New Prospects for Quantitative Magnetometry at the Nanoscale

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Magnetic Nirth III, June 8-10, 2012, Banff, Alberta

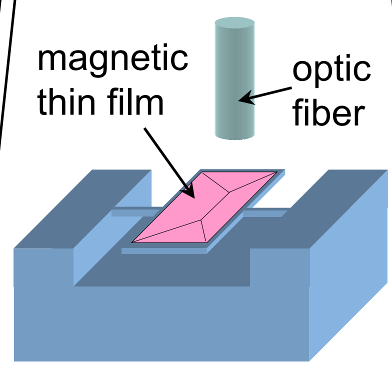
Motivations

- Develop methods to determine magnetic properties of nano/micro fabricated structures quantitatively.
  - How does the fabrication process alter magnetics?
- What are the statistics of nanoscale structures and devices?
  - What is the variation from structure to structure and why?
- Focus on "direct" methods.
  - Eliminate the need for "secondary standard artifacts."
  - Quantum based standards easily implemented in the lab.

MEMS Integration of Electromagnetic Systems for the Next Generation of Magnetometers.

Magnetometer Sub-Systems ➤ MEMS Integration ➤ Industrial Impact

Magnetometer Sub-Systems	MEMS Integration	Industrial Impact
optical	**magnetism laboratory on a chip**	*near term*
microwave		smart substrates
mechanical		new probe microscopes
magnetic		*long term*
		nanometer scale MRI
		spin quantum mechanics



MEMS torque resonator

Outline

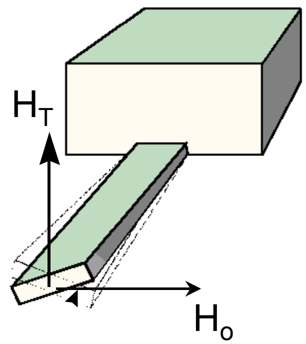
Two examples of microsystem instrumentation based on torque measurements.

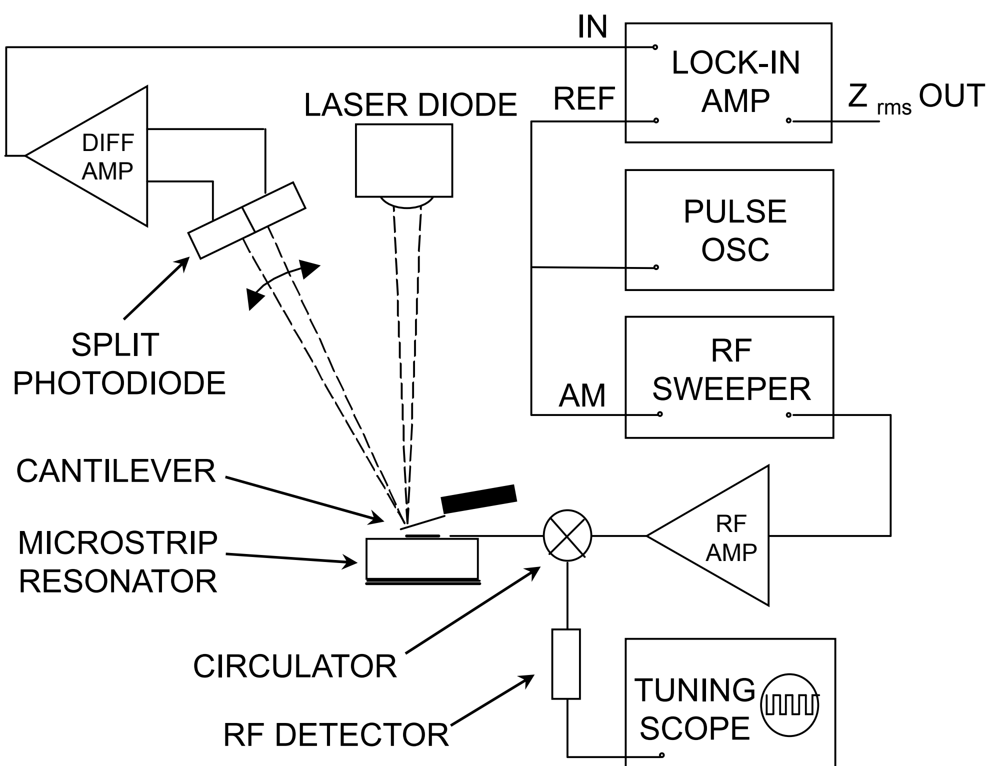
- Micro resonating torque magnetometer.
- Converting magnetic resonance into mechanical torque.

Two examples of new approaches.

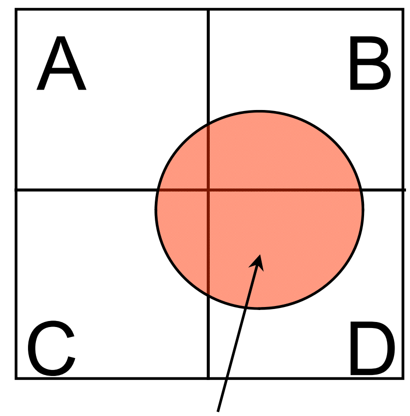
- Magnetic Particle Imaging (MPI) with a cantilever.
- Magnetic particle magnetometry using proton NMR.

Microsystems instrumentation for torque measurements





FOUR QUADRANT PHOTODIODE



LASER SPOT

Torsion mode $\frac{(A+C)-(B+D)}{A+B+C+D}$

Deflection mode $\frac{(A+B)-(C+D)}{A+B+C+D}$

Commercial AFM cantilever characteristics.

Deflection

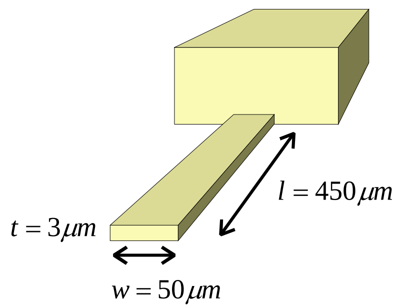
$$K_s = Ewt^3/4l^3$$

$$F_{noise}\big/\sqrt{Hz} = \sqrt{\frac{2K_s k_b T}{Q\ f_o}}$$

$$K_s = 0.2\ N/m$$
$$f_o = 15\ kHz$$
$$Q = 200$$

$$F_{noise} \approx 10^{-14}\ N/\sqrt{Hz}$$

Si Cantilevers



Torsion

$$K_s = \frac{E(wt^3)}{6(1+m)l}$$

$$T_{noise}\big/\sqrt{Hz} = \sqrt{\frac{2K_s k_b T}{Q\ f_o}}$$

$$K_s = 3\cdot 10^{-8}\ N\cdot m/rad$$
$$f_o = 250\ kHz$$
$$Q = 250$$

$$T_{noise} \approx 10^{-17}\ N\cdot m/\sqrt{Hz}$$

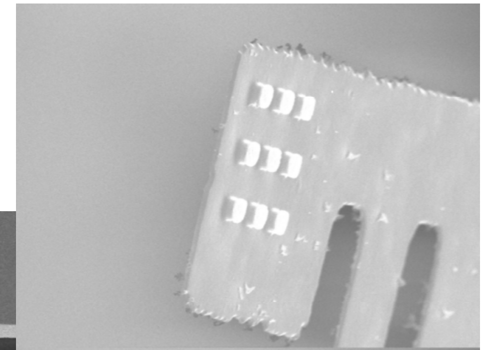
More sensitive custom cantilevers

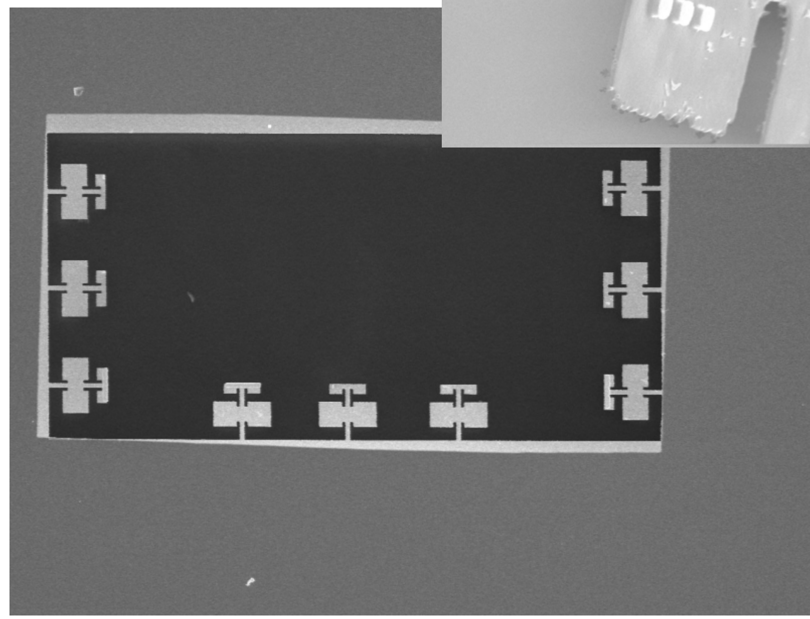
Challenges:

