Magnetization Dynamics and X-Ray Spectroscopy: Opportunities and Challenges at Low Emittance Storage Rings

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21 October 2013

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a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

- Timing @ Low Emittance Rings: Issues from NSLS-II
- Overview Magnetization Dynamics
- XMCD + FMR
  - Efforts @ APS
  - Non-Local Effects
  - Prospects for higher frequencies
- Other Applications
- Concluding Thoughts

Bunch Patterns @ NSLS-II

NSLS-II Harmonic #: 1,320

Bunch patterns

Baseline

80%/20%

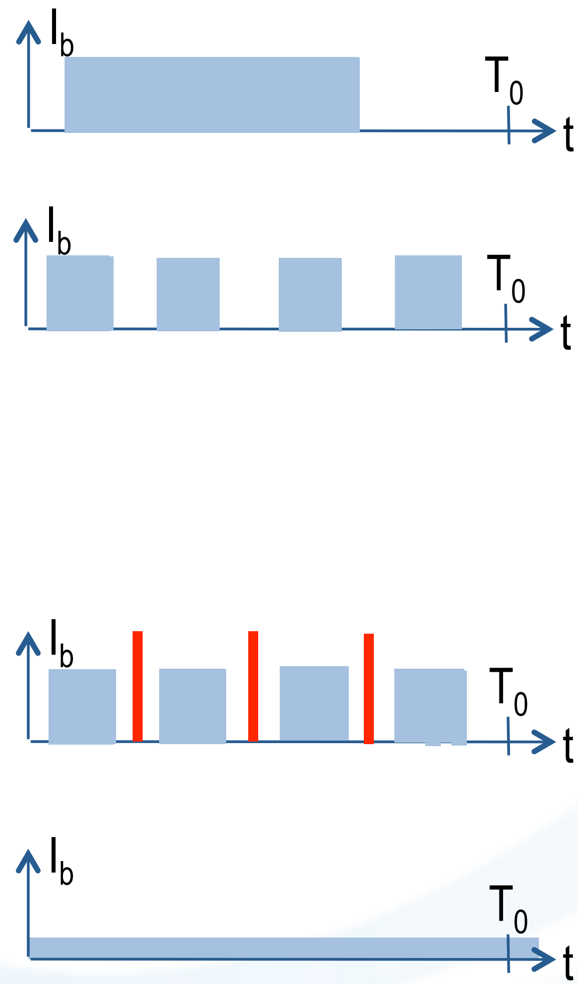
Bunch trains

+

Upgrades

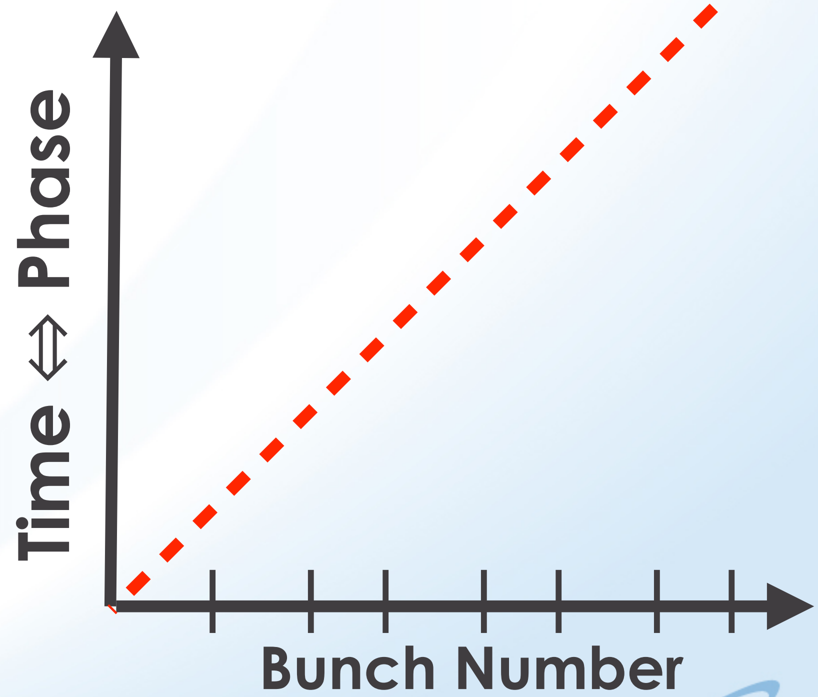
Camshaft

Uniform



What do I want for timing experiments?

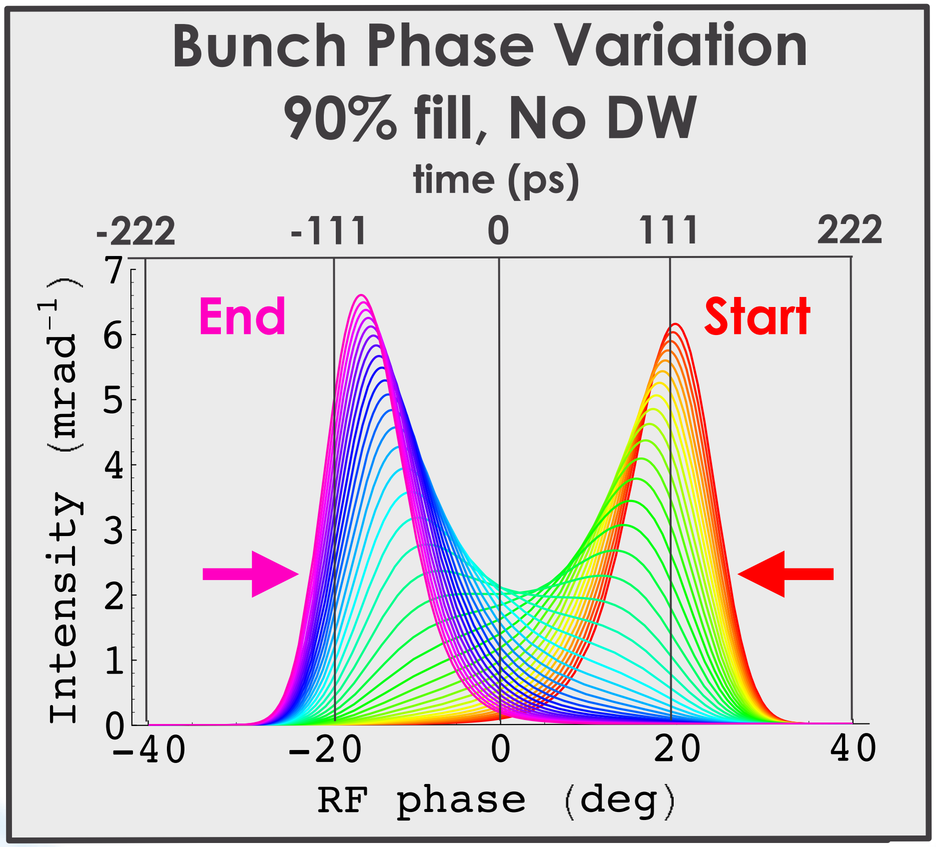
1. Uniform bunch length
2. Linearity

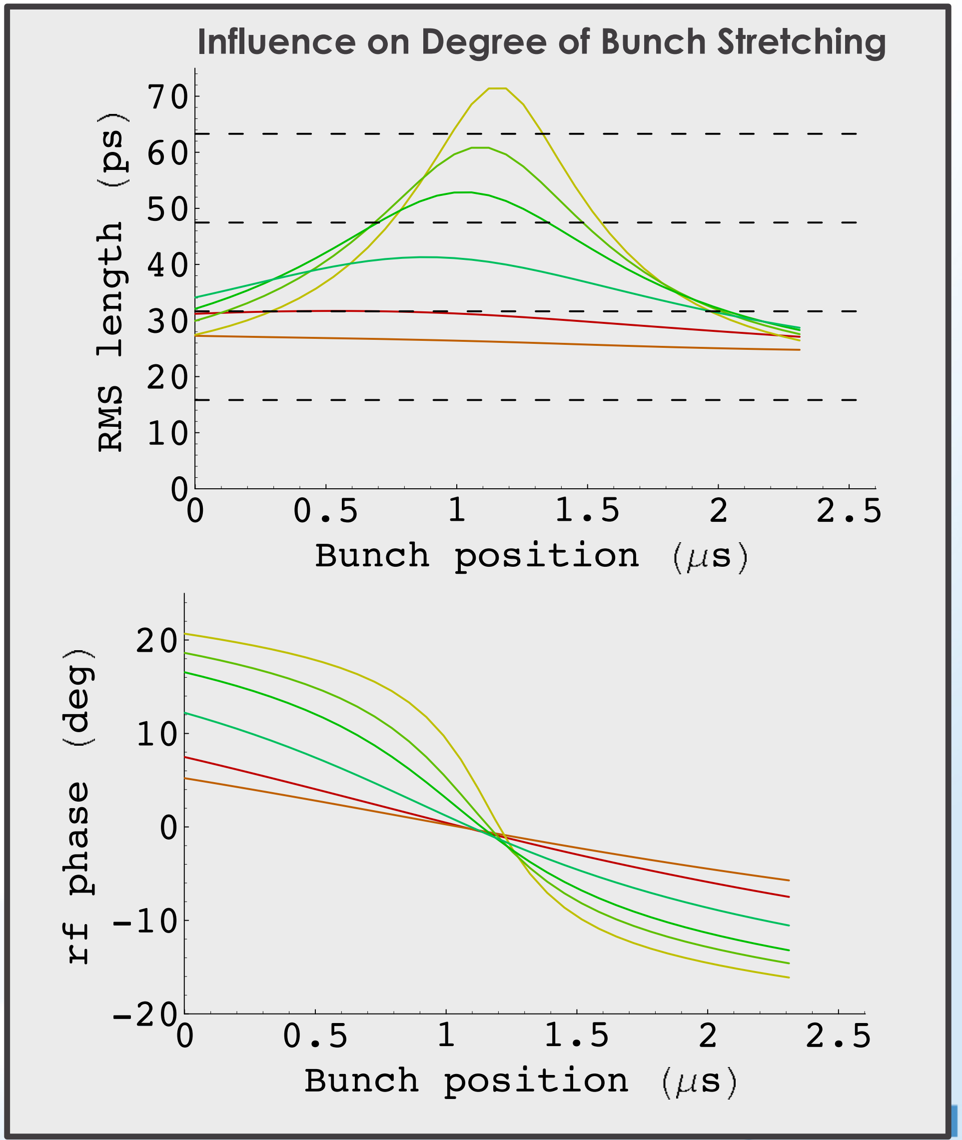


From Timur Shaftan, PS, Accelerator Div.

