Micromagnetic dynamics
as revealed by optical microscopy

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Maxtor, Read-Rite, Seagate

Outline

- spin dynamics inside a ferromagnet
- spatiotemporal imaging
- microstructure examples
  - -- ferromagnetic resonance
  - -- dynamic magnetization reversal
  - -- device physics
- prospects

spin dynamics inside a ferromagnet

oscillation and damping

dictated by precession around an effective magnetic field **H** with contributions from: dipolar and exchange coupling to other spins; crystalline anisotropies; external sources.

dictated by electron, spin wave (magnon-magnon) and phonon scattering processes

the *equation of motion* for a macrospin **M** (subvolume of essentially parallel alignment enforced by exchange interaction)

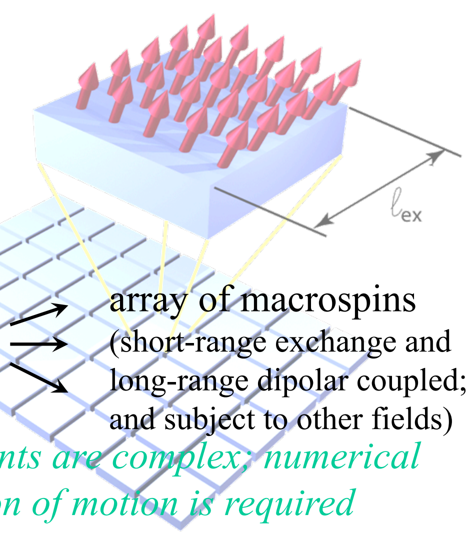
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \; \mathbf{M} \times \mathbf{H} - \frac{\gamma \lambda}{M^2} \mathbf{M} \times (\mathbf{M} \times \mathbf{H})$$

first written down by Landau and Lifshitz; phenomenological damping description has been remarkably successful

or, in Gilbert form:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \; \mathbf{M} \times \mathbf{H} + \frac{\alpha}{M} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$

("frictional" damping proportional to the time rate of change of **M**; the length of vector **M** is not allowed to change, however)



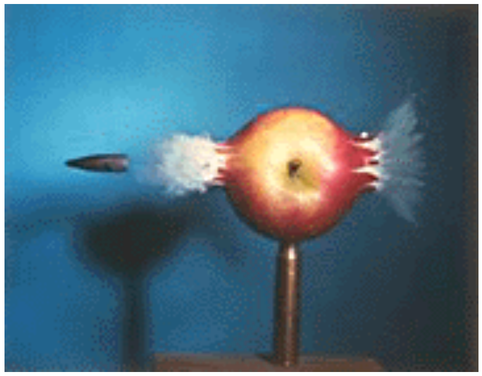
levels of organization:

single spin → "macrospin" (small ensemble of spins, Heisenberg exchange coupled) → array of macrospins (short-range exchange and long-range dipolar coupled; and subject to other fields)

typical arrangements are complex; numerical solution of equation of motion is required