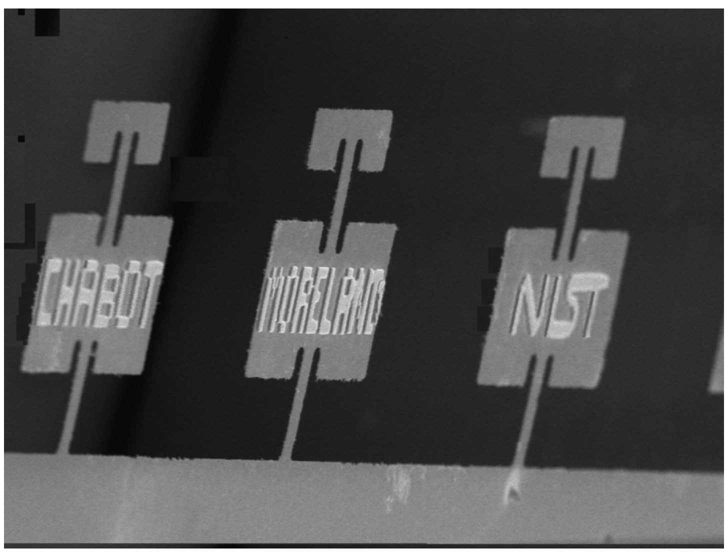
• Combine diverse fabrication technologies to get nanostructures on MEMS resonators.

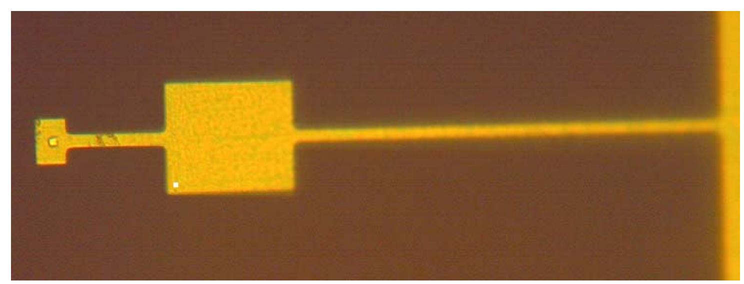
• Dimensions large enough to accommodate optical beams.

• Surface contamination dominates Q for ultra thin structures.

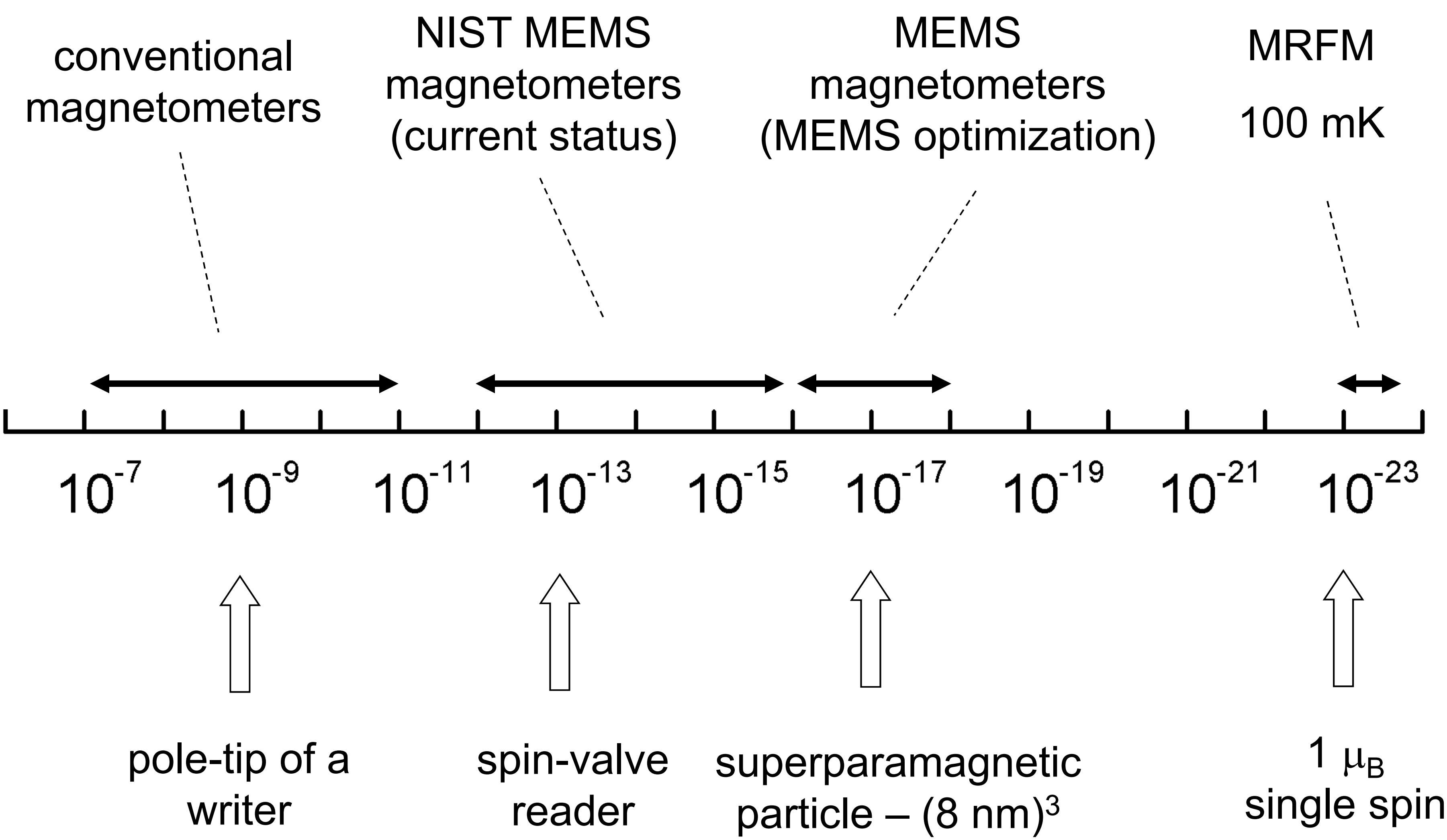






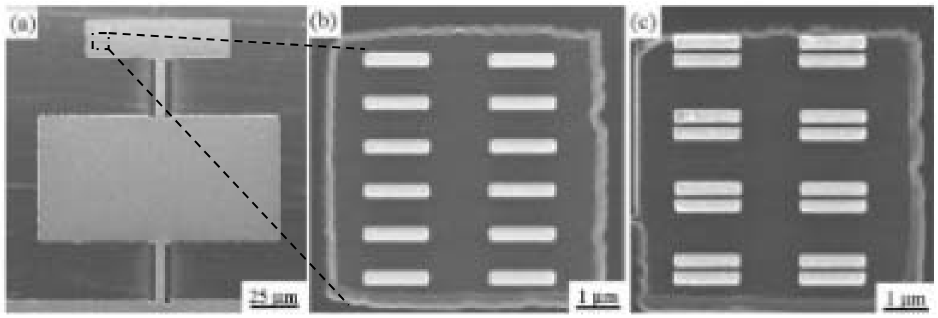


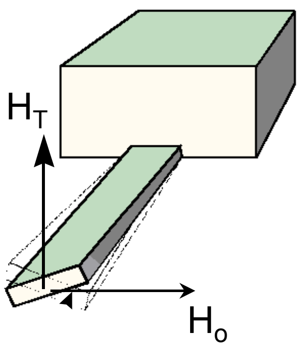
Magnetic moment sensitivity comparisons (A·m^2).