The Issue:

- **Timing experiments at NSLS-II will be challenging at the tens of ps timescale**



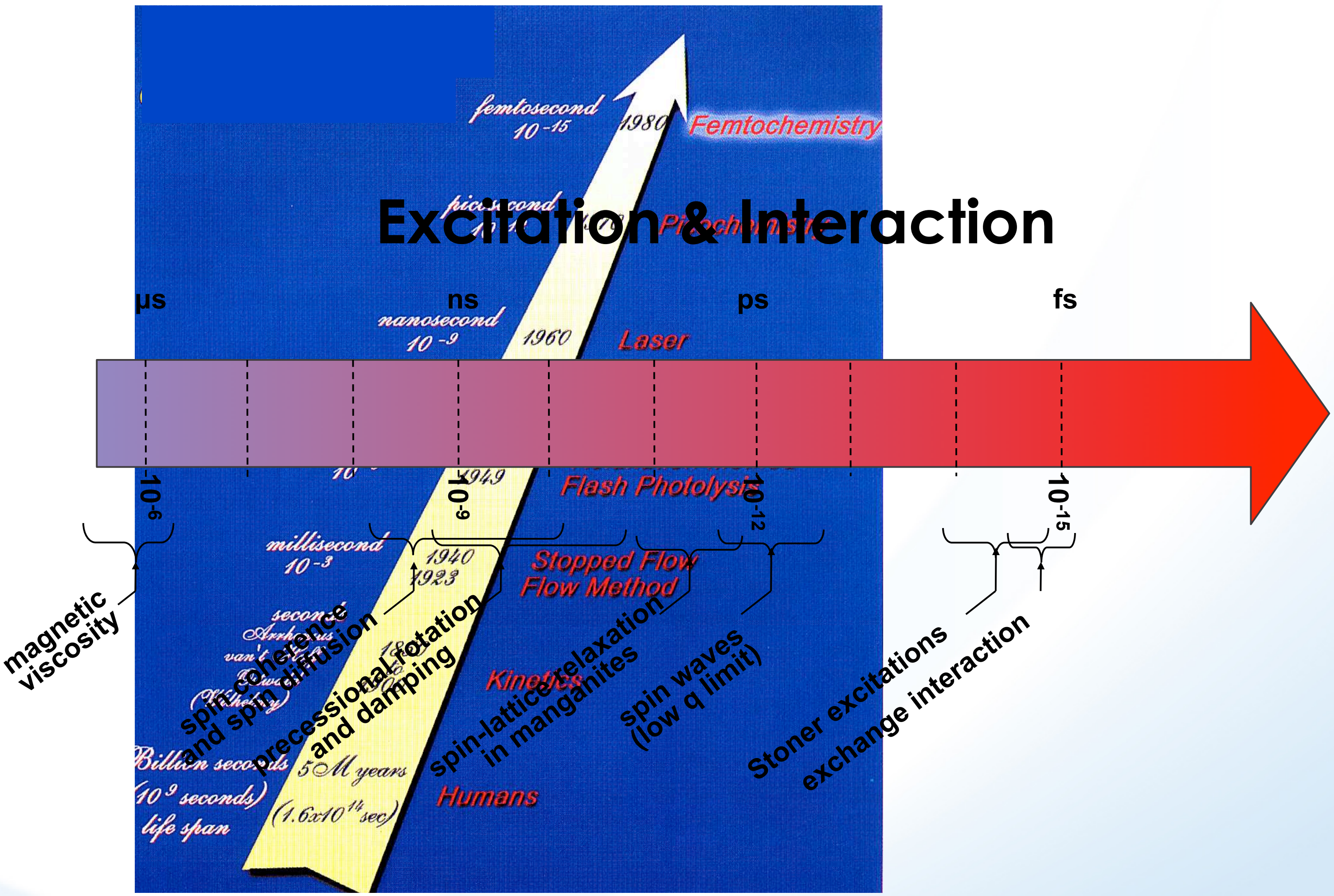


Effective Bunch Length: > 220 ps

Source: Nathan Towne,

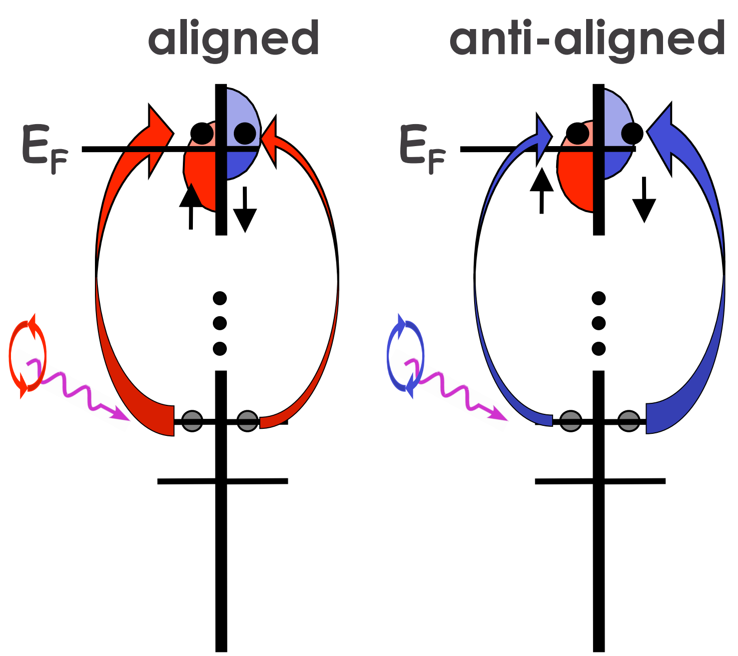
NSLS-II Technical Note #19, Aug. 2006

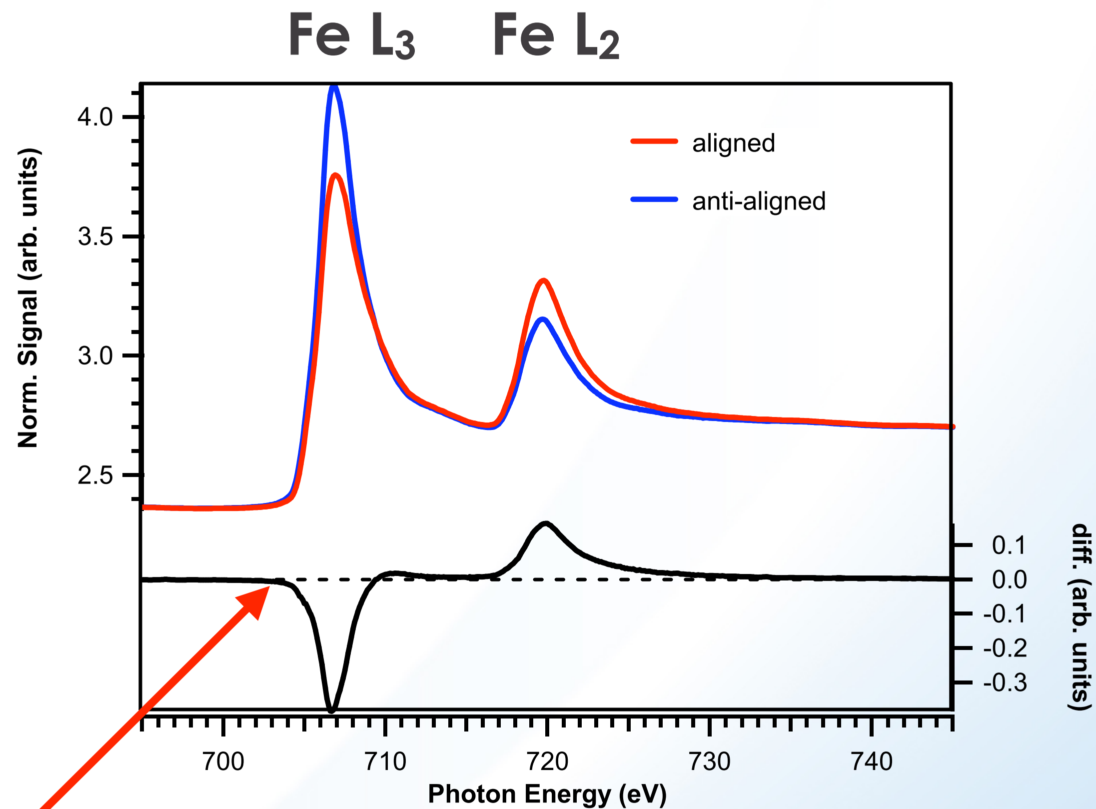
"The Arrow of Time": Hierarchical Timescales in Physical Processes



Ahmed H. Zewail, CalTech
Nobel Lecture, 1999

XMCD Spectra

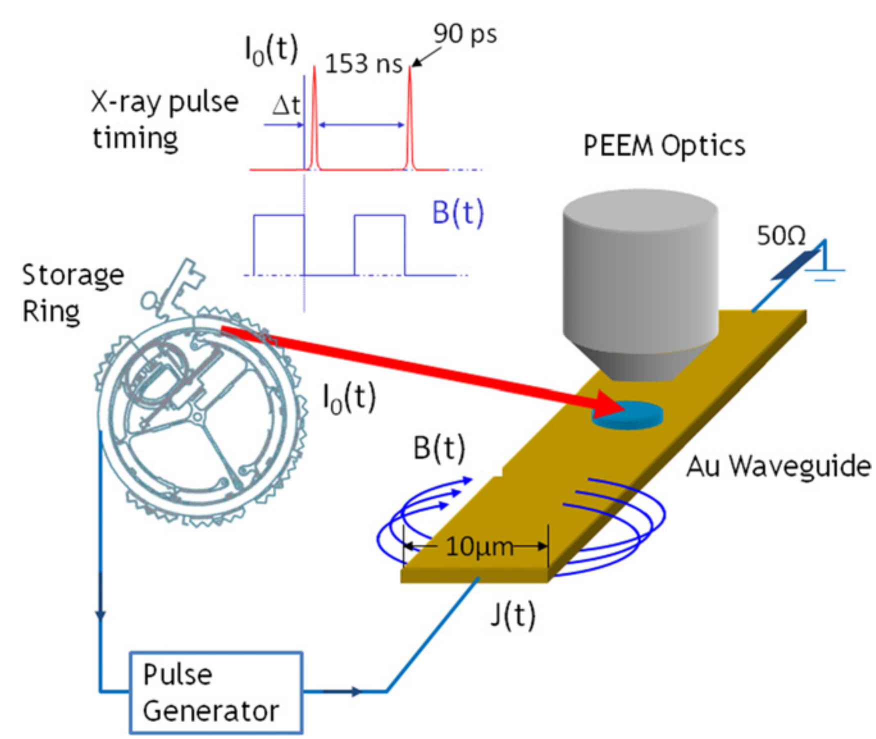


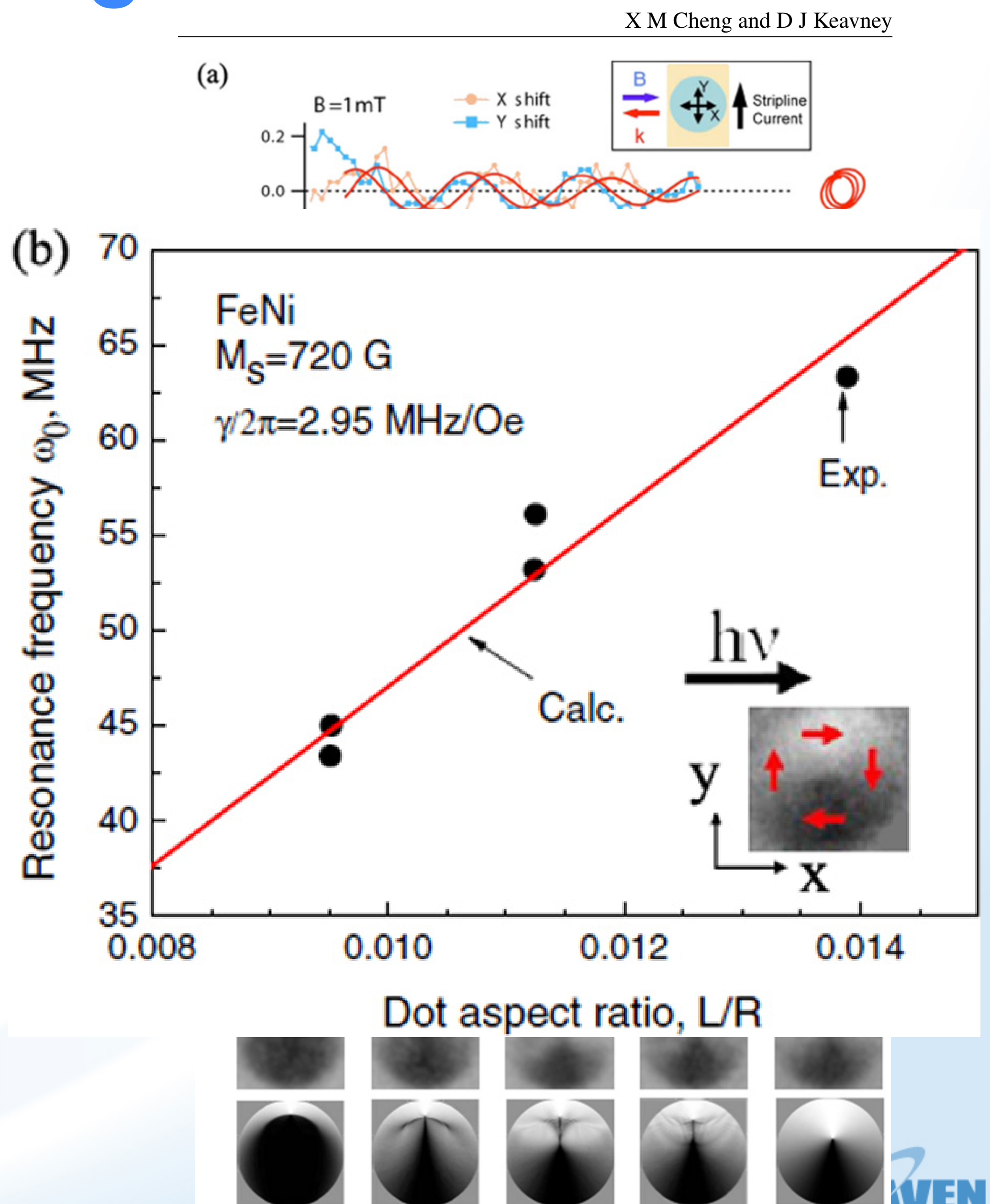


XMCD: differential absorption of x-rays depending on alignment of helicity & magnetism