and for the experimentalist: what about ***spatiotemporal imaging*** *?*

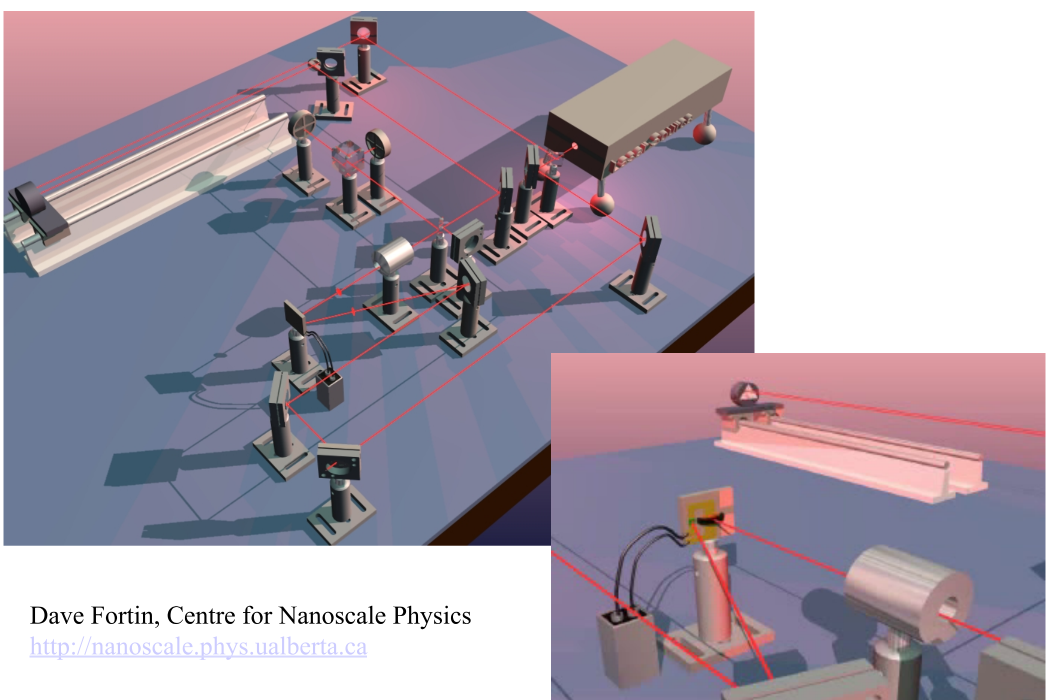
How do we image fast dynamic processes?



Stroboscopic photograph,
H.E. Edgerton, 1931.

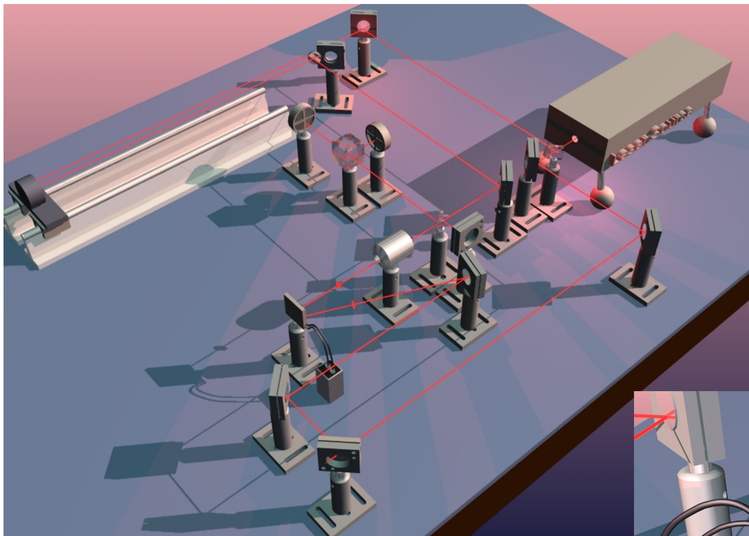
"What to do when it's too fast to see: Freeze-frame imaging, from racehorses to atoms", M.R. Freeman, Physics in Canada 54, 148 (1998)

