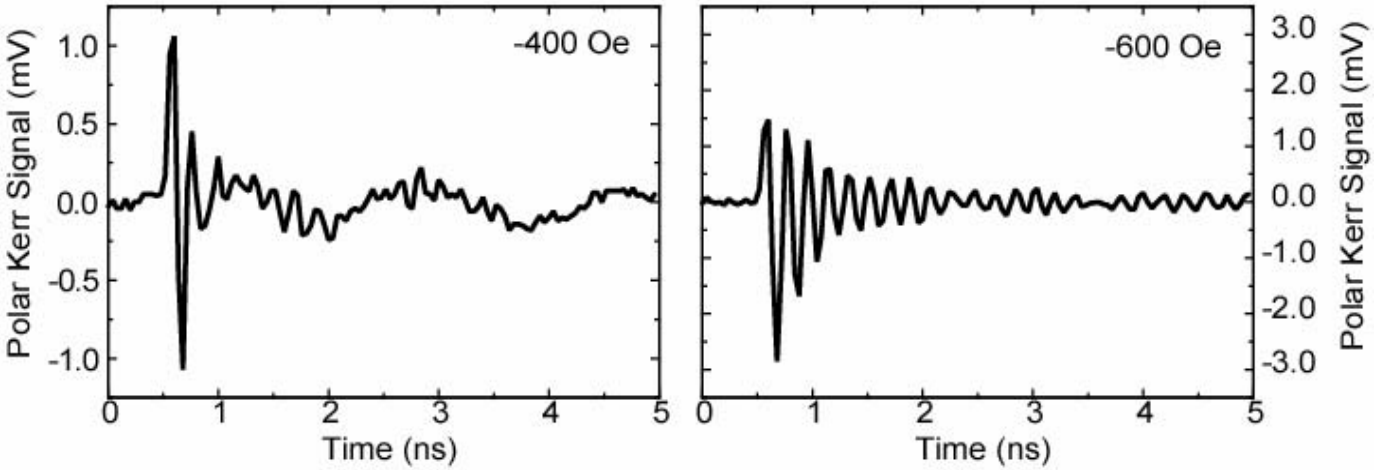
[Two-vortex model with no side surface charges]