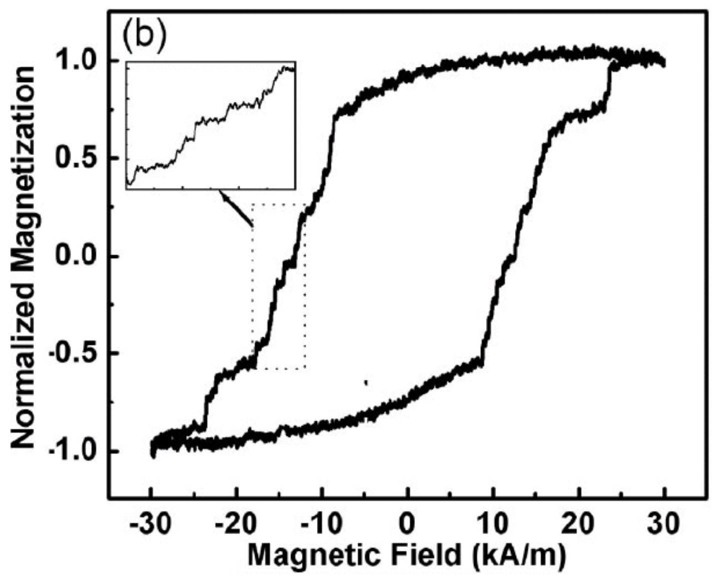


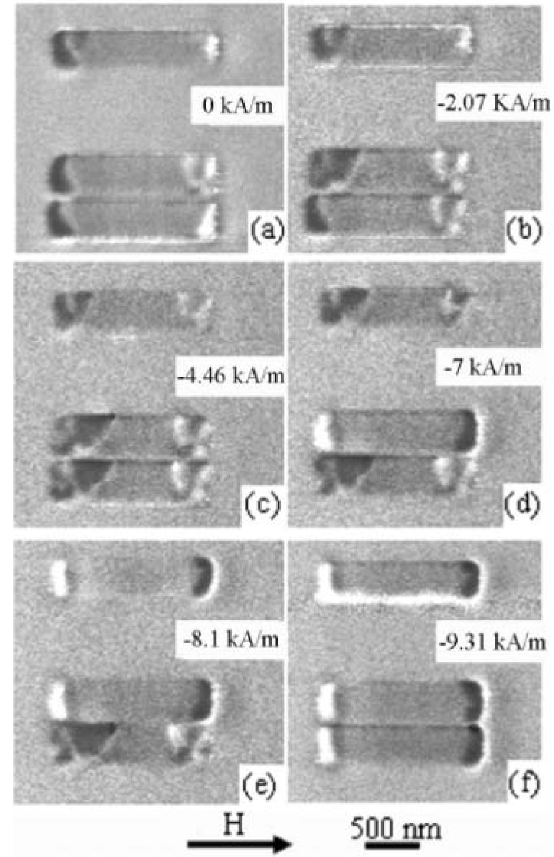
Switching in micron scale permalloy bars

Micro resonating torque magnetometer







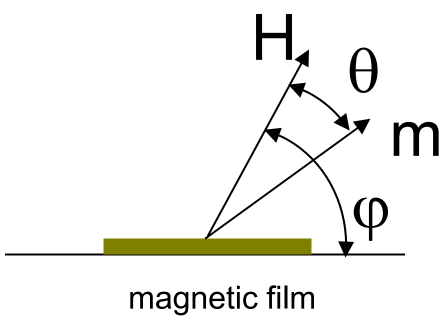


MFM

Thanks to Sy-Hwang Liou
University of Nebraska

Making it quantitative:

Applied field “magnetically” stiffens the mechanical spring constant and shifts the resonant frequency.

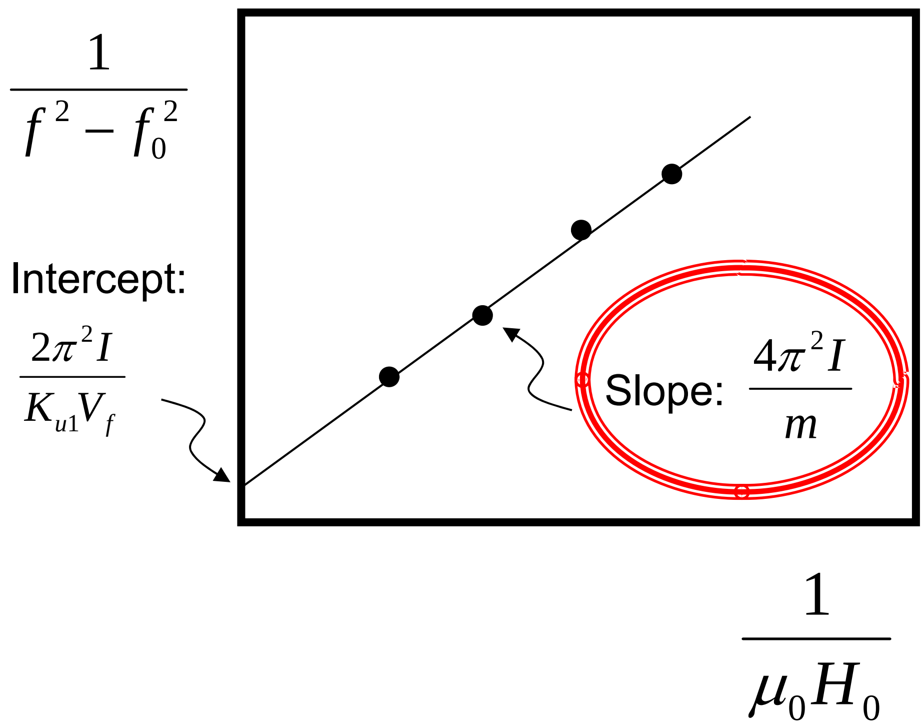


G. F. Dionne and J. F. Fitzgerald, IEEE Trans. Mag. **21**, 1590(1985).

J. Morillo, etal., Rev. Sci. Instrum. **69**, 3908(1998).

Linear equation relating *f* and H_0

$$\frac{1}{f^2 - f_0^2} = \frac{2\pi^2 I}{K_{u1} V_f} + \frac{4\pi^2 I}{\mu_0 H_0 m}$$



Traceable to frequency – a quantum based measurement.

Atomic clocks are readily available and getting cheaper by the minute!

Determine I based on dimensions of the resonator.

$$\frac{1}{f^2 - f_0^2} = \frac{2\pi^2 I}{K_{u1} V_f} + \frac{4\pi^2 I}{\mu_0 H_0 m}$$

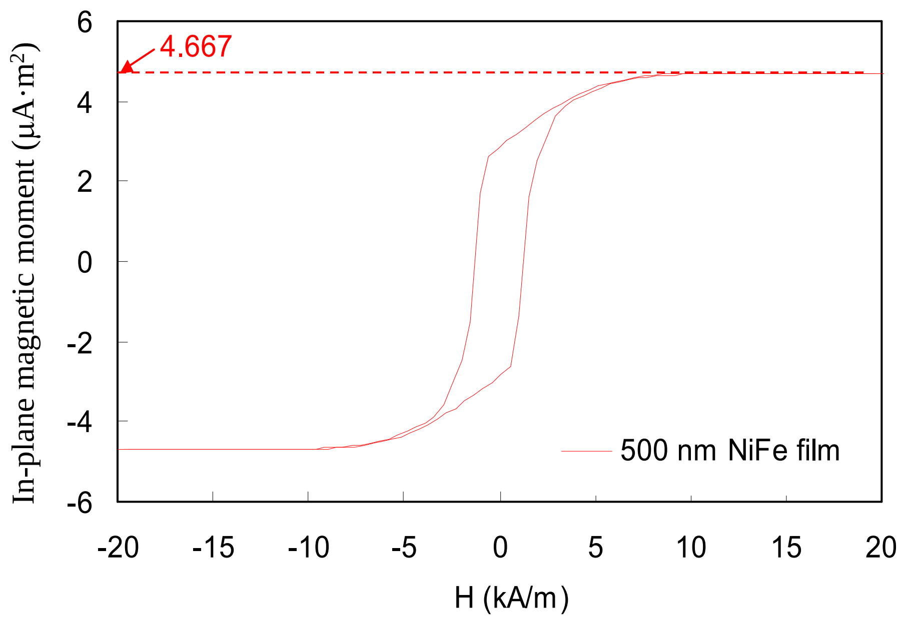
Atomic frequency reference for better than 1 part in 10^9 accuracy.

Constant K_{u1} over the field range of measurements.

Frequency based magnetic resonance field probe integrated into the apparatus.