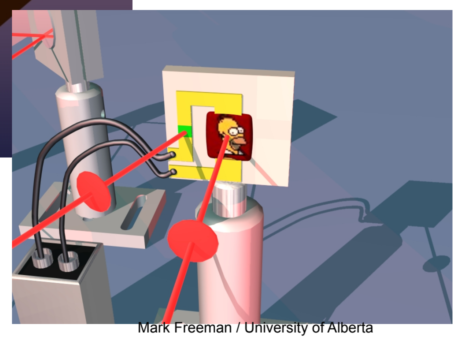
Time-Resolved Scanning Kerr Microscopy



Dave Fortin, Centre for Nanoscale Physics
http://nanoscale.phys.ualberta.ca

Time-Resolved Scanning Kerr Microscopy





Dave Fortin, Centre for Nanoscale Physics
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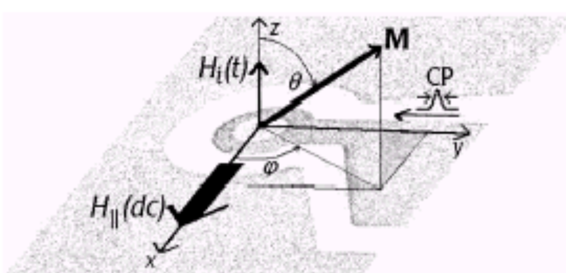
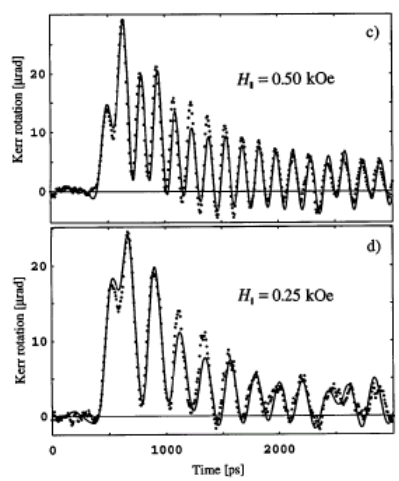
Time-resolved ferromagnetic resonance



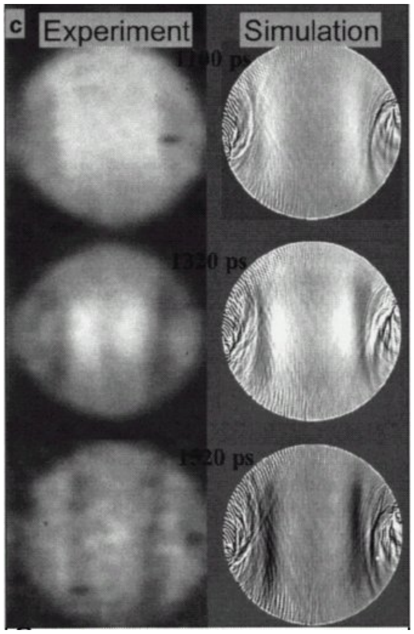
scanning electron micrograph of sample and coil, with superimposed field geometry



characteristic time domain data (and simple fit, neglecting finite size of specimen)

Ferromagnetic resonance imaging:

correspondence of spatiotemporal experiment and simulation



H_{ext} = 250 Oe

t = 1100

1320

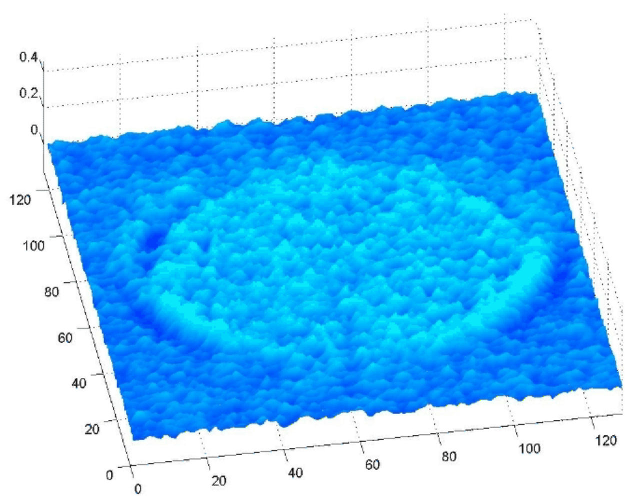
1520 ps

Hiebert, Ballentine, Freeman,
Phys Rev. B **65**, 140404(R) (2002)

long wavelength modes seen directly; short wavelength, indirectly

Ferromagnetic resonance imaging:

animation of response of elliptical resonator



Miro Belov

H_{ext} = 70 Oe

Hecht, *Optics*

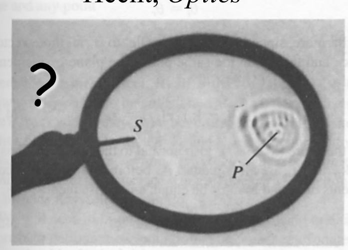


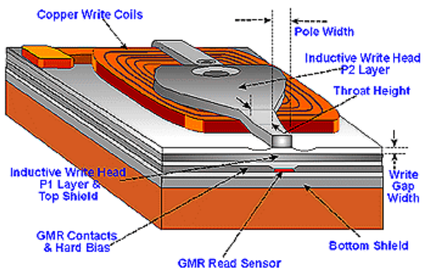
Figure 4.37 Reflection off an ellipsoidal surface. Observe the reflection of waves using a frying pan filled with water. Even though these are usually circular, it is well worth playing with. (Photo courtesy *PSSC College Physics*, D. C. Heath & Co., 1968.)