XMCD = <u>difference</u> *between the two XAS spectra*

X-Ray Microscopy & Magnetization Dynamics



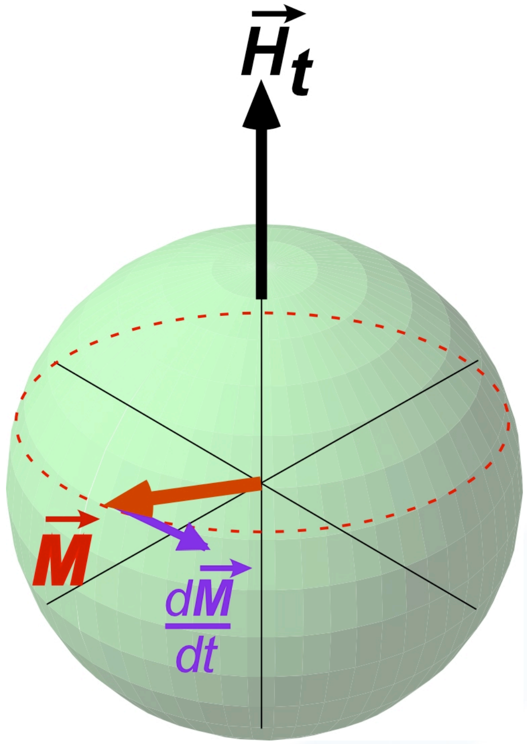


X.M. Cheng and D.J. Keavney

Rep. Prog. Phys, 75 026501 (2012)

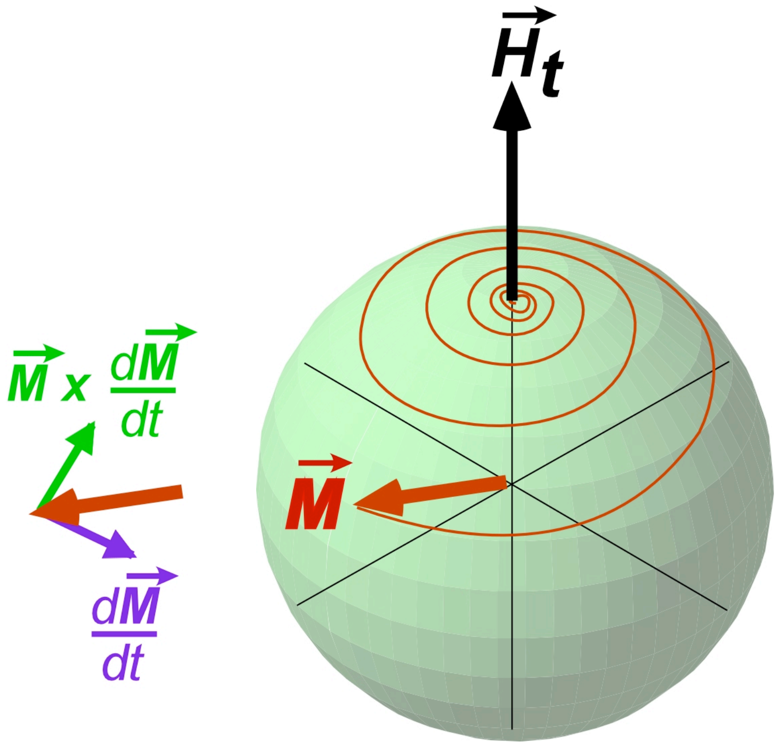
What causes magnetization motion to stop?

$$\frac{d\mathbf{M}}{dt} = -|\gamma|(\mathbf{M} \times \mathbf{H}_t)$$



$$\vec{H}_t = \vec{H}_a + \vec{H}_k + \vec{H}_d$$

Magnetization Dynamics: Damping



Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{d\mathbf{M}}{dt} = -|\gamma|(\mathbf{M} \times \mathbf{H}_t) + \frac{\alpha}{M_s}\left(\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right)$$

precession (first term) — damping (second term)

γ = gyromagnetic ratio

M_s = saturation magnetization

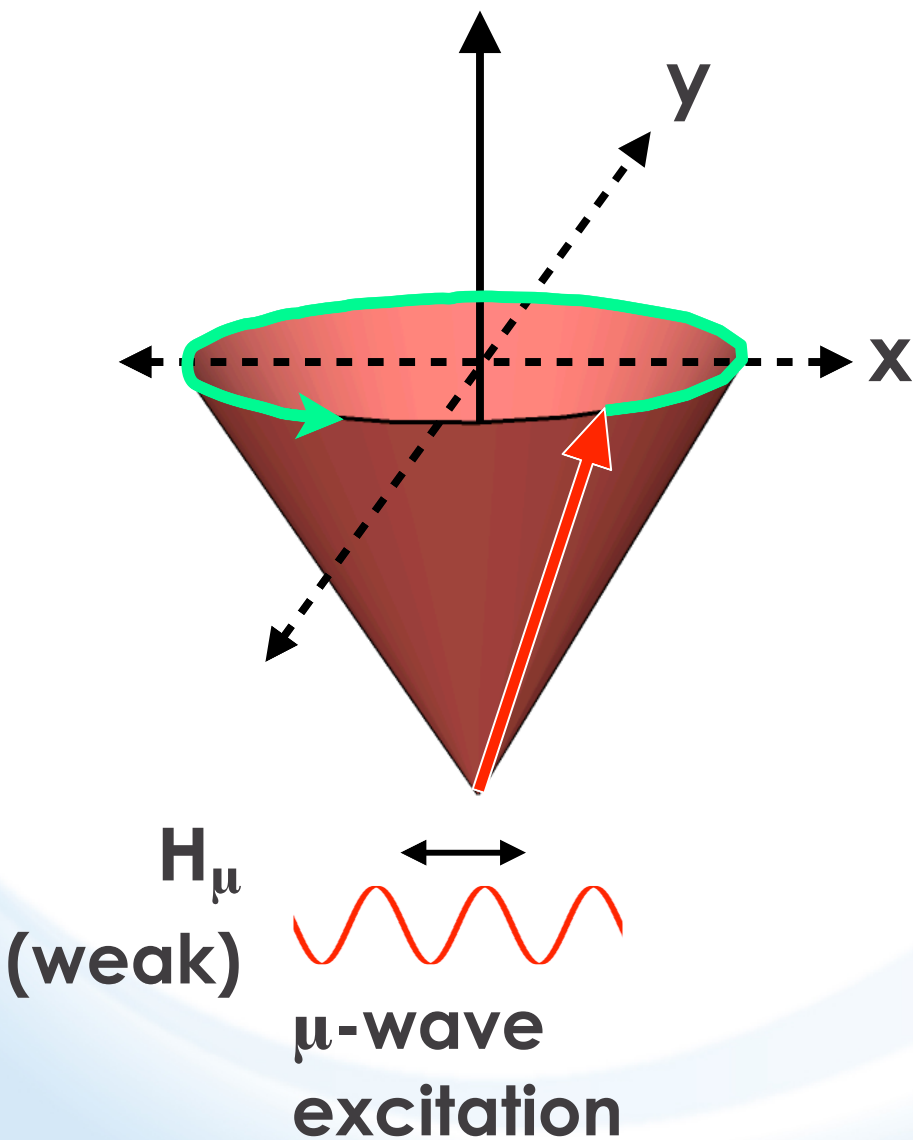
α = dissipation (damping) constant → phenomenological

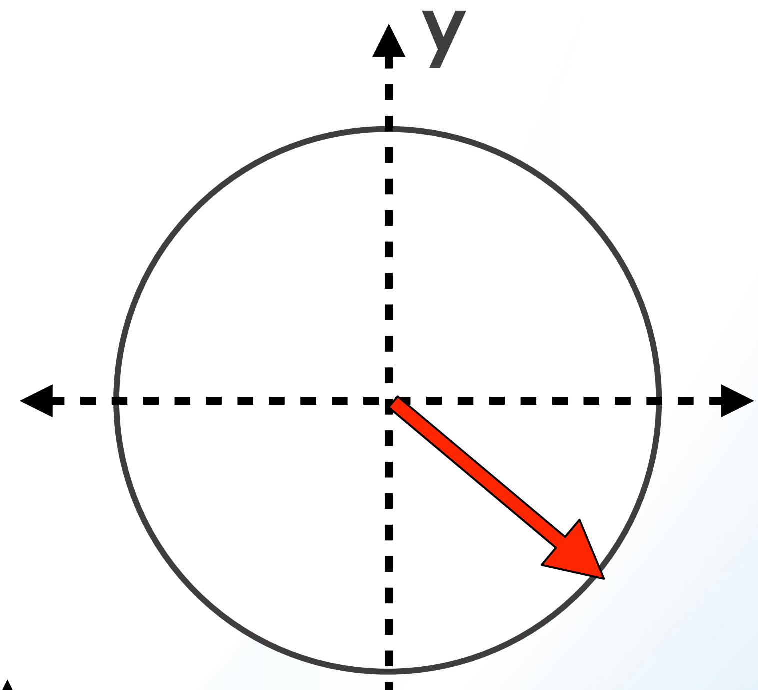
XMCD + Ferromagnetic Resonance (X-FMR)

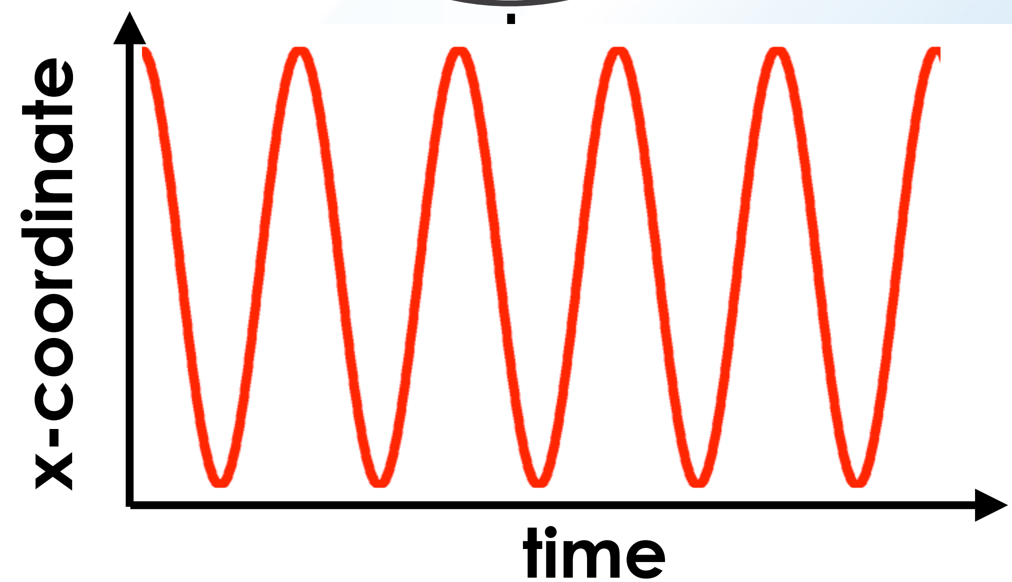
XMCD Properties:
- Element-specificity
- Spin / Orbit moments
- Cation valence
- Crystal field symmetry

FMR Properties:
- Saturation moment (M_S)
- g-factors (orbital moment)
- Damping (energy loss)
- Anisotropy
- Coupling constants