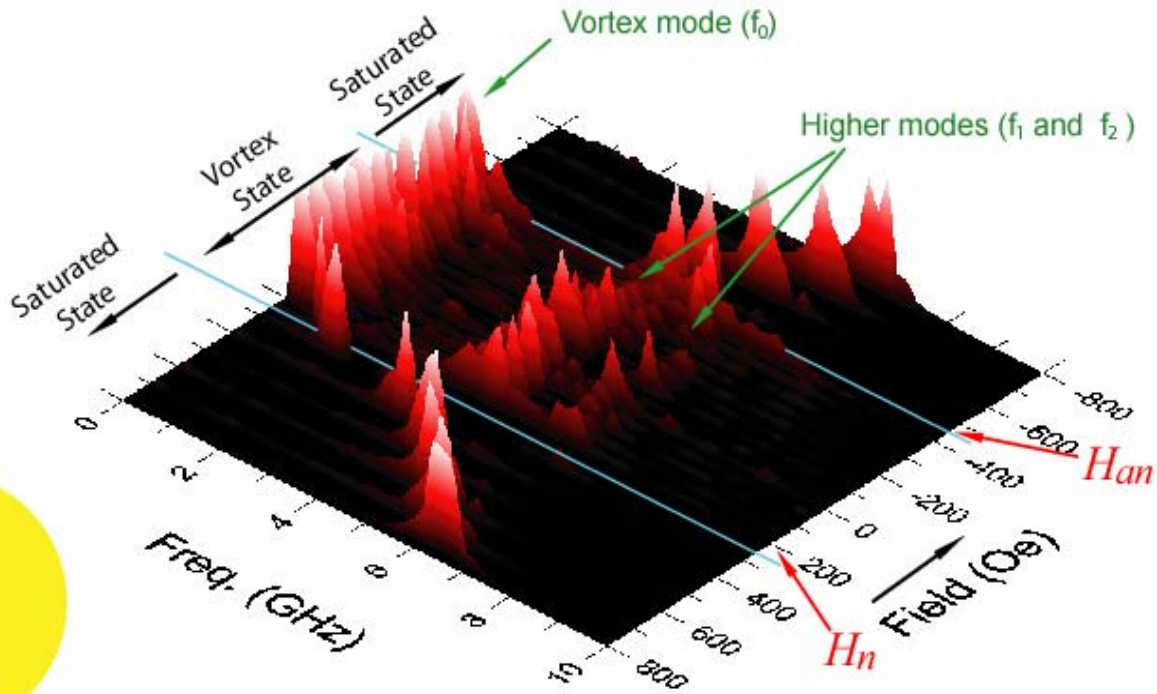


Summary of Results



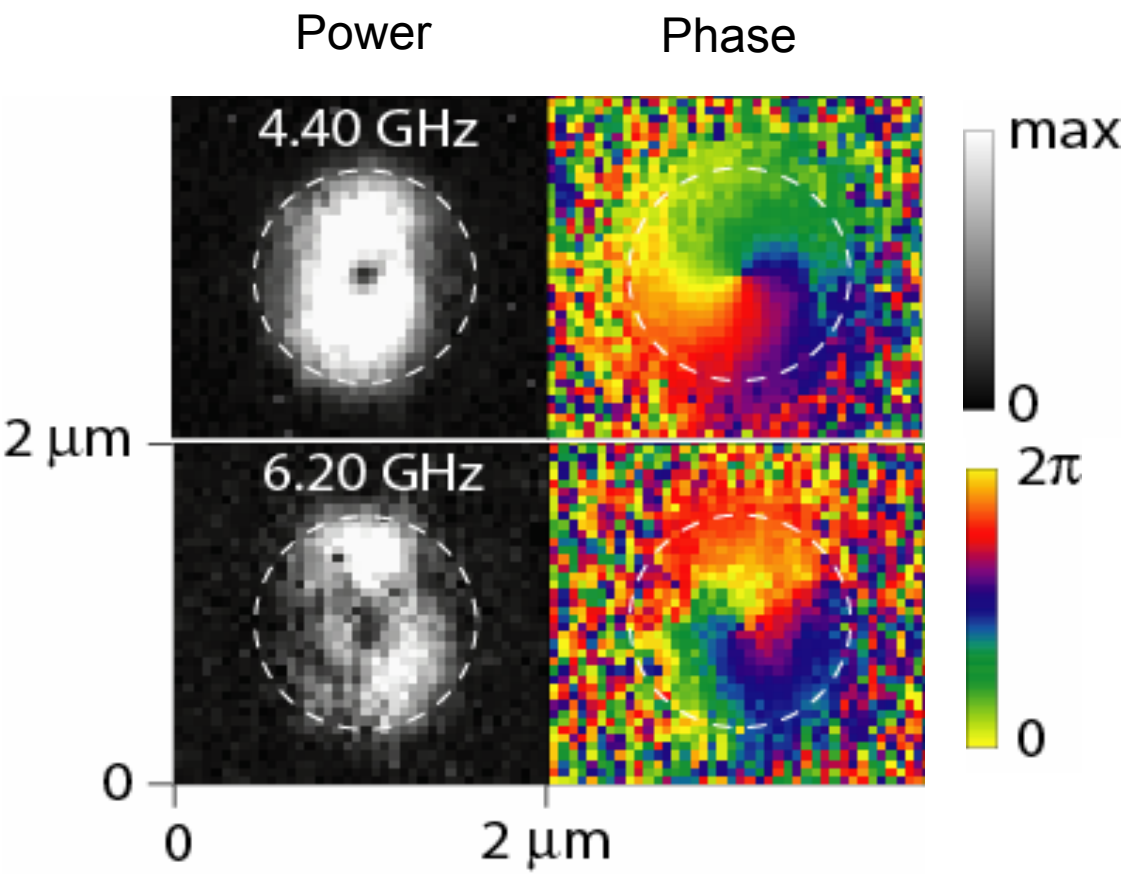
Vortices in a Magnetic Field

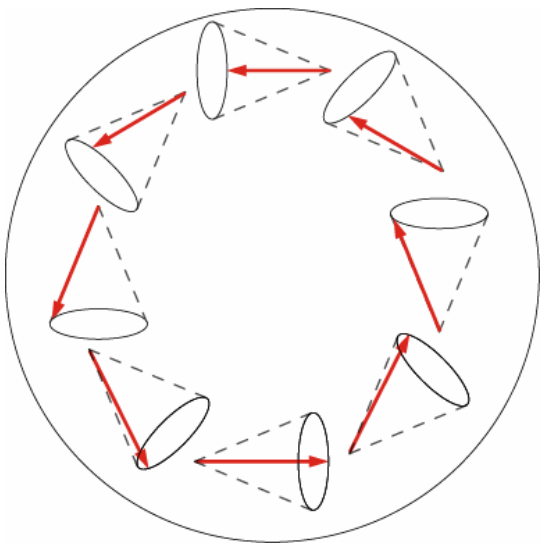




Power and Phase Maps of Higher-Order Modes

FFT power and phase maps corresponding to 4.4 GHz and 6.2 GHz spin-wave modes measured on a 1 μm disk