Magnetization reversal dynamics

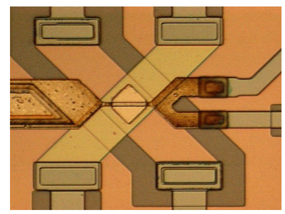
How ?
How fast ?
Controllable ?

practical interests:

performance of recording devices and media



www.almaden.ibm.com/sst

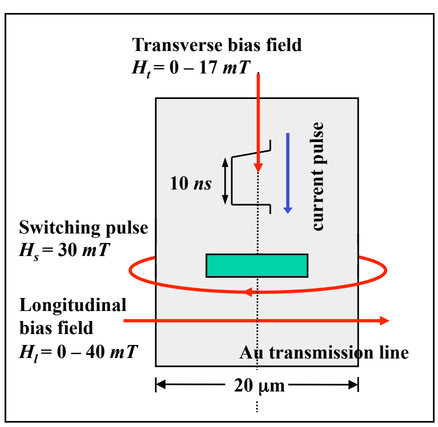


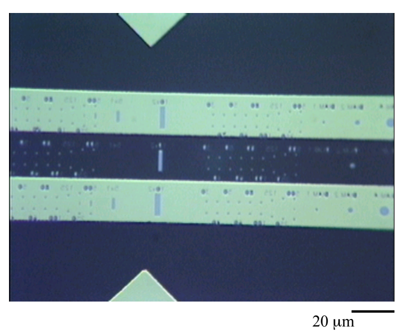
Naval Research Lab

speed of integrated magnetic memory?

Mark Freeman / University of Alberta

Dynamic magnetization reversal in a $Ni_{80}Fe_{20}$ microstructure





$Ni_{80}Fe_{20}$ microstructures

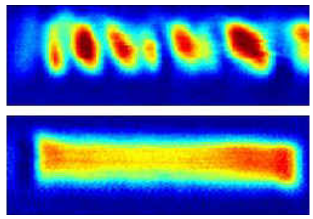
Sample: $Ni_{80}Fe_{20}$ microstructure,
10×2 µm^2, 15 *nm* thick

"Time domain optical imaging of ferromagnetodynamics", B.C. Choi and M.R. Freeman, in "Magnetic Microscopies of Nanostructures", H. Hopster and H.P. Oepen, editors, Springer Verlag, (2004).

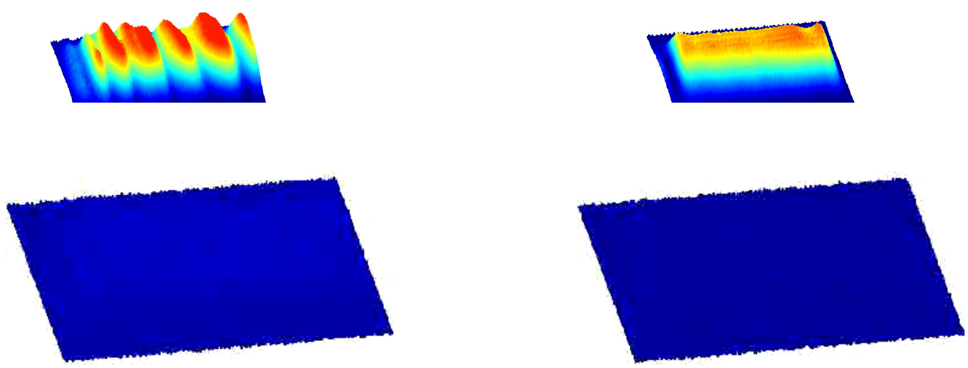
Mark Freeman / University of Alberta

Dynamic magnetization reversal: coherent vs. incoherent

B.C. Choi, M. Belov, W.K. Hiebert, G.E. Ballentine, M.R. Freeman, *Phys. Rev. Lett.* **86**, 728 (2001); *Phys. Rev. Focus* vol. 7, st. 3 (http://focus.aps.org/v7/st3.html)



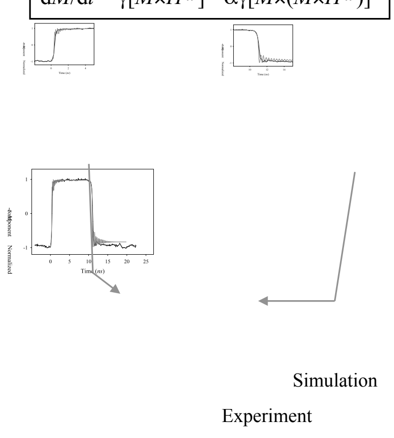
"**Coordination is key.** A region of magnetic material flips direction quicker and in a more coordinated way when an extra magnetic field is present (bottom)…. The experiments show how the read and write operations in disk drives work at a microscopic level."