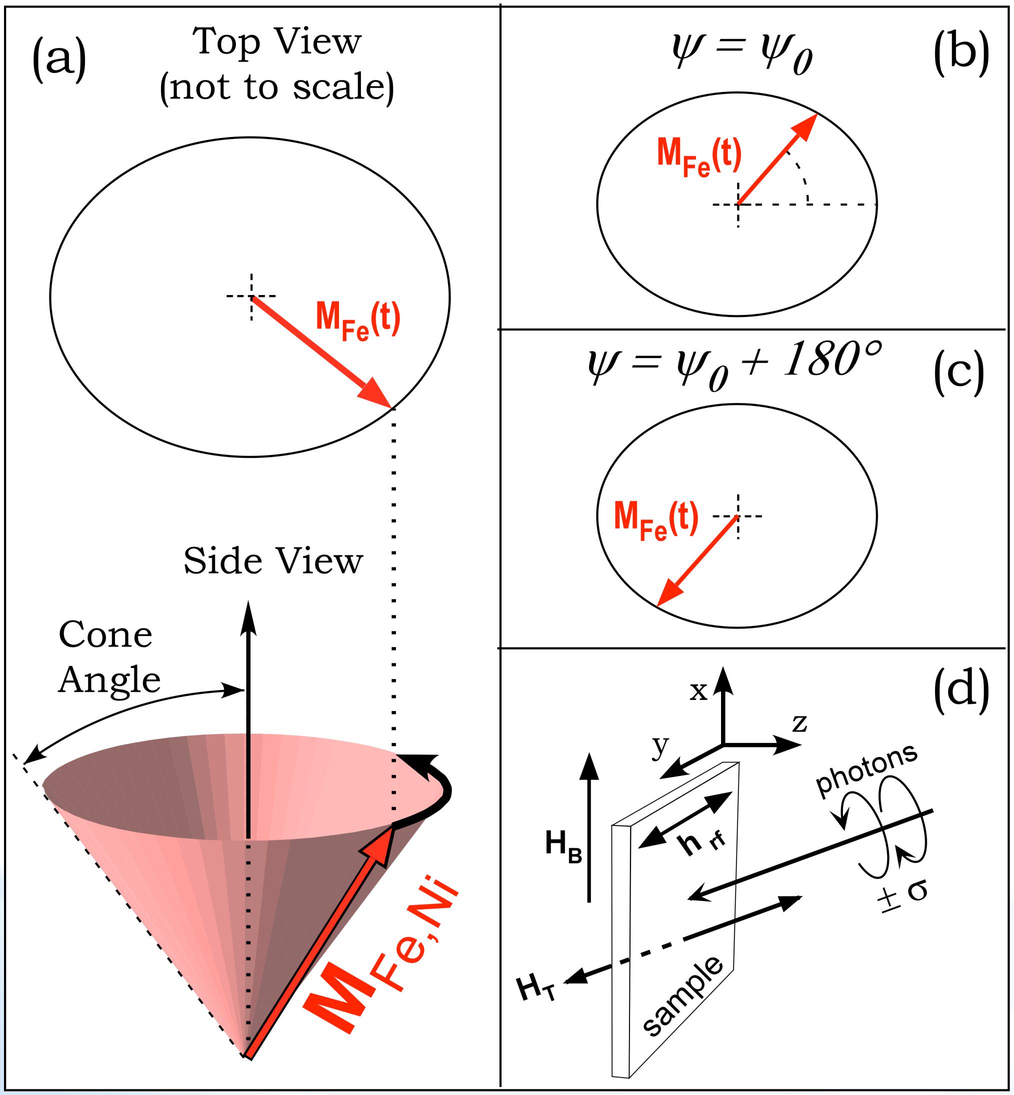
Driven Harmonic Motion:
A Useful Way to Examine Dynamics





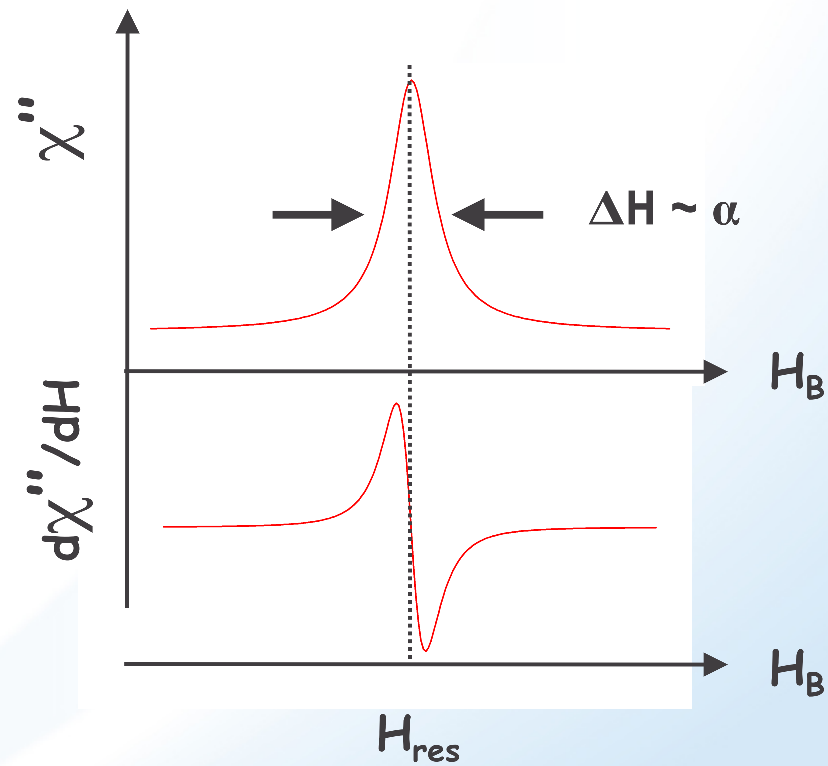


Motion in FMR



FMR motion parameterized by:

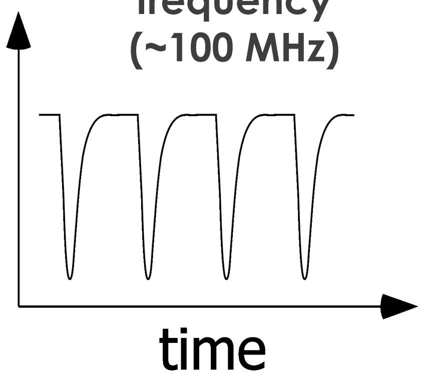
1. **Cone Angle**
2. **Phase of oscillation**



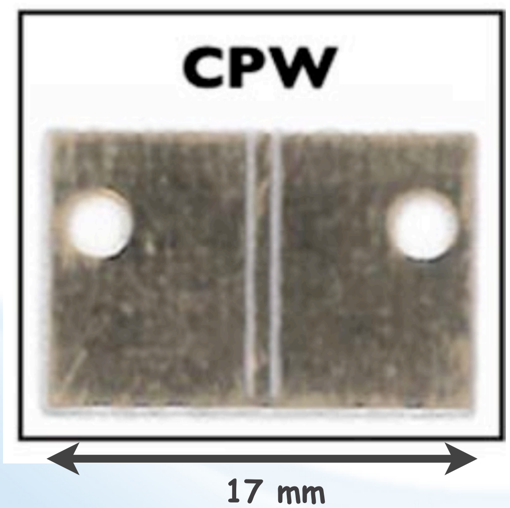
Uniform precession ⇔ Q=0 magnon

Microwave Excitation: Custom Electronics to Generate Phase Locked Source

BRF =
bunch repetition
frequency
(~100 MHz)



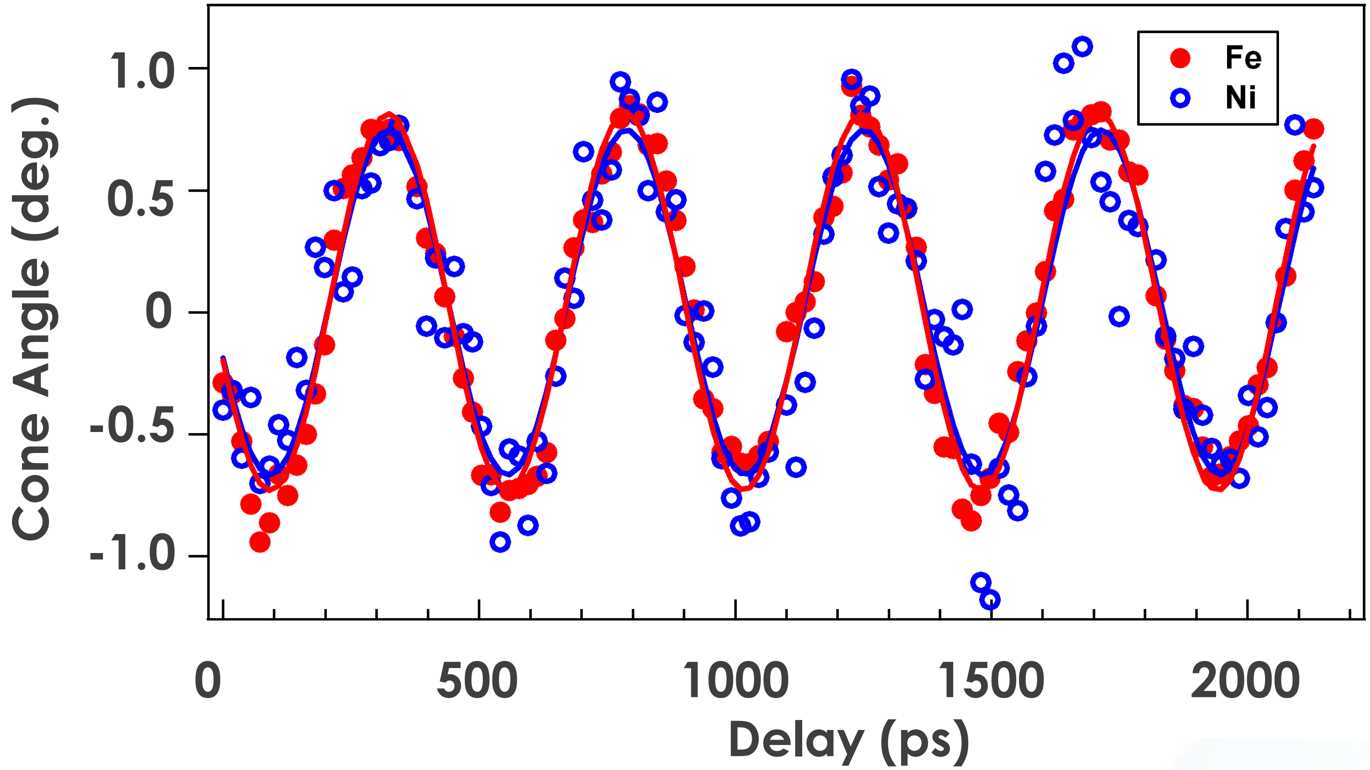
→ Delay Generator → Frequency Multiplier n * BRF (n ~10 - 45) → Hi Power Amplifier (~30 dBm) → GHz-range Excitation To Sample



Co-Planar Waveguide (CPW)

- Central conductor
- width W
- Peak field ~ W
- Small central hole (~250 μm)

Preliminary Studies:
Does it Work on Simple System?