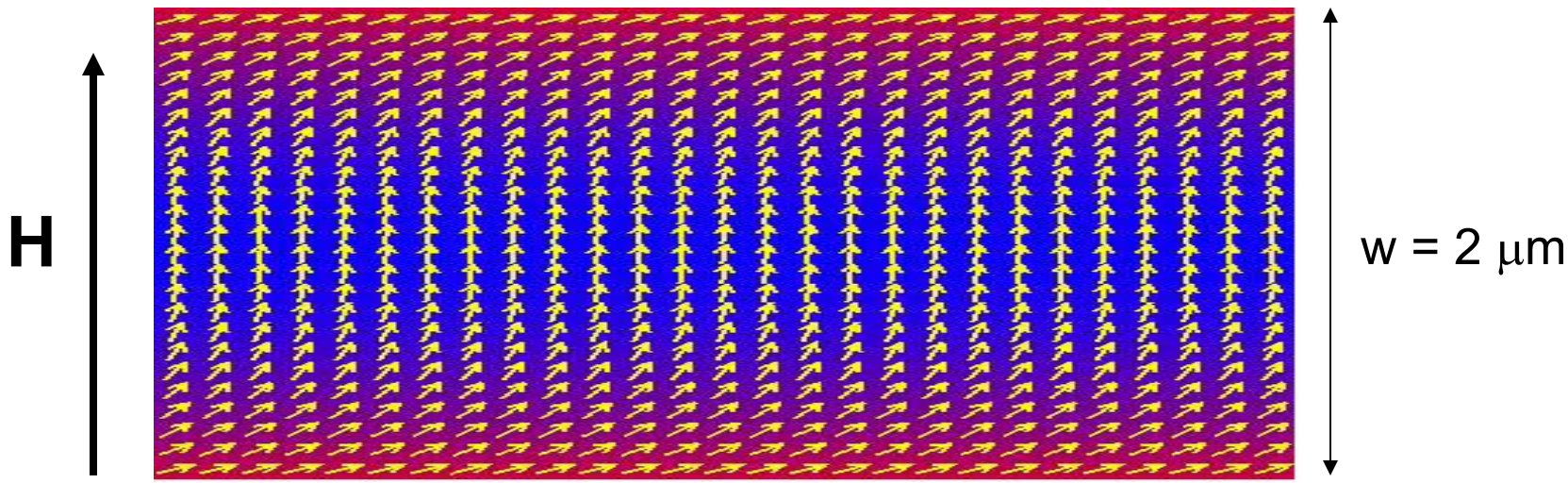


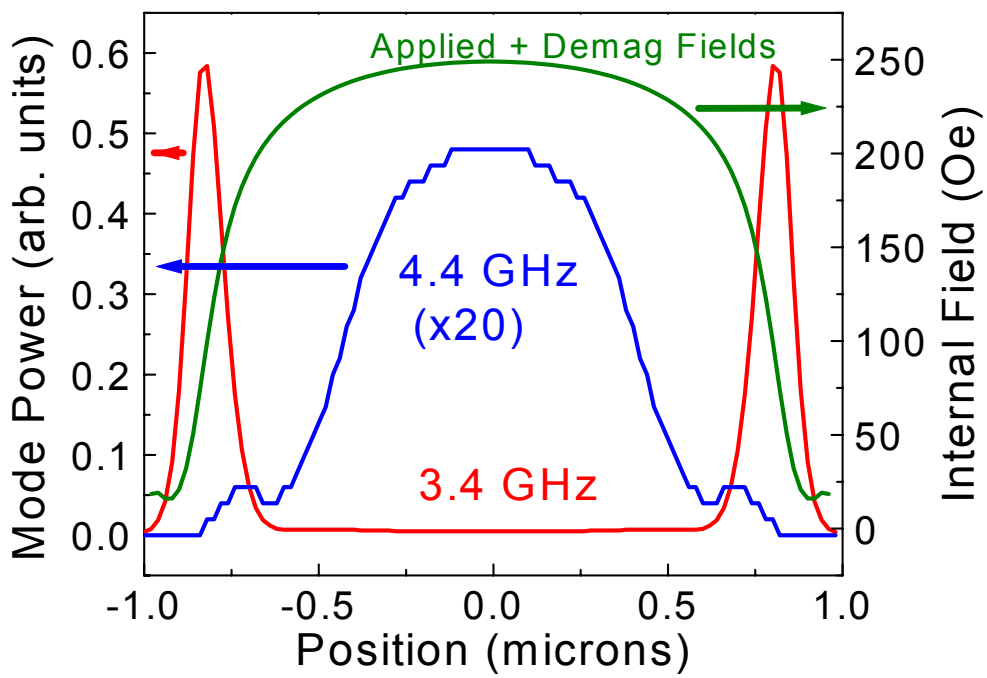


$\vec{q} \,//\, \vec{M}$

The 6.2 GHz mode is not completely understood.....