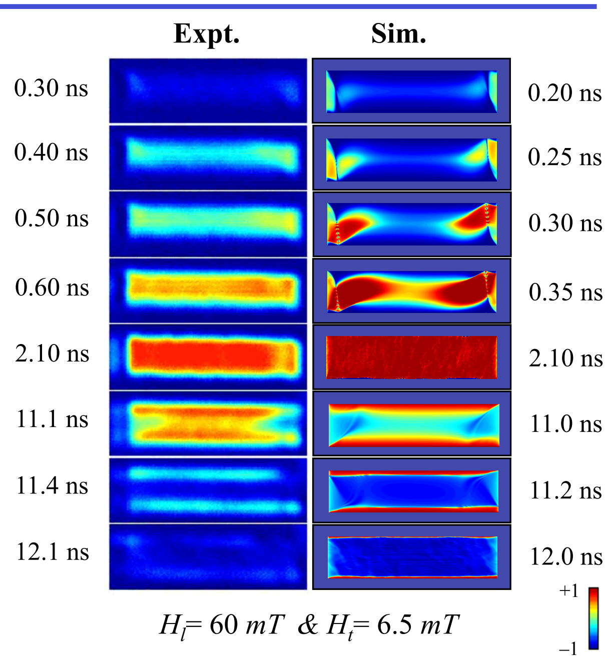


Mark Freeman / University of Alberta

Temporal evolution of easy axis magnetization, experiment *vs.* model: with transverse bias field H_t; (Quasi-coherent rotation)

Micromagnetic modeling, by solving LLG equation:
$dM/dt = \gamma[M \times H^{eff}] - \alpha\gamma[M \times (M \times H^{eff})]$



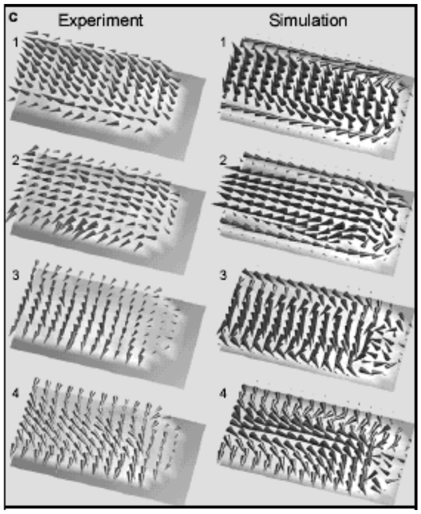


$H_l = 60\ mT\ \ \&\ H_t = 6.5\ mT$

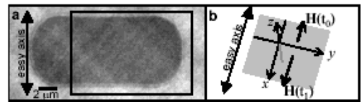
B.C. Choi *et al.*, Phys. Rev. B 64, 144418 (2001)

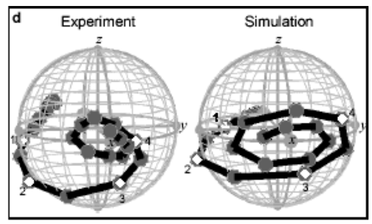
Mark Freeman / University of Alberta

Vector measurement of precessional reversal in a complementary geometry



shape anisotropy takes over the role of the transverse bias field in this experiment