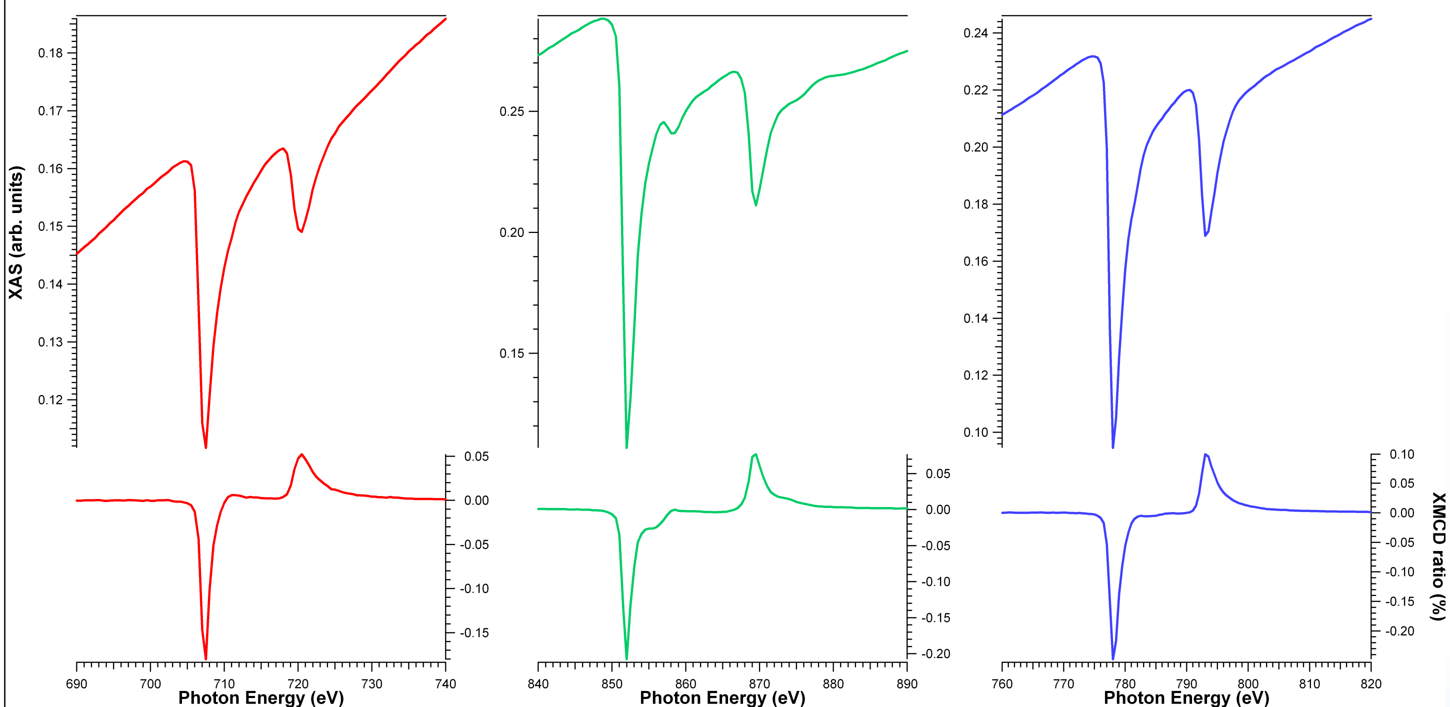
- Single Fe-Ni layer
- microwave frequency 2.3 GHz
- H_{APP} near resonance condition

- Fe & Ni precess together (strong coupling inside single layer)
- Simple sinusoidal motion (easy to extract amplitude & phase)
- Small angle motion ($\phi < 1°$)
- High precision (resolution: amplitude < 0.1°, phase < 5 ps)

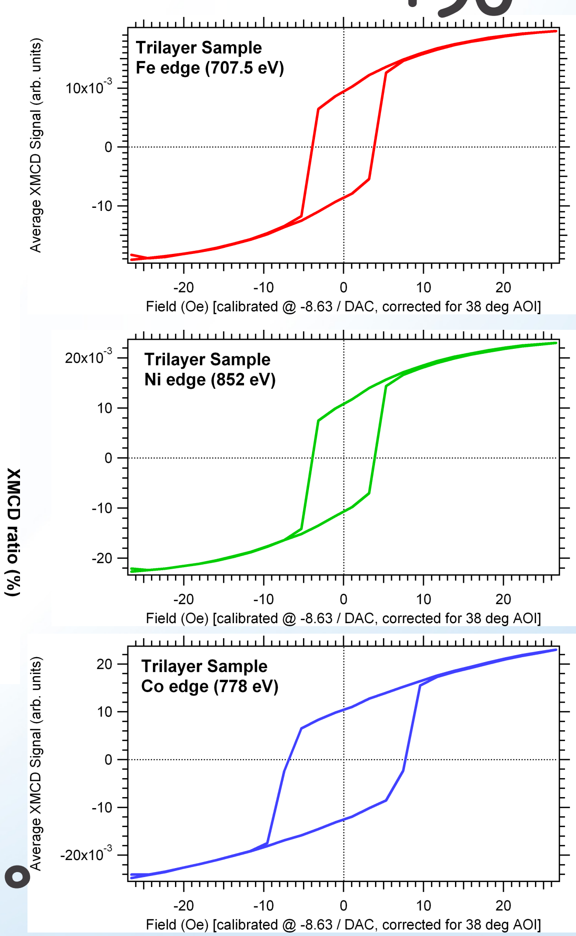
D. A. Arena et al., **JMMM, 312**, 374-378 (2007).

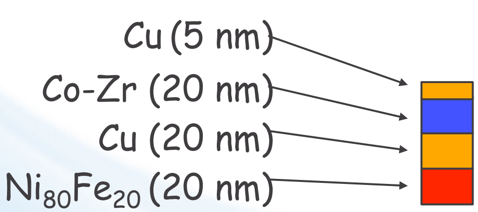
XMCD Measurements, Trilayer / Transmission

XAS / XMCD



Hysteresis





COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK Bailey Group

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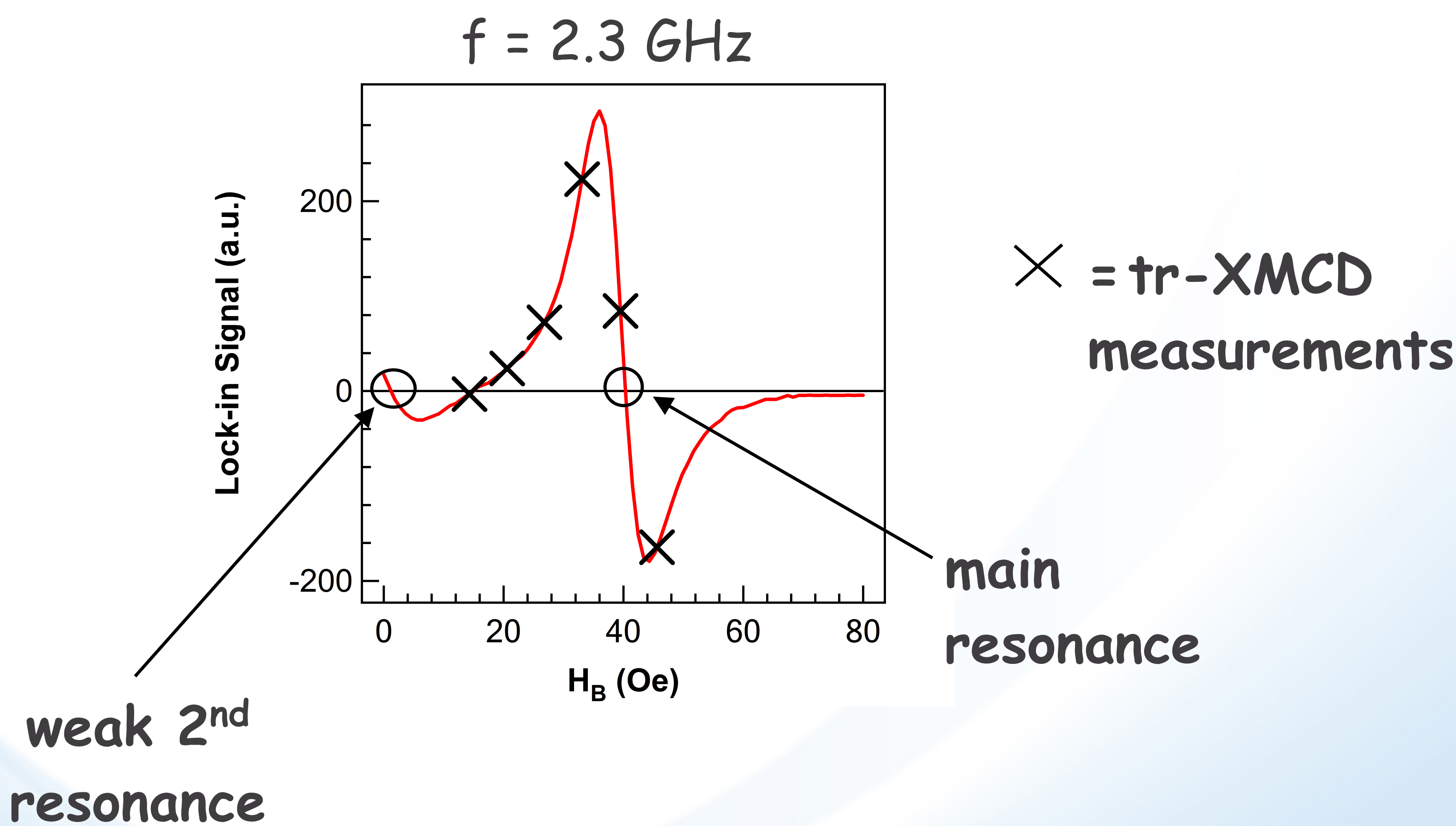
In-situ Conventional FMR, Trilayer

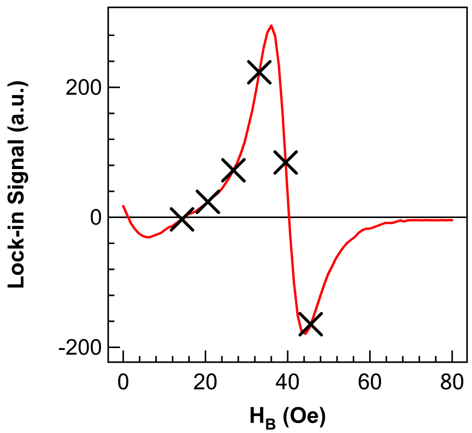


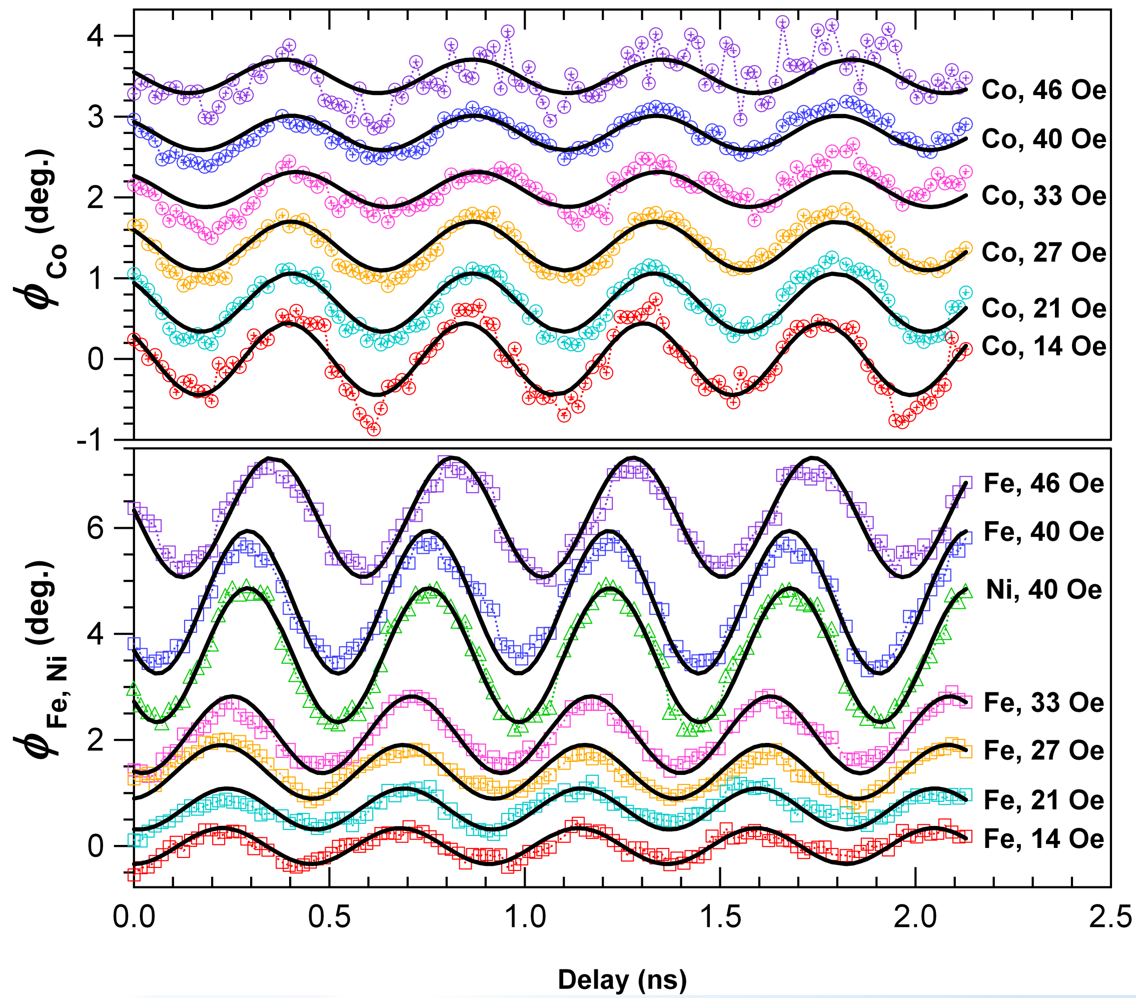
Columbia University in the City of New York
Bailey Group
Workshop on Multi-bend Achromat Lattice at the APS, 21-22 Oct. 2013
Brookhaven National Laboratory