Quasi-One Dimensional Wires: Spin-wave Localization





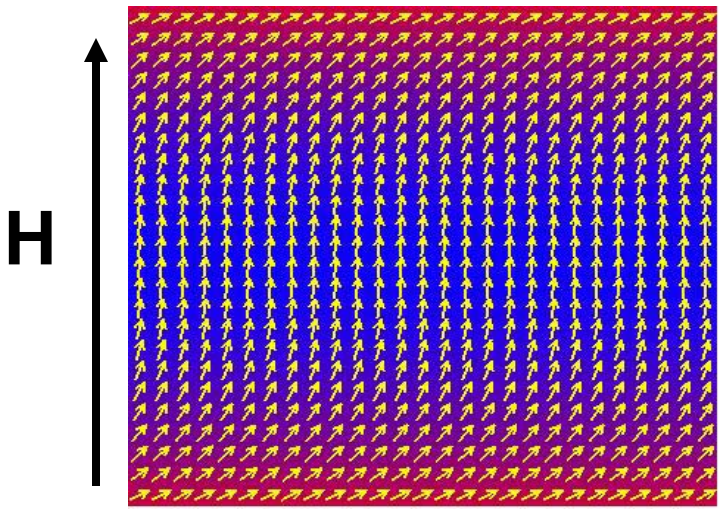
- J. Jorzick *et al.*, Phys. Rev. Lett. **88**, 047204 (2002)
- J. P. Park *et al.*, Phys. Rev. Lett. **89**, 277201 (2002)
- C. Bayer *et al.*, Appl. Phys. Lett. **82**, 607 (2003)

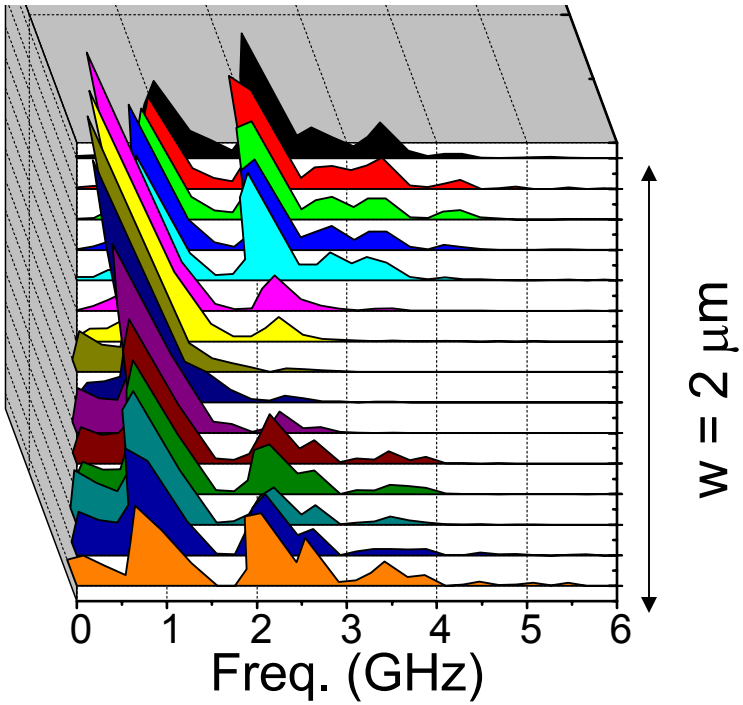
What about the magnetization gradient?

- Spin-waves are localized by *magnetic field gradients.* What about the magnetization gradient?

Soft modes: M. Bailleul *et al*., Phys. Rev. Lett. **91**, 137204 (2003)

Crossover Modes: C. Bayer *et al.,* Phys. Rev. B **69**, 134401 (2004)





Modes above the fundamental FMR mode are observed only in regions where the magnetization gradient is large. These are not localized modes! They are extended across the wire but only have a small wave-vector near the edge.

What else is being done now?

- Other systems: exchange biased films, composites, switching (see talk by Mark Freeman)
- "All-optical" pump-probe: high effective bandwidth, but difficult to model; can address other problems (e.g. AFM, see recent work from Njimegen)

What is needed?

- Higher spatial resolution - approaching the exchange length (to study "real" spin waves)
- Full-field technique - useful for characterization tools; essential for measurements at low repetition rates.....

- Time-resolved PEEM: S.-B. Choe *et al.,* Science 304, 420 (2004)

- Increased bandwidth? (to match optical pump-probe)
- Operation in magnetic field?
- Buried structures
- Element specificity.....