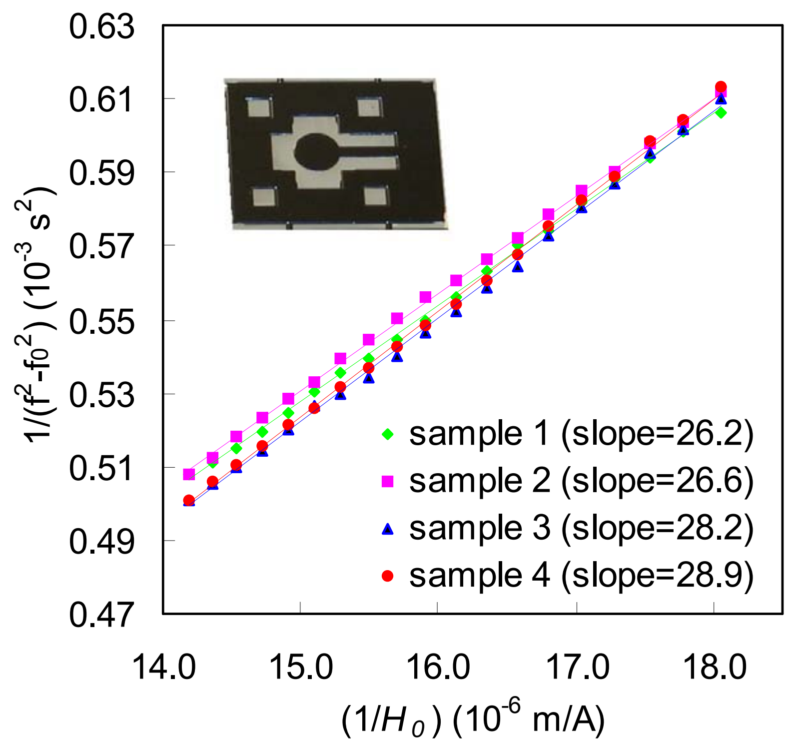
Comparison of AGM and resonator methods on 500 nm thick 4 mm diameter Permalloy samples.

AGM



$$m = 4.67 \pm 0.46\ \mu\mathrm{A\cdot m^2}$$

Resonator Method

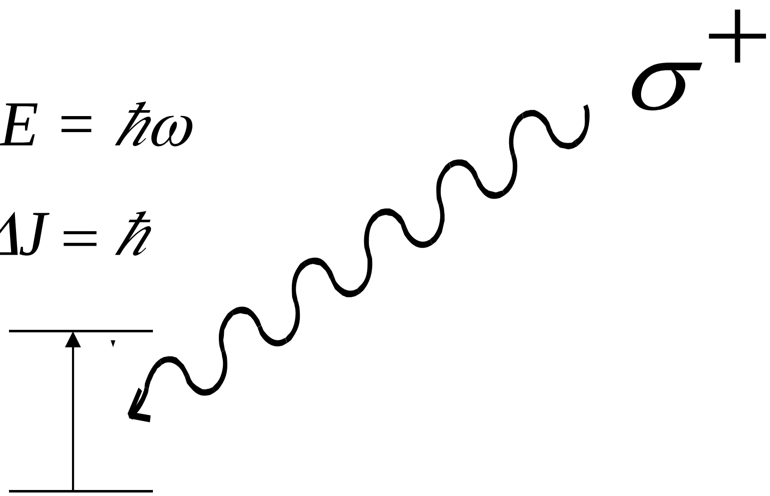


$$m = 5.04 \pm 0.37\ \mu\mathrm{A\cdot m^2}$$

Converting magnetic resonance into mechanical torque

$$\Delta E = \hbar\omega$$

$$\Delta J = \hbar$$



$$T = \frac{dN}{dt}\hbar$$

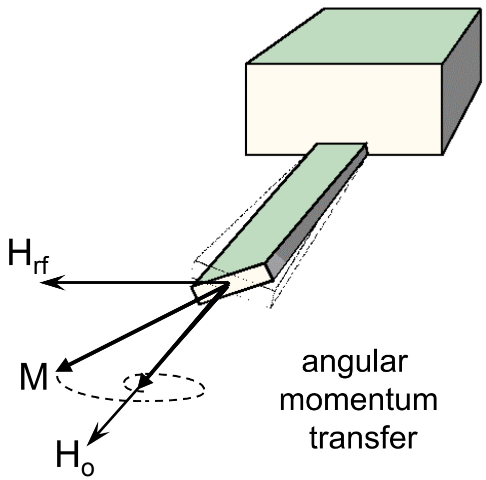
$$P = \frac{dN}{dt}\hbar\omega$$

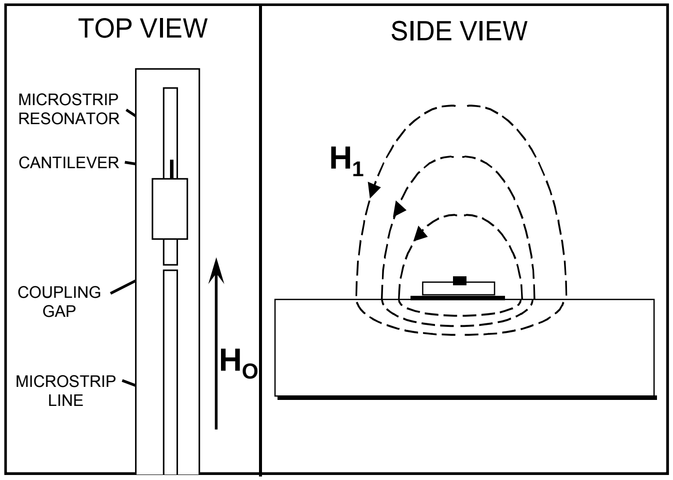
$$\boxed{T = P/\omega}$$

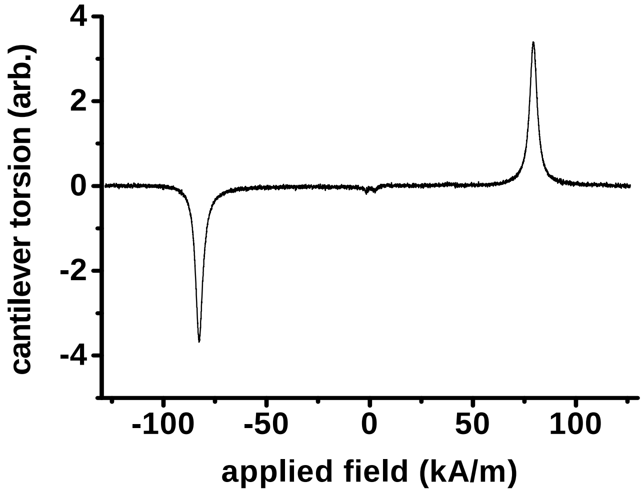
NMR - G. Alzetta,et al., Nuovo Cimento, **54 B**, 107 (1968).

ESR - C. Ascoli, et al., Appl. Phys. Lett., **69**, 3920 (1996).

FMR spin angular momentum damping torque

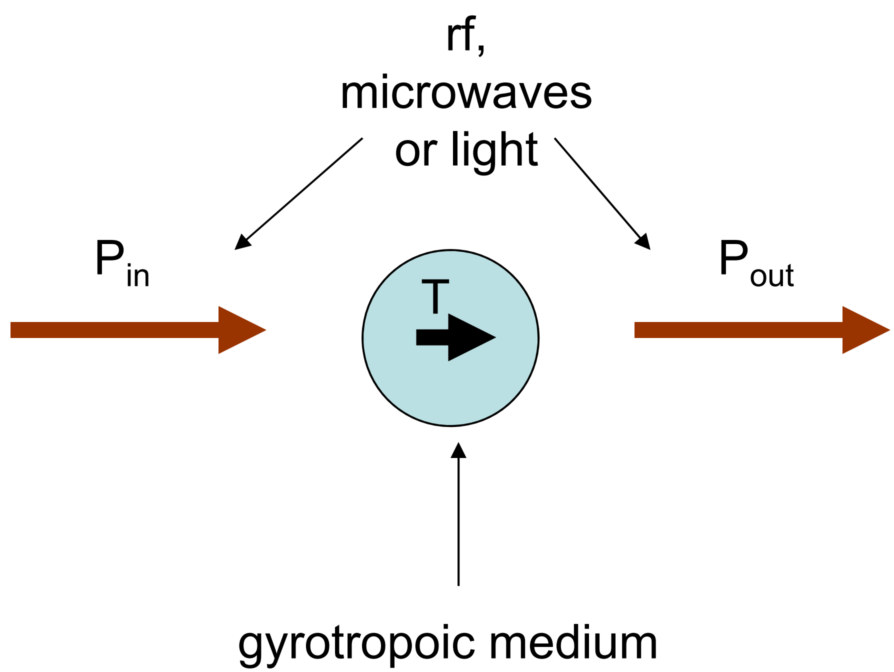






A. Jander, *etal*., Appl. Phys. Lett. **78**, 2348 (2001)

Making it quantitative:

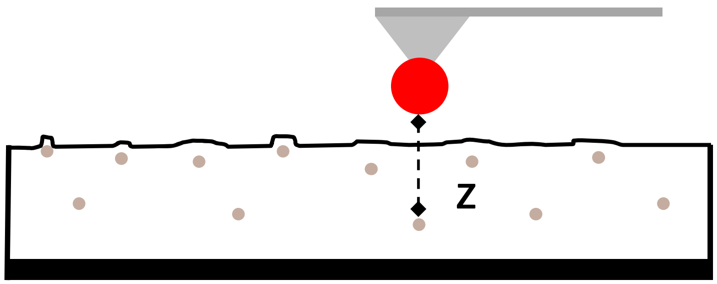


Magnetic film,
electron or nuclear
magnetic resonance
materials, or atoms.