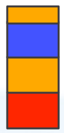
Time-Resolved XMCD, Trilayer sample

Mesurements at beam one 4-ID-C, Advanced Photon Source, ANL

f = 2.3 GHz





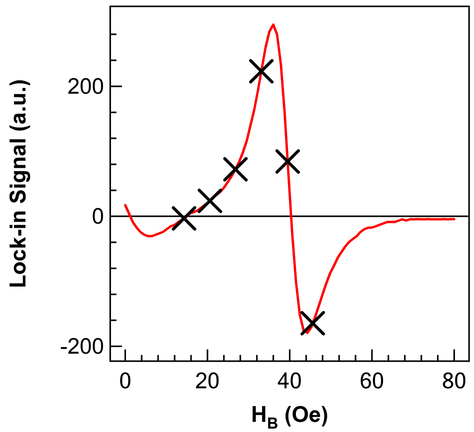


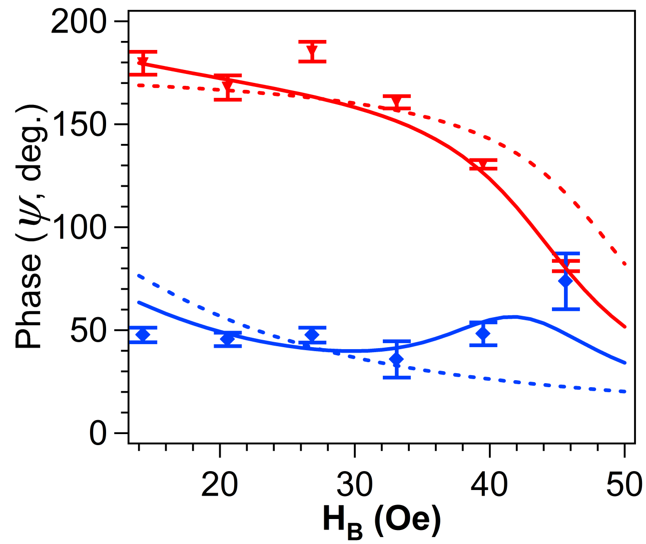
D.A.Arena et al., PRB 74, 064409 (2006)

Columbia University in the City of New York — Bailey Group

Analysis w/ Coupled LLG Eqn's

f = 2.3 GHz

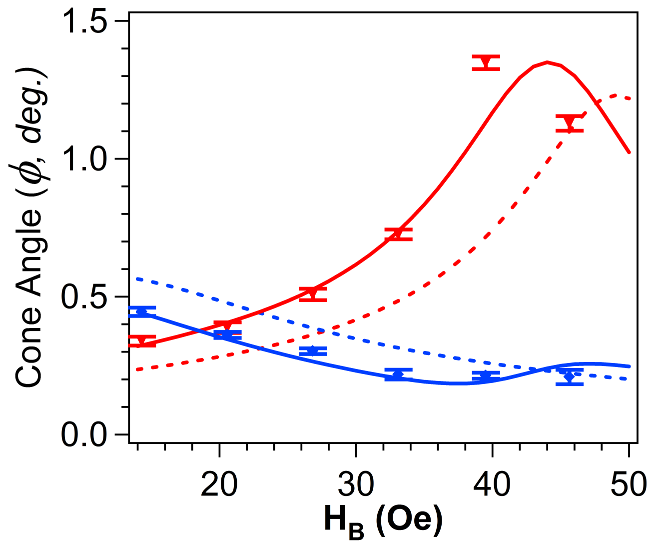


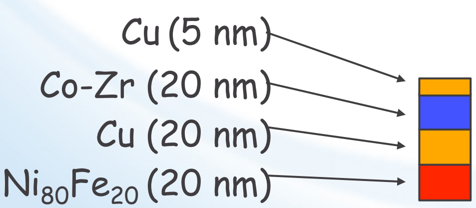


Model Calculations:

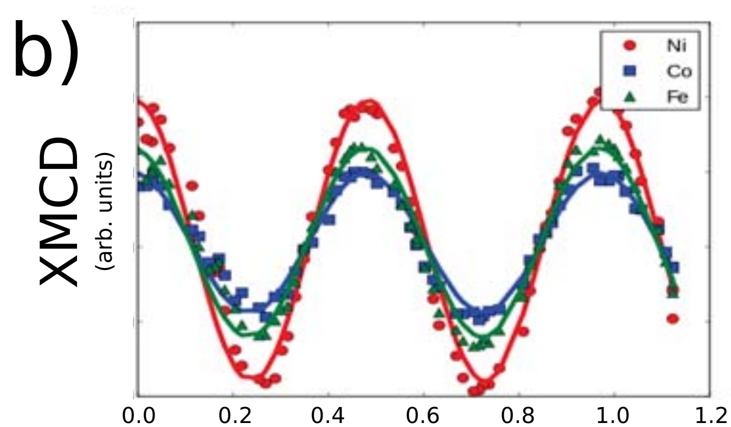
A = 0 (no coupling)

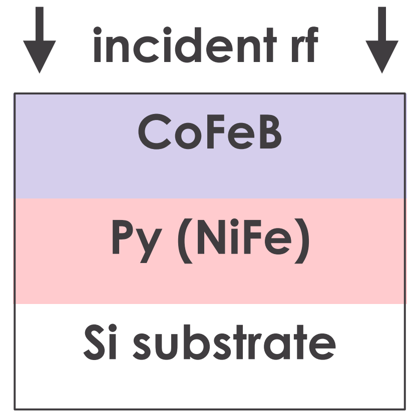
A = 0.22 ergs /cm^2 (weak coupling)



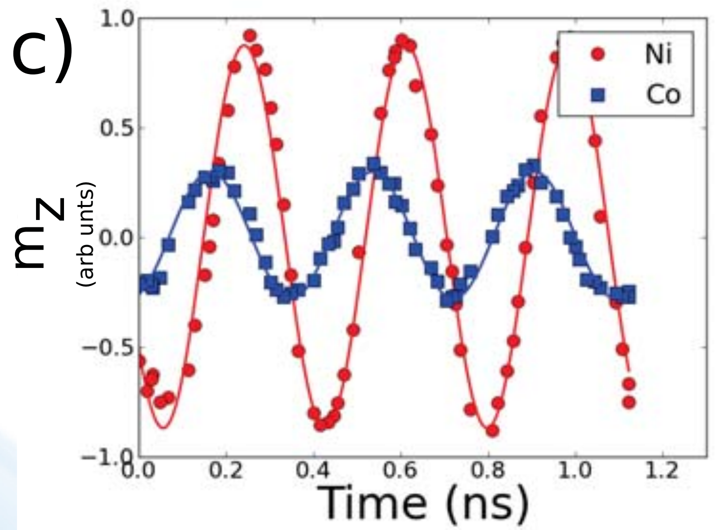


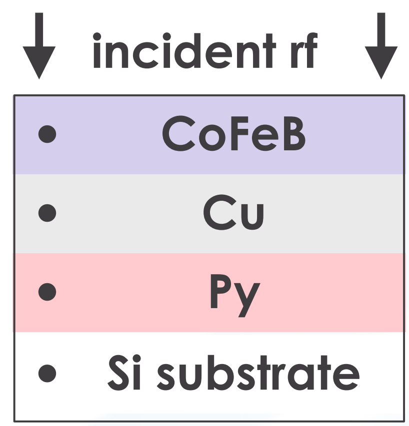
Extrinsic Non-Local Effect: Phase and Amplitude Variation of Driving RF Field





- Direct-Coupled Layer
- Precession in-phase
- Comparable amplitude

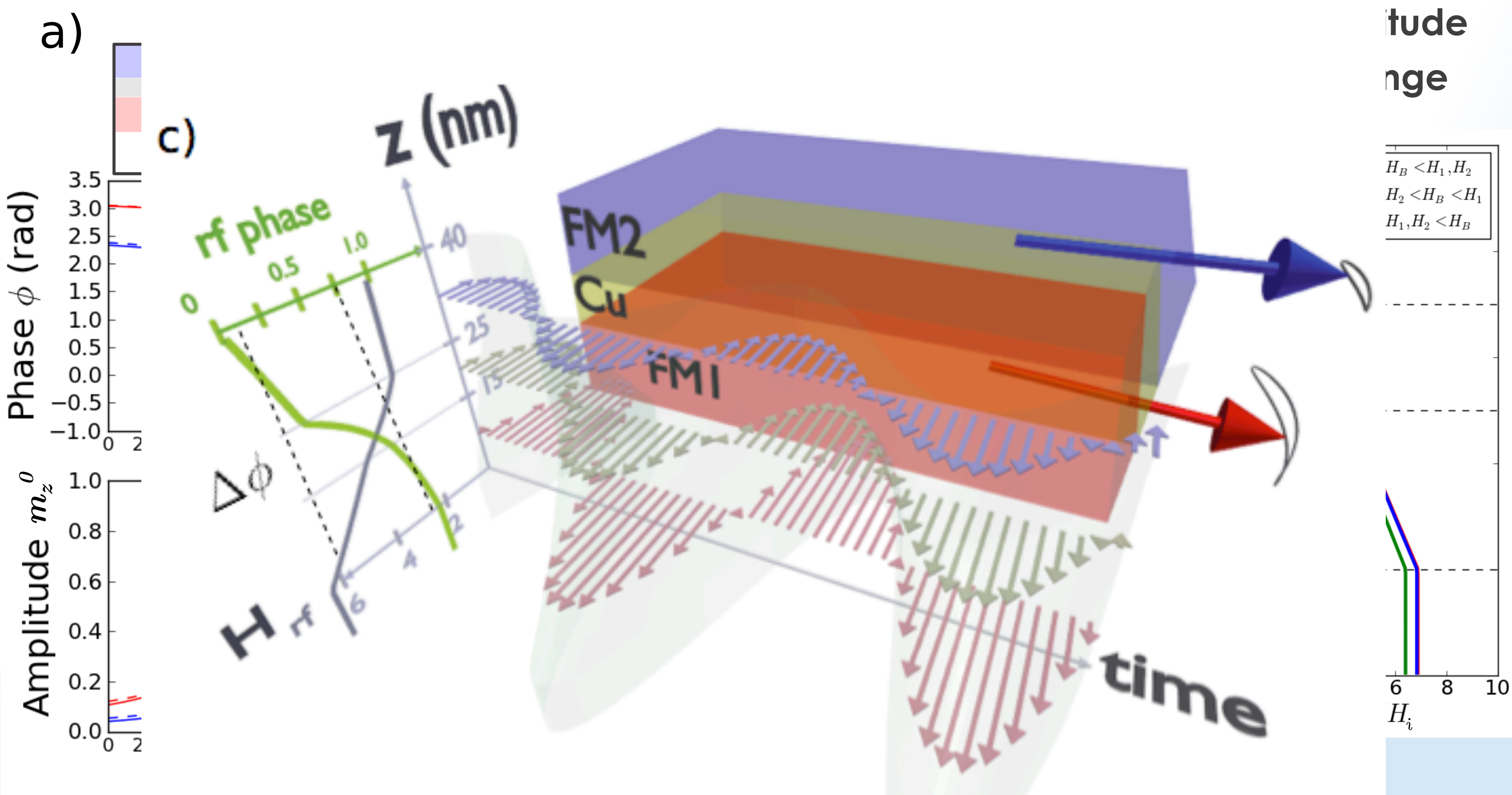




- Indirect-Coupled Layer
- Precession *not* in-phase
- Variation in amplitude
  - ➡ Larger response for layer closer to substrate