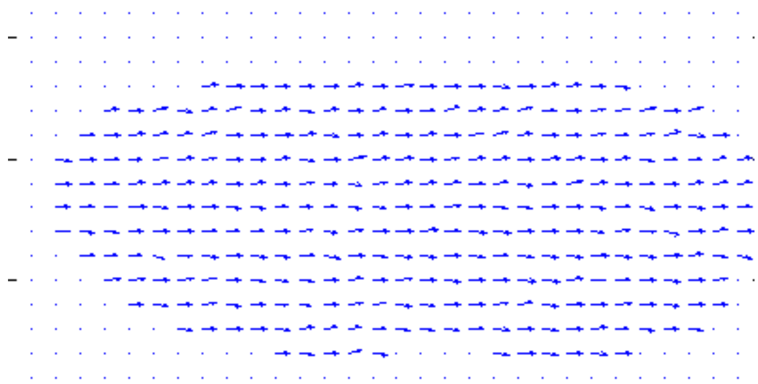


W.K. Hiebert *et al*., Phys Rev B **65**, 140404(R) (2002)

Coherent Rotation ("resonant switching")
in a transverse shape anisotropy thin film element

Ultrafast magnetization process in ultraslow motion
(50 ps/frame shown in 6 frames/second)

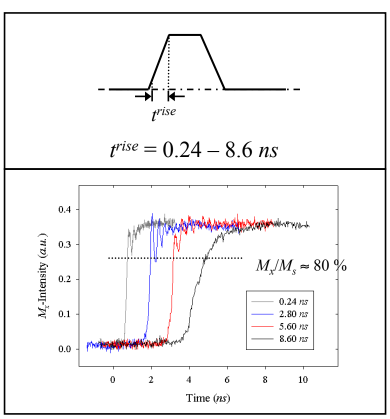
Reversal by incoherent rotation (the movie)

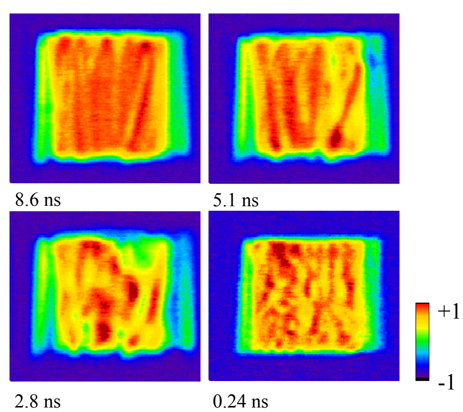


subnanosecond scale reversal in a lithographic nickel-iron element, 3 by 10 micrometre by 15 nm thick

Hiebert, Ballentine, Freeman,
J. Appl. Phys. (15 Jul. 2002)

Dynamic domain patterns vs. speed of reversing field

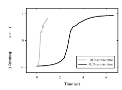


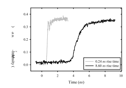


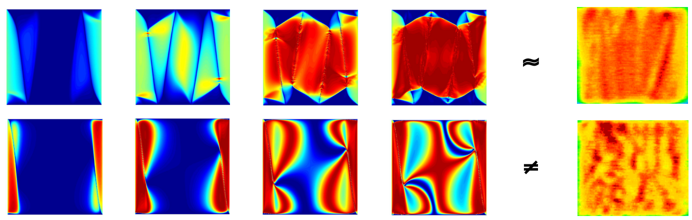
Stripe domain ⟺ Labyrinth domain

- **Rule of thumb for driven system:**
  increasing complexity with increasing departure from equilibrium

Dynamic domain pattern formation : Simulation vs. Experiment

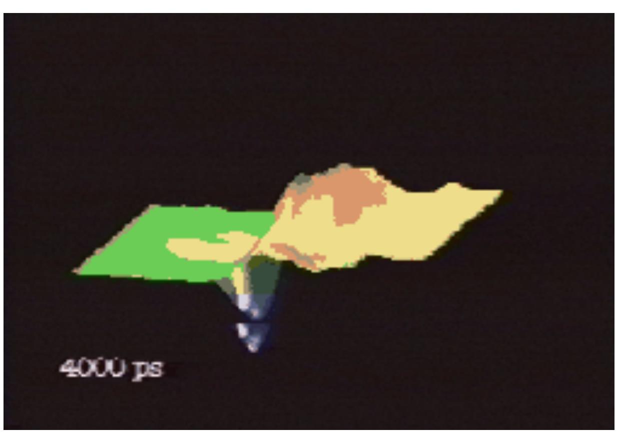




10.0 *ns*		8.6 *ns*
0.25 *ns*		0.24 *ns*

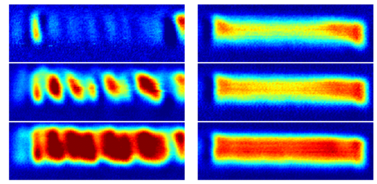
Simulation **Experiment**

Magnetization dynamics in micromagnetic devices:



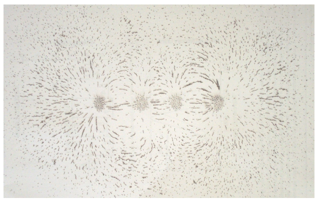
magnetization reversals
of the pole tips of a
hard disk writer

prospects…



ultrafast

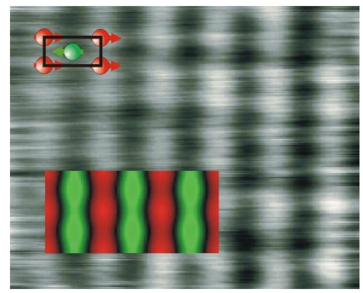
?



19^{th} century imaging: field lines visualized; large scale, static

√

√



atomically resolved! AFM Mn monolayer on W(110) (Bode, Weisendanger *et al.*)

for a review, see
M.R. Freeman and B.C. Choi, Science **294**, 1484 (2001)

Summary

- Ultrafast microscopy is a great way to study the dynamics of small systems
  - *direct* observation of *individual* structures
- broad spectrum of implementations possible
  - optical; scanned probe. Tailored to specific physical properties, resolution requirements
- examples
  - ferromagnetic dynamics
    - long standing fundamental questions
    - device applications
  - stroboscopic STM
- a discipline very much in its infancy
  - just beginning to open "4D" window on solid state dynamics

and so many other contributors to this work, past and present:

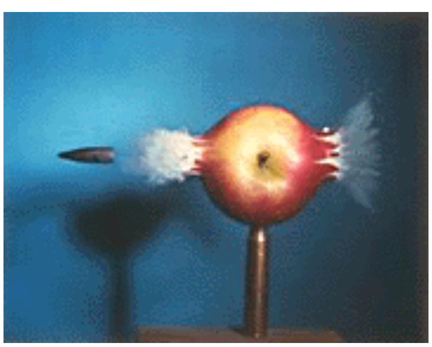
Abdul Elezzabi
Geoff Steeves
James Stotz
Andrzej Stankiewicz
Tom Clement
Rahim Janmohamed
Ken Marsh
Mark Roseman
Kristen Beaty
Marek Malac
Zhigang Liu
Mirwais Aktary
Lindsay LeBlanc
Graham Nelson
Don Mullin
Greg Popowich
Dave Fortin
Rick Sydora
Al Meldrum
Ken Westra
Mark Johnson
Scott Zelakiewicz

We gratefully acknowledge our federal, provincial, and industry supporters:

Mark Freeman / University of Alberta

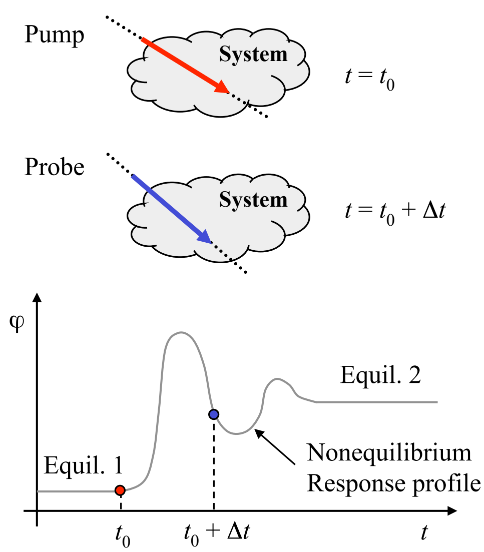
backup slides

How do we image fast dynamic processes?



Stroboscopic photograph, H.E. Edgerton, 1931.