3-D Super Resolution Imaging of Magnetic Particles

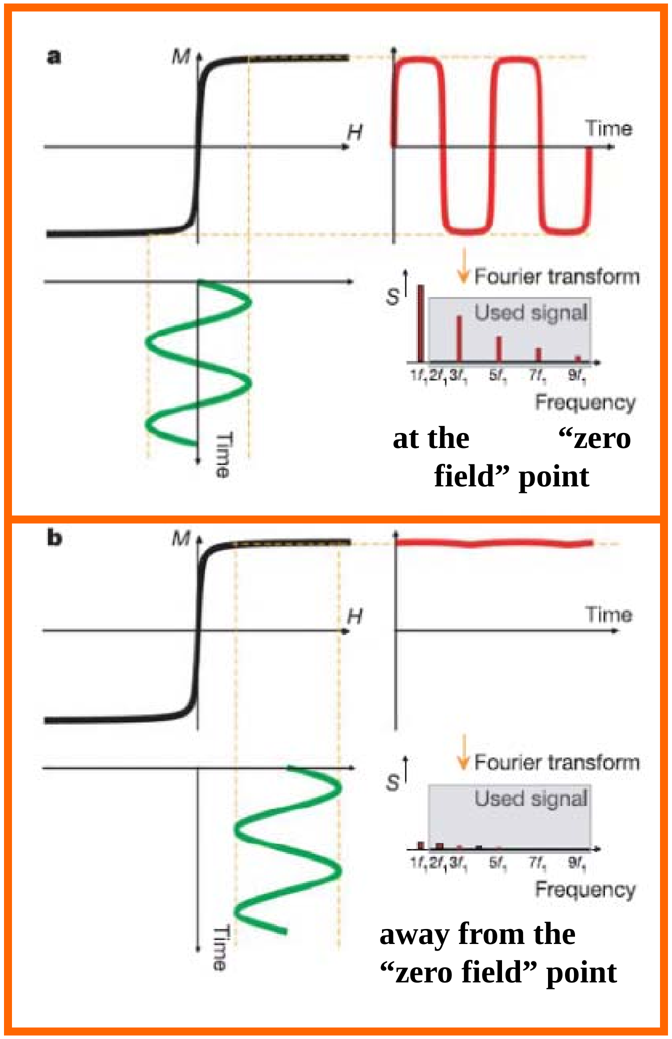
Potential Applications

- Magnetic micro structures
- Biosciences
- Geosciences
- Forensics

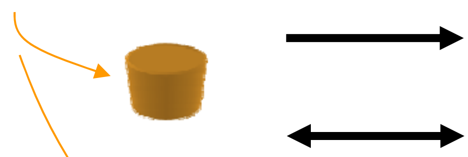


Jacob Alldredge, NIST

Magnetic particle imaging (MPI)

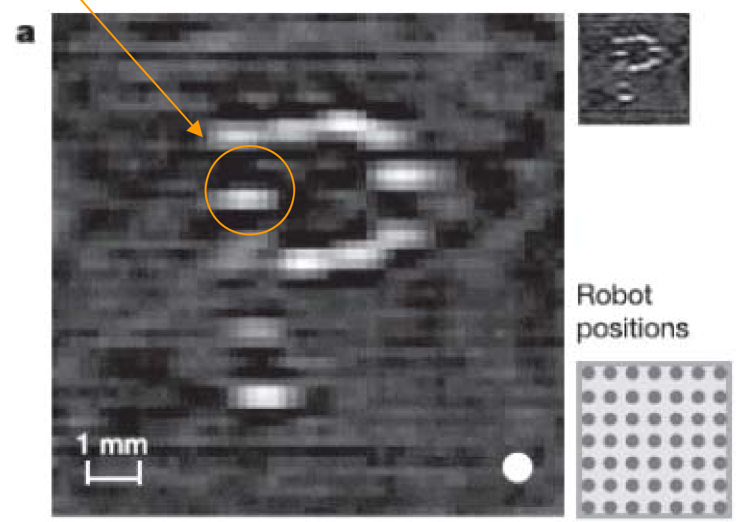


1 mm vial of nanoparticles



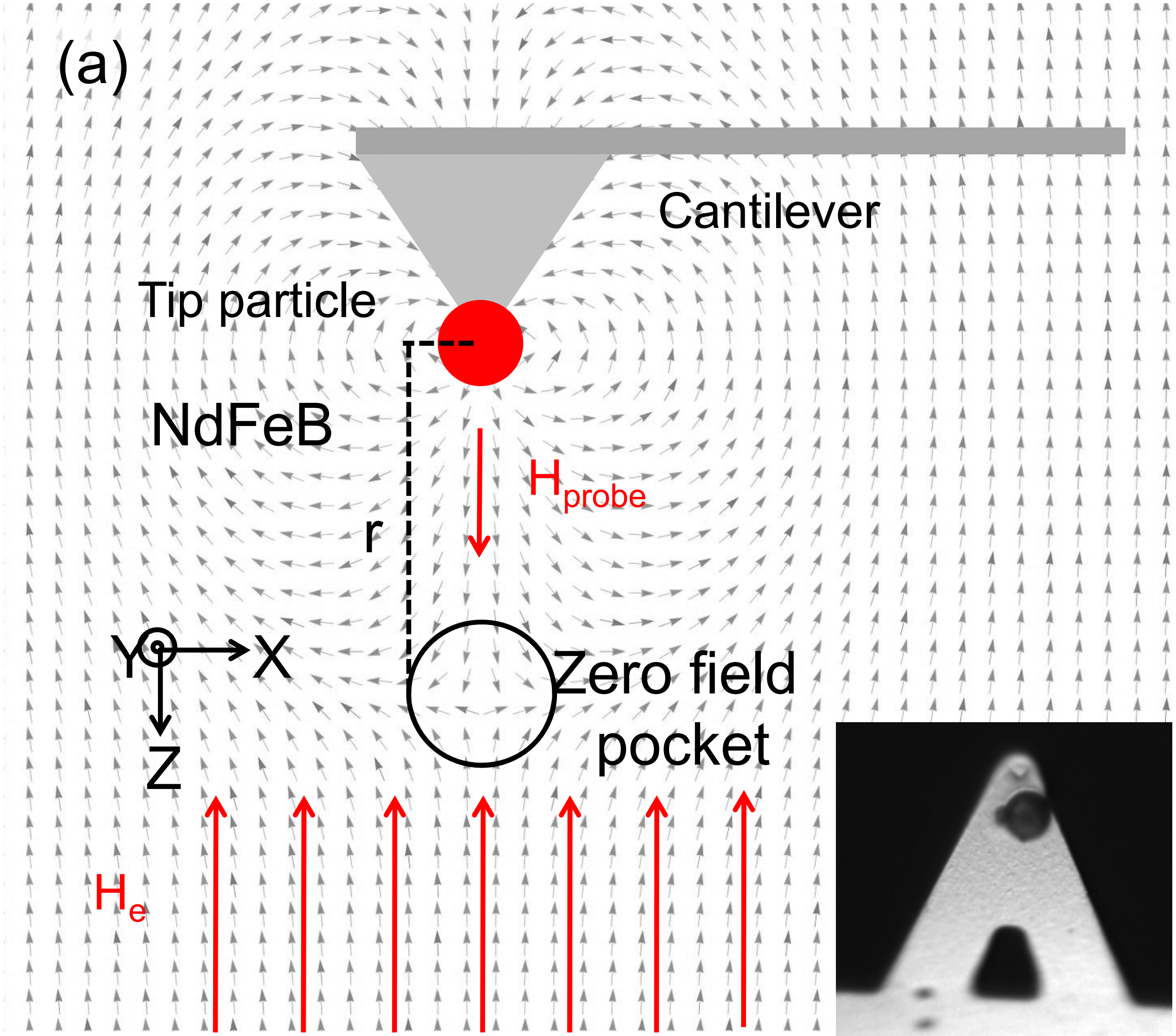
$$H = H_o - x\nabla H$$

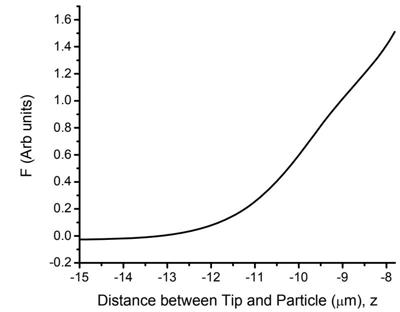
$$H_1$$



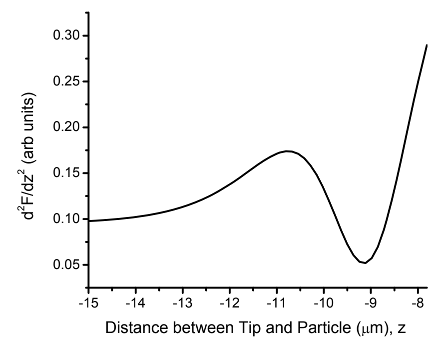
B. Gleich and Weizenecker, Nature 435, 1214 (2005)