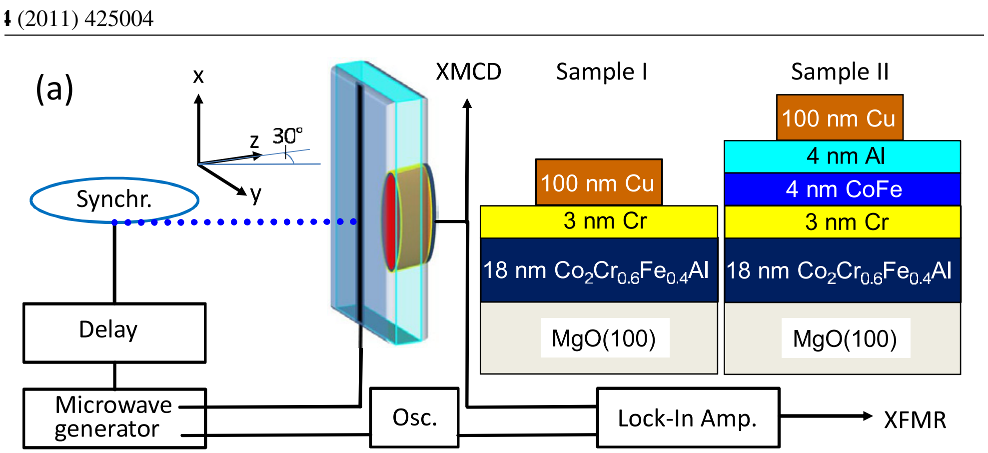
W.E. Bailey, C. Cheng D.A. Arena et al.,
Nature Communications, 4 2025 (2013)

Reconstructing Propagating EM Fields via *Local* Spectroscopy



W.E. Bailey, C. Cheng D.A. Arena et al.,
Nature Communications, 4 2025 (2013)

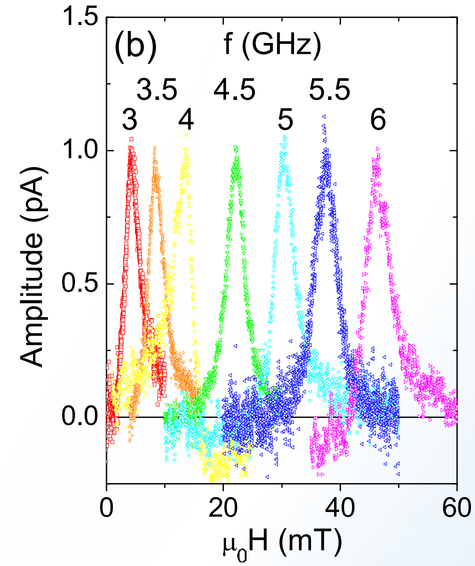
Non-Local Effects: Increased Damping in Epitaxial GMR-type Structures



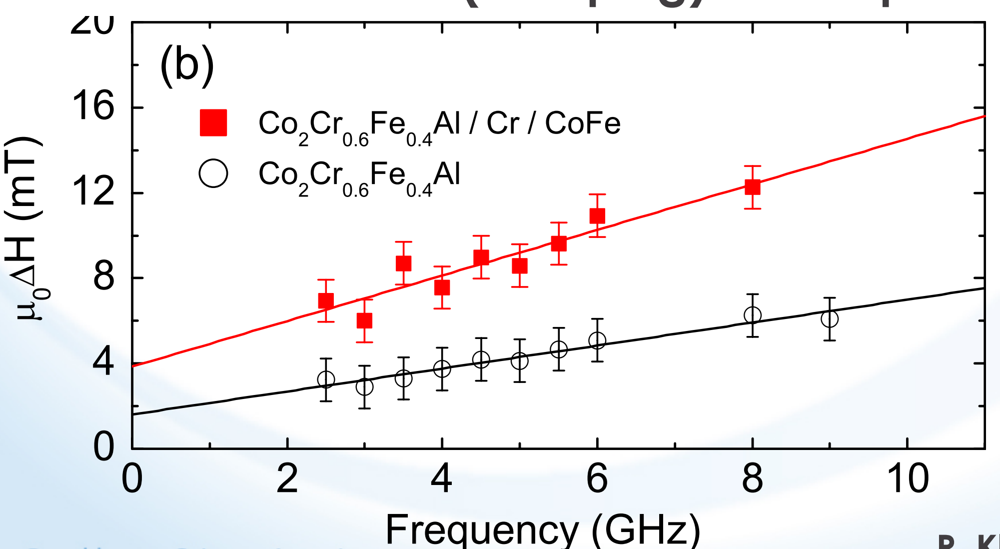
CoFe

Cr

$Co_2Cr_{0.6}Fe_{0.4}Al$



Line Width (damping) vs. Freq.

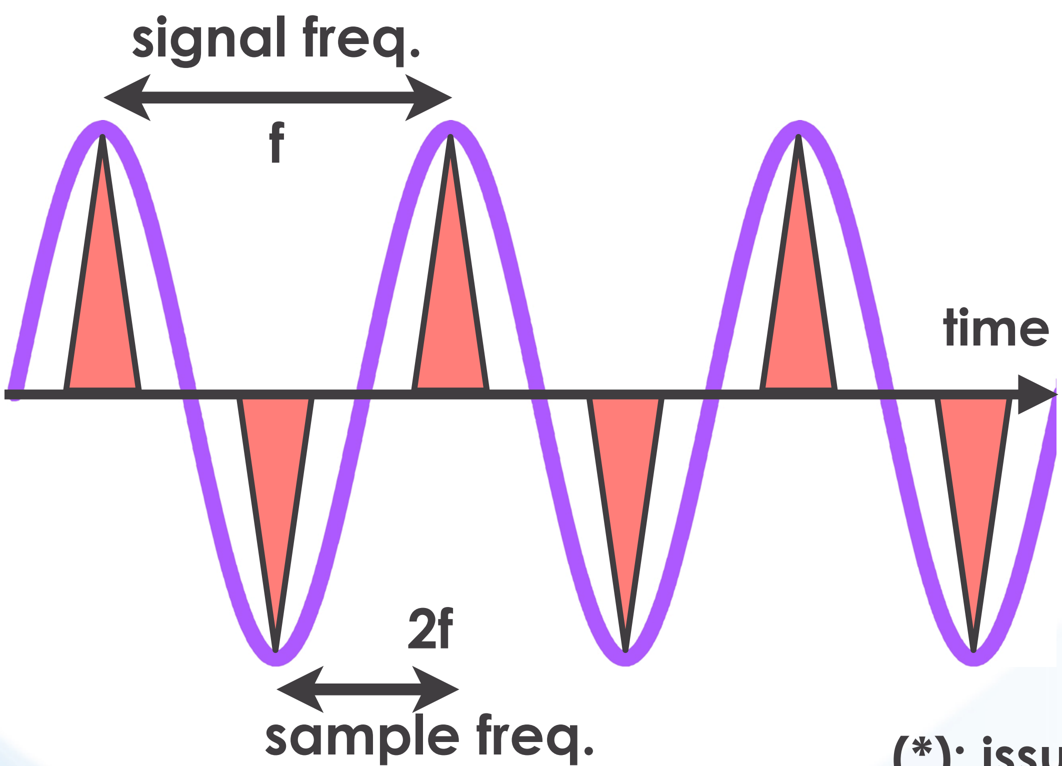


- Measurements at BESSY-II (50 ps)
- Pushing up to 10 GHz
- Main result: increase in damping from multilayer
- ***NOT*** two-magnon contribution (interface, impurity scattering)
- Possible explanation: non-local spin dynamics (spin pumping / spin torque)

P. Klaer et al. JAP 44, 425004 (2011)

Shorter Pulses → Higher Frequencies

Nyquist / Shannon Sampling Criterion

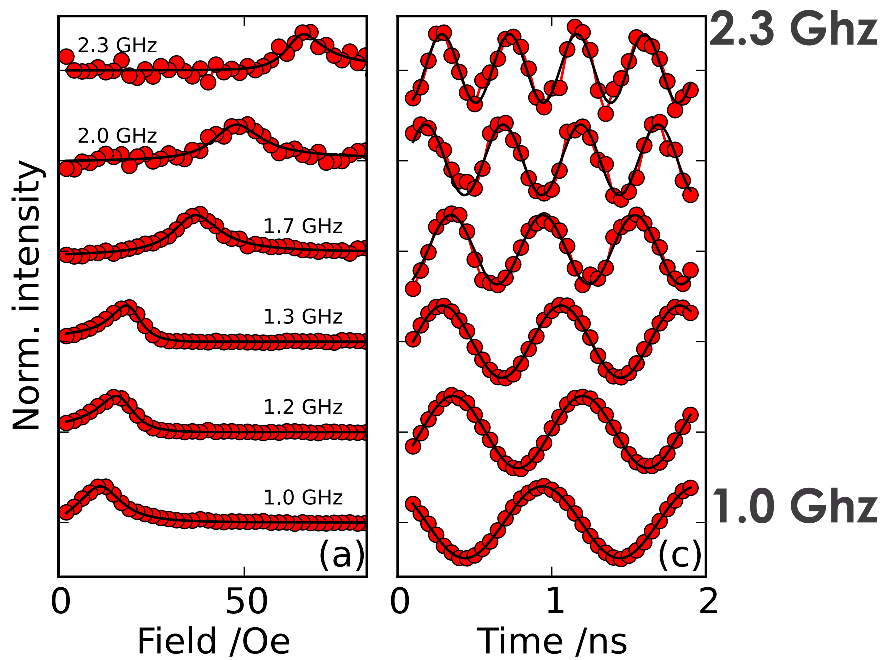


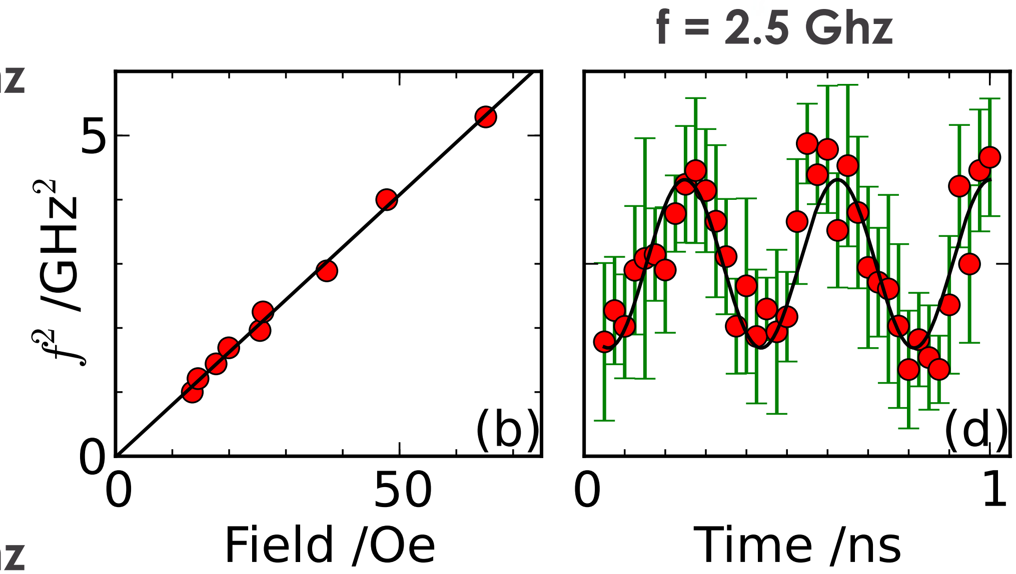
	Bunch length	f,max
APS 2013	~70 ps	~7 GHz