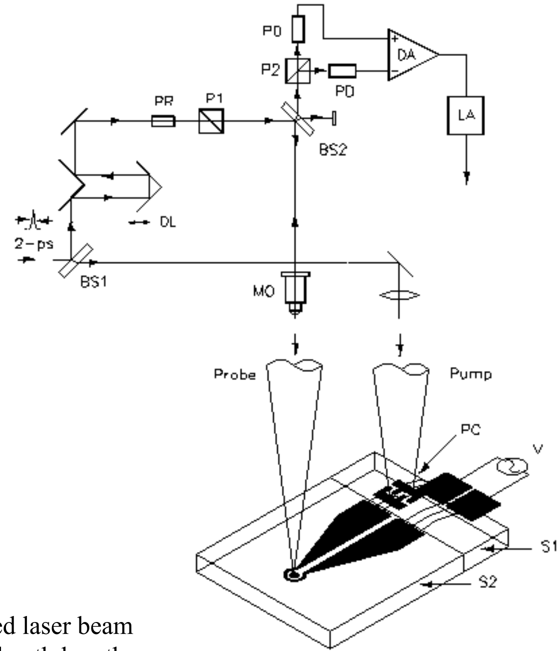
"What to do when it's too fast to see: Freeze-frame imaging, from racehorses to atoms", M.R. Freeman, Physics in Canada 54, 148 (1998)



Pump-Probe Technique

Experimental setup

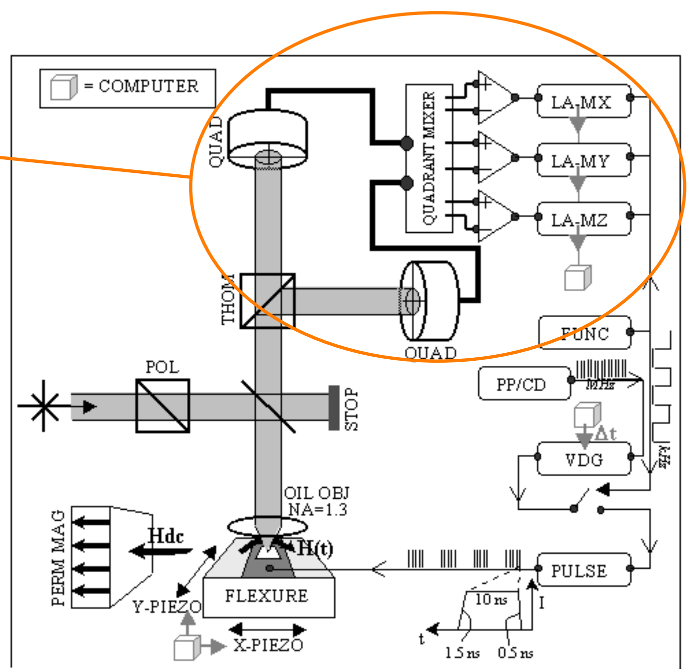
for optically-detected, time-domain ferromagnetic resonance



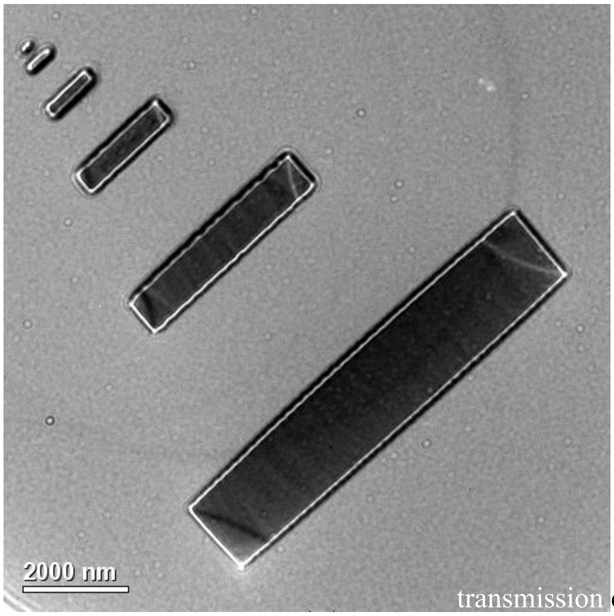
pump, probe: split from a single pulsed laser beam
variable time delay: adjustable optical path length
magnetization monitored through polarization change of reflected probe

Quadrant detectors

for *vectorial* measurements of the magnetization



Sample fabrication, and static magnetic and structural characterization:



electron beam lithography
(UofA Nanofab; Miro Belov)

transmission electron microscopy
(UofA Physics and Brookhaven NL; Marek Malac)