MPI with a cantilever – magnetic particle force microscopy (MPFM)



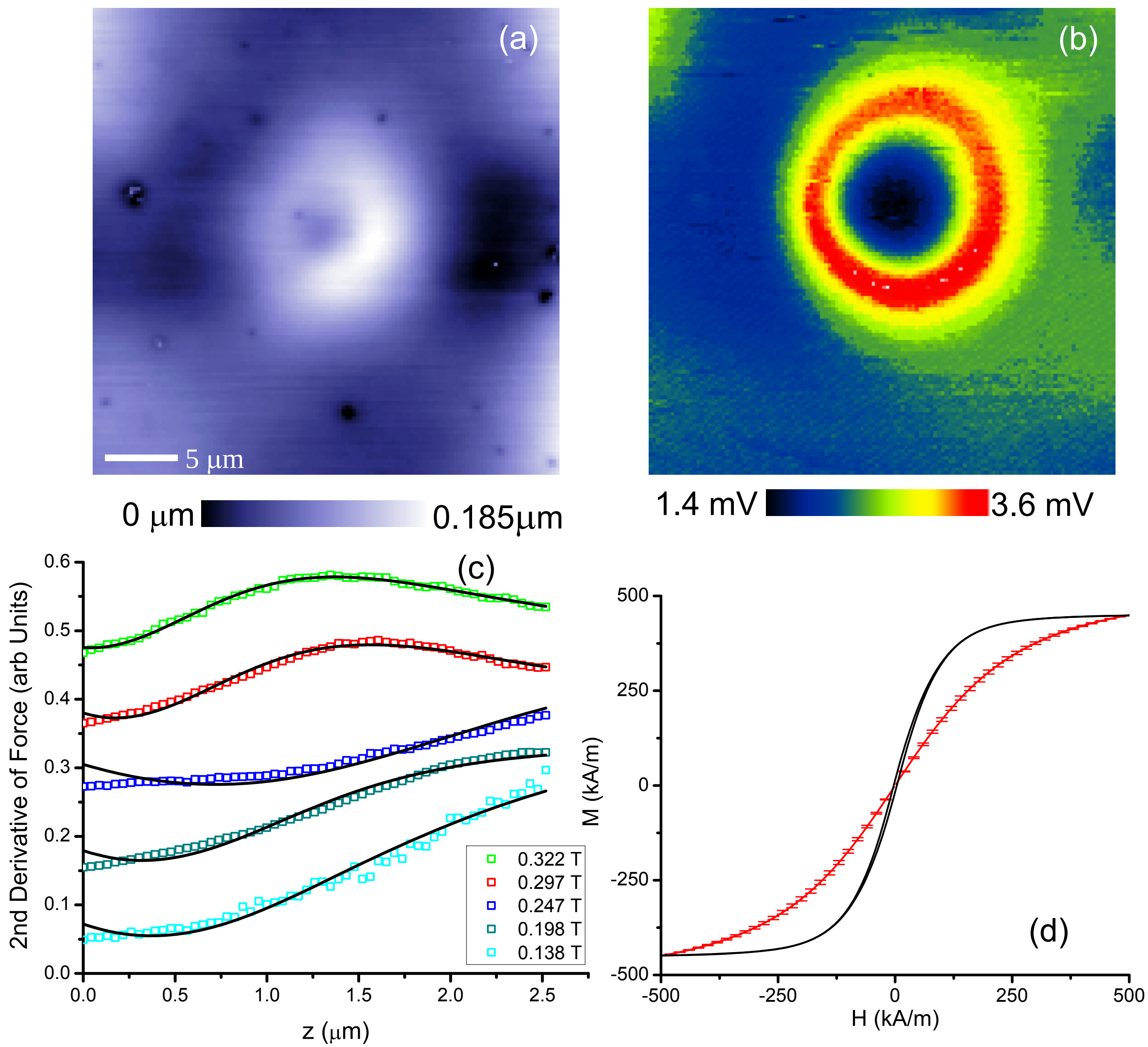


Force versus distance curve

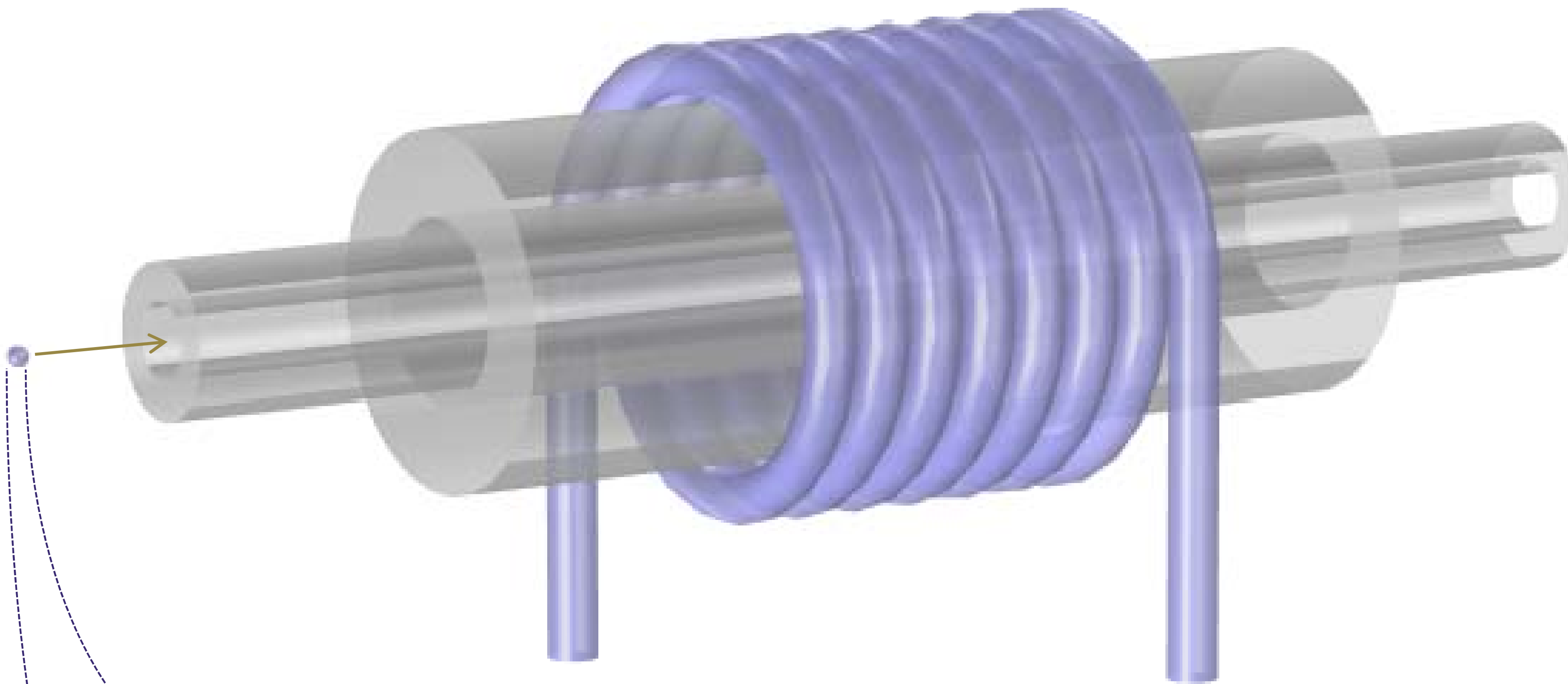


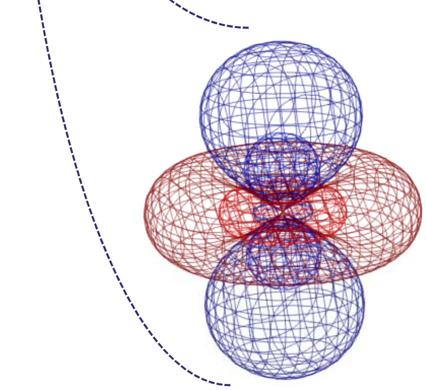
Second derivative force versus distance curve

MPFM images of a 1 micron $Mn_{0.68}Zn_{0.32}Fe_2O_4$ embedded in epoxy



Single particle proton NMR metrology





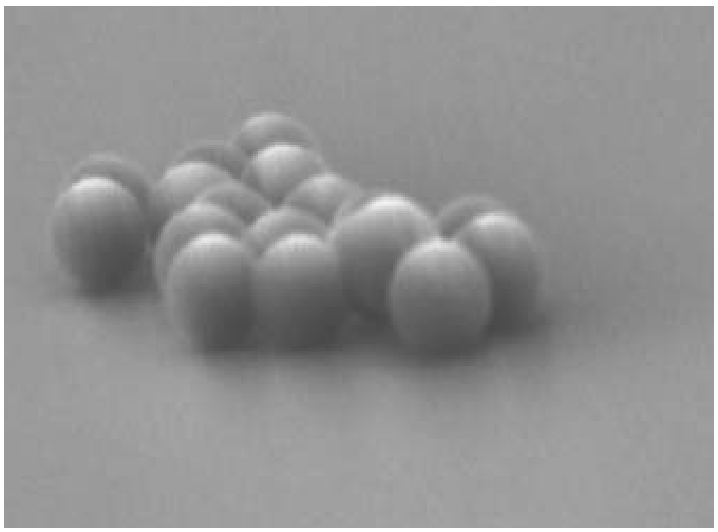
Developing new contrast agents for MRI

Yoshihiro Nakashima, NIST

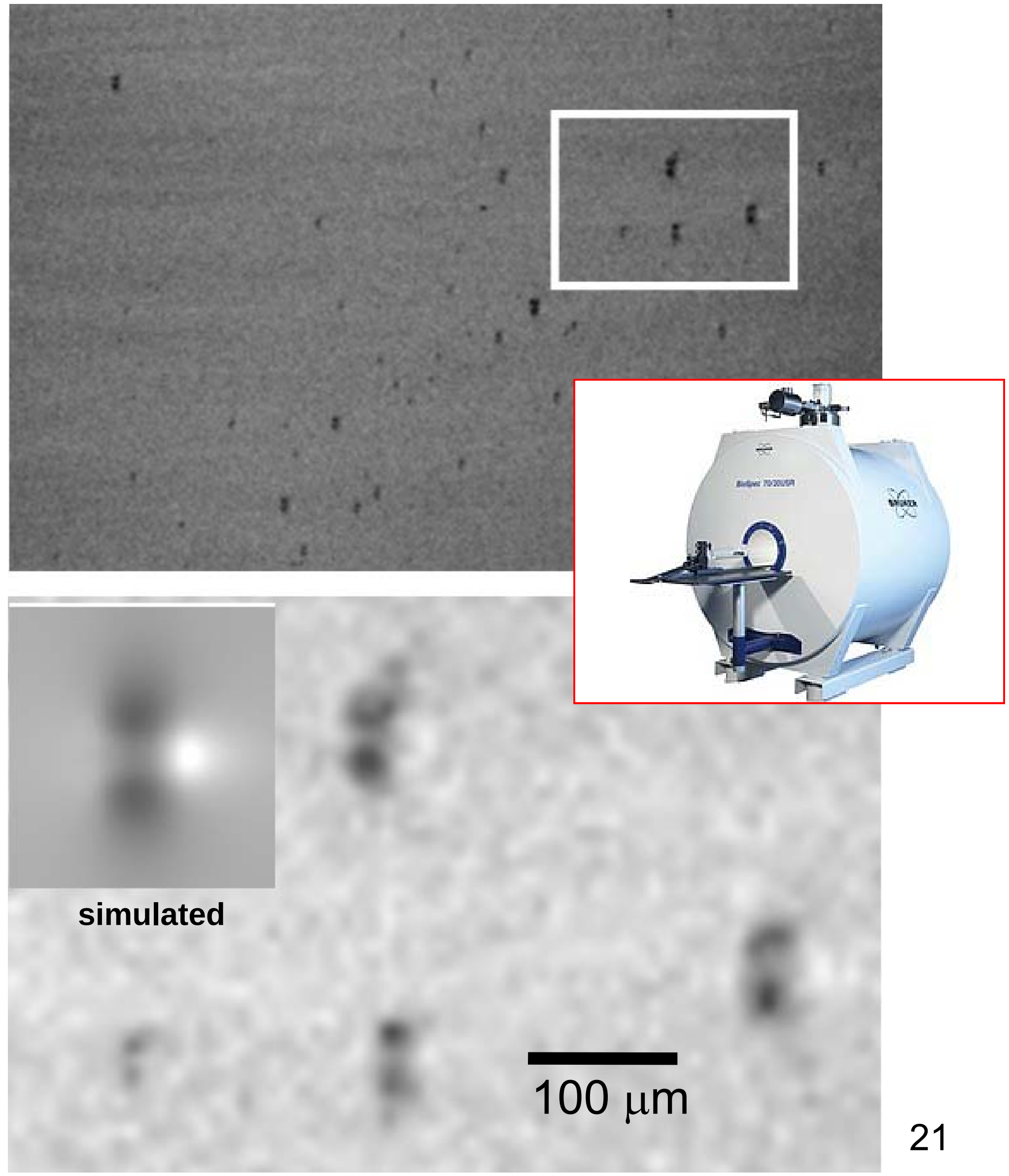
Effect of Single Magnetic Particle on proton MRI

Simulated vs. experimental MRI images of 1 μm superparamagnetic particles

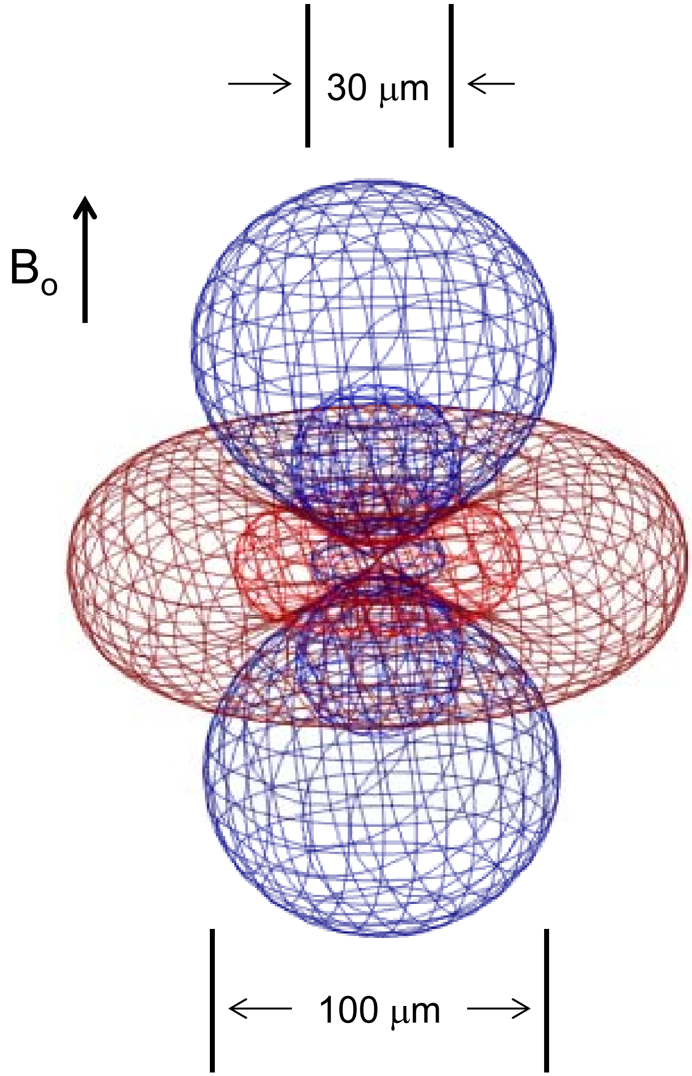
Zabow, Shapiro, Koretsky, NIH



1 μm polystyrene/iron-oxide beads



ΔB_o contours near a dipole



1 μm diameter superparamagnetic iron oxide bead

Magnetic dipole at center

Azimuthal lobe:

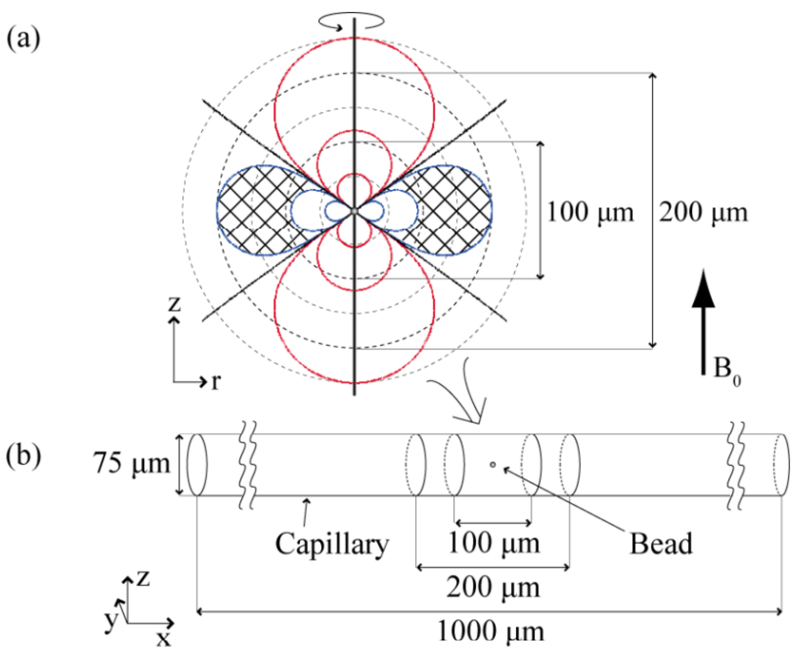
- 30 μm dark volume (proton resonance shifted outside of the bandwidth of the spectrometer).

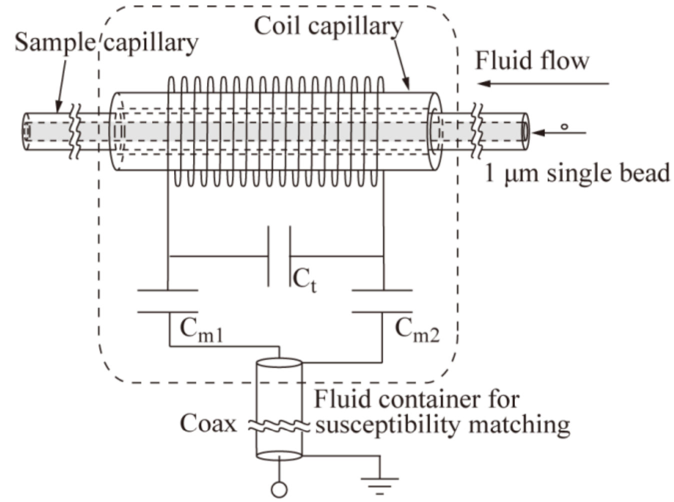
- 100 μm light volume (proton resonance within in the instrument bandwidth but dephased).

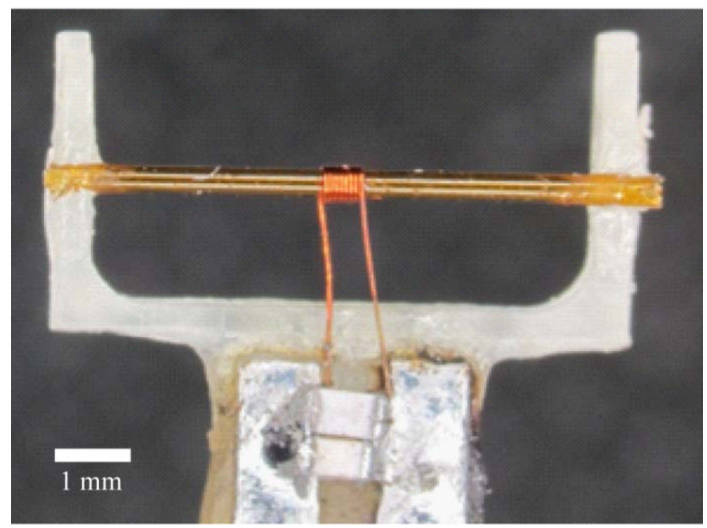
Similarly for the equatorial lobe.

∴ 1 μm affects a large volume of water.

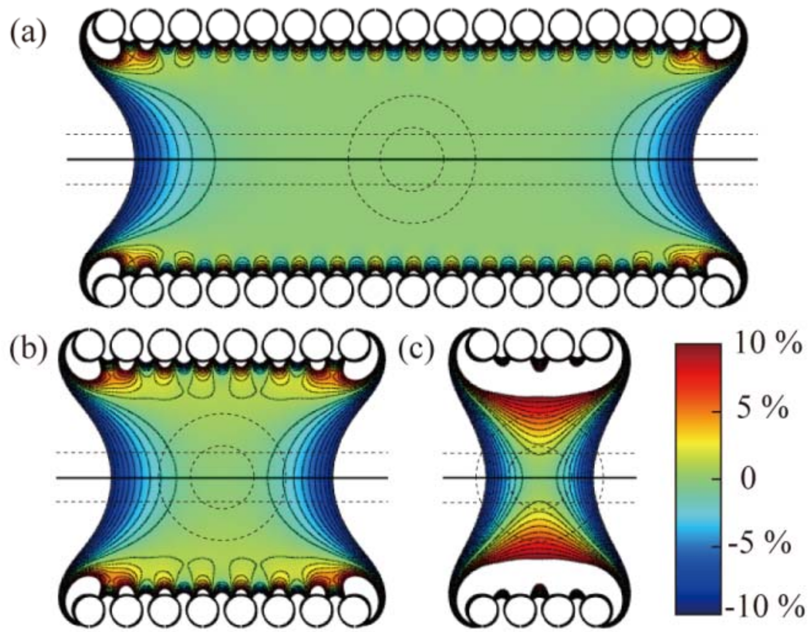
Microfluidic RF probe for pulsed NMR spectroscopy of single particles in fluids

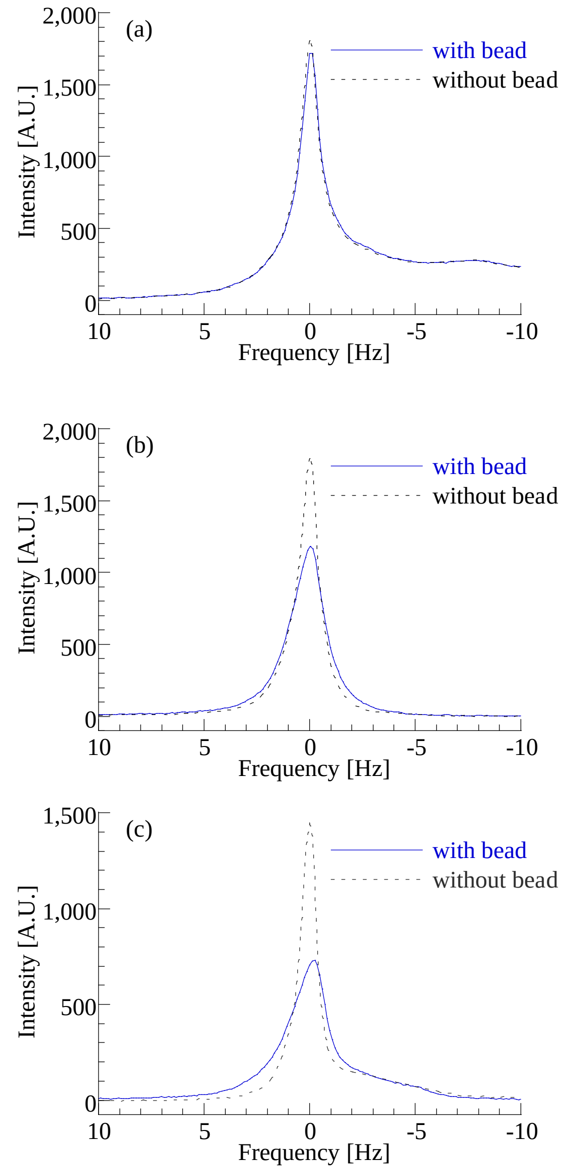






Optimizing RF detector coils for pulsed NMR spectroscopy of single particles in fluids.





Summary

I reviewed some of the basics of micro resonating torque magnetometers regarding design and sensitivity.

The magnetic moment of the sample can be determined from the resonant frequency shift of the resonator as a function of applied field. In principle, the method can be traced to frequency.

The torque on a micro resonator can be quantified by measuring the RF power absorbed by a gyrotropic material deposited on the resonator.

I described a new variant of MFM based on the concepts behind MPI for measuring the M-H curves and position of isolated magnetic particles with submicron accuracy.

I described how pulsed NMR spectroscopy of water nearby a micro particle can be used to measure it's moment quantitatively.