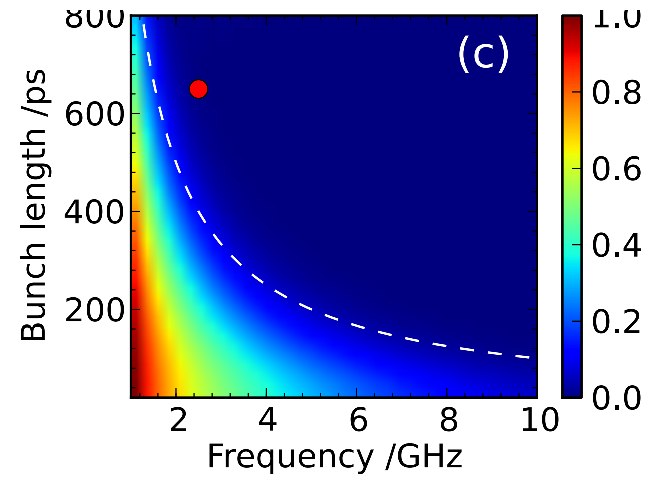
(*): issues of phase stability, cone angle

A ~ 1/f

Beyond the Nyquist Criterion: Exploring the Limits of XFMR at Storage Rings







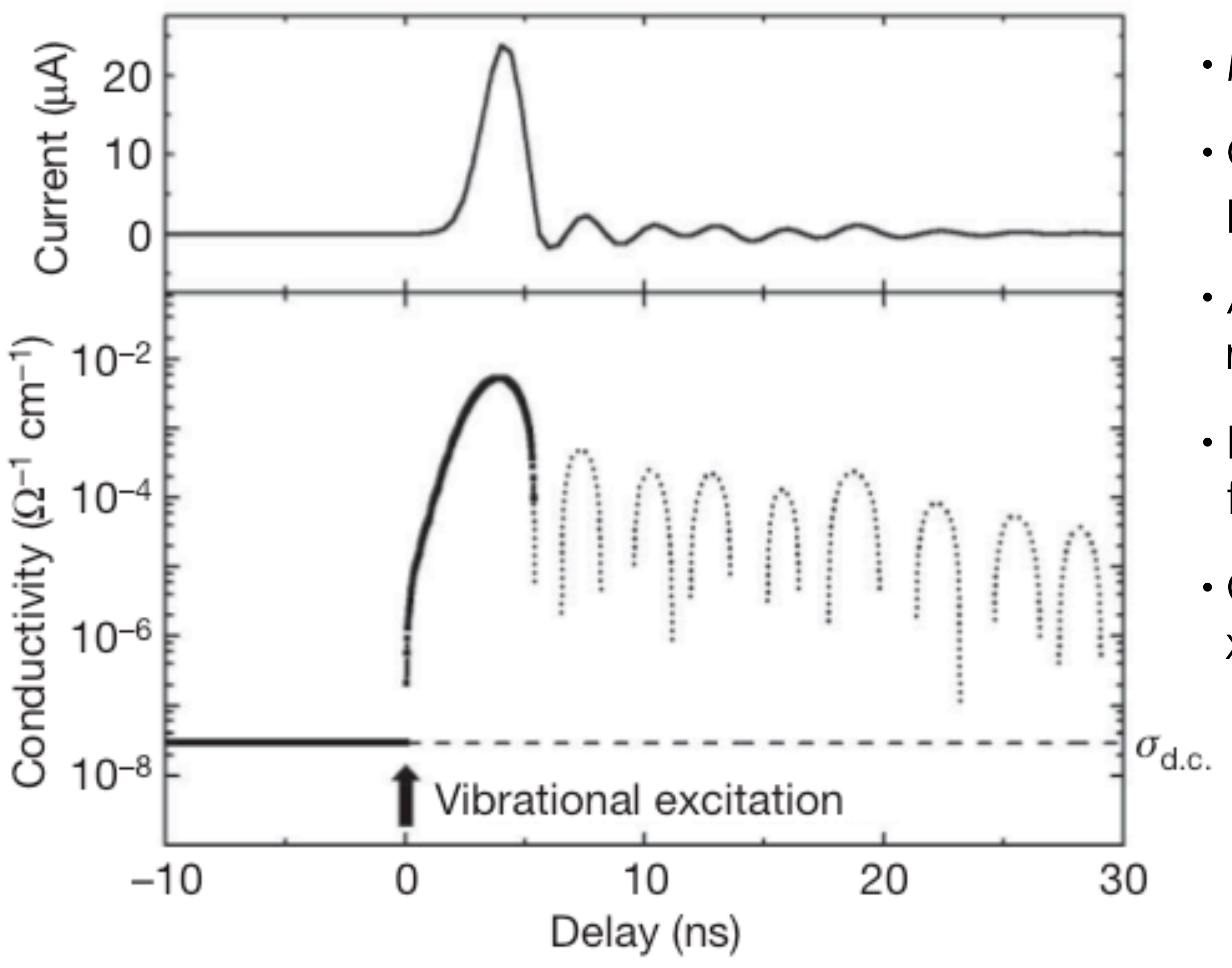
- **Measurements at MAX-II Storage Ring**
- **Pulse length: 650 ps ⇒ Nyquist limit ~ 0.75 GHz**
- **GHz dynamics clearly observe (Kittel Plot)**
- **Modeling verifies sampling beyond 1/f limit**

P. Warnicke, D.A. Arena et al.

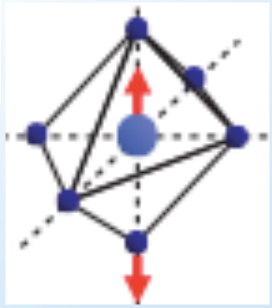
JAP 113, 033904 (2013)

THz Intiated Phase Transitions

Metal-Insulator Transition in PCMO Driven by THz Excitation



- MIT occurs in < 4 ns
- Other phonons do not participate
- At limit of temporal resolution
- Phonon mode alters x-tal field around Mn
- Can we follow transition x-ray techniques? (XLD)



M. Rini, R.Tobey, N Dean, J. Itatani, Y. Tomioka, Y. Tokura, R Schoenlein, A. Cavalleri, Nature (2007)

Thoughts on Low Emittance Beams & Timing / Dynamics

- Keep a close eye on accelerator developments
- Smaller beams have a direct improvement on rf excitation sources
  - Improved signal stability w/ under filling aperture
  - Higher rf fields via smaller waveguides
  - Scattering geometries ⇒ super lattices / interfaces
- Advantages of Shorter Pulses
  - Upper frequency limit
  - Address different dynamic regimes (Non-Gilbert type damping, acoustic / optic modes in multilayers)
- New excitation sources desirable (e.g. THz source)
- Opportunities in Complex Oxides (XMCD / XLD)

Co-Workers & Collaborators

Brookhaven National Lab
National Synchrotron Light Source
- Dr. Darío A. Arena
- Dr. Yi Ding
- Dr. Peter Warnicke
- Dr. Elio Vescovo
- Dr. Chi-Chang Kao*

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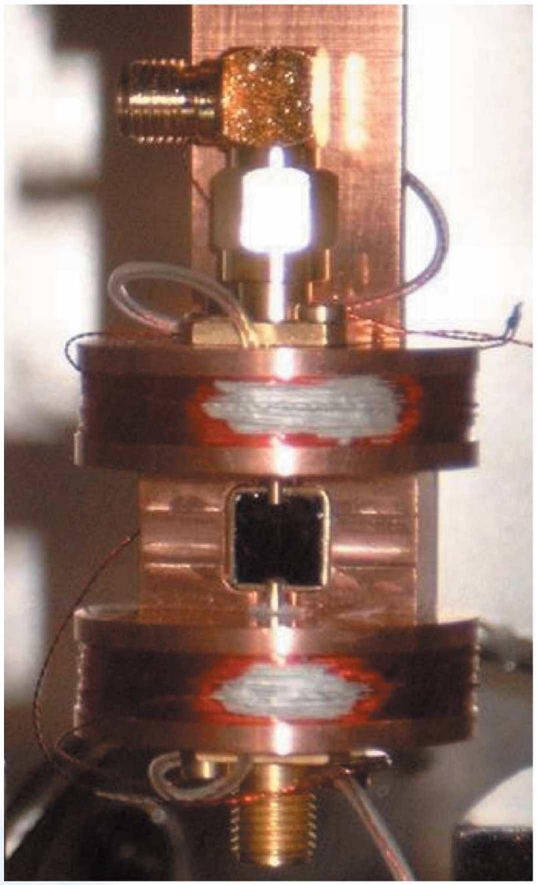
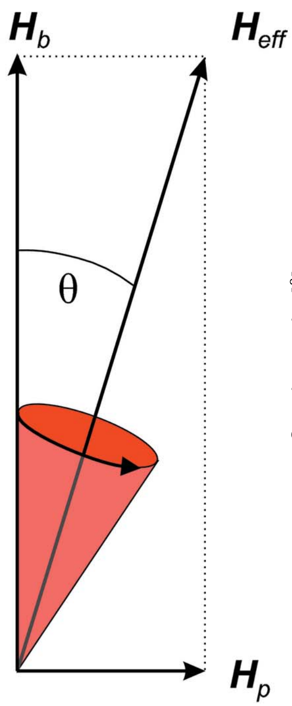
- Prof. William Bailey
- Ms. Cheng Cheng
- Dr. Sioan Zohar
- Dr. Yongfeng Guan
- Dr. Lili Cheng

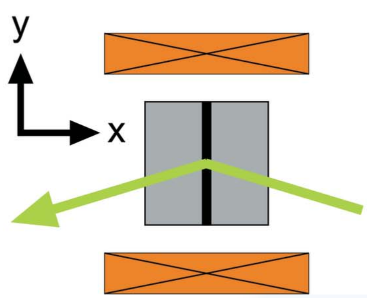
Uppsala University, Sweden
Dept. of Physics
- Prof. Olof "Charlie" Karis
- Dr. Ronny Knut
- Dr. Daniel Bedau

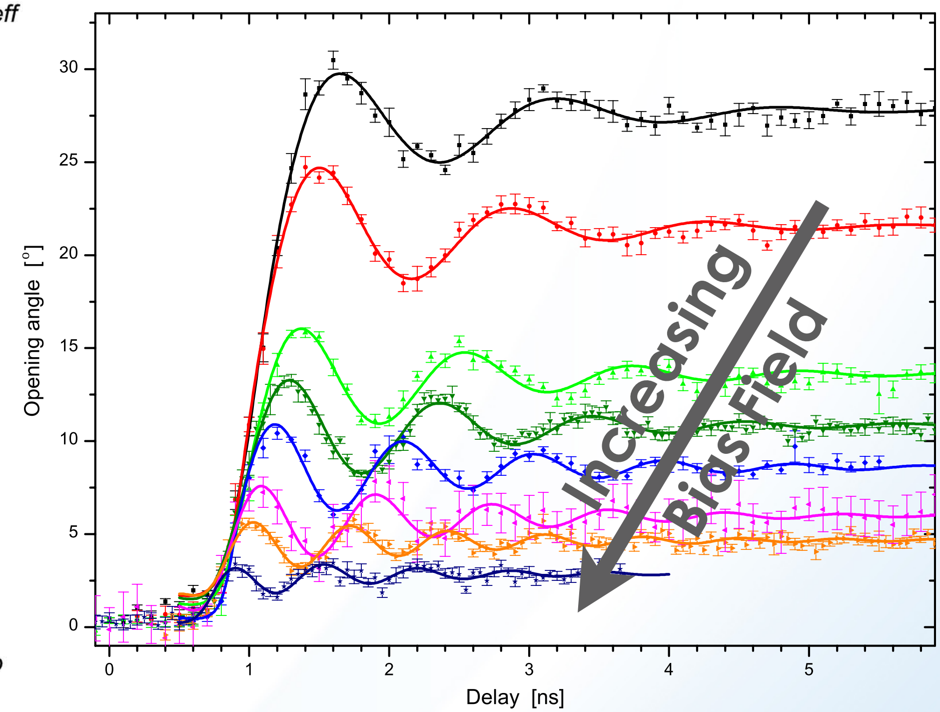
[redacted]

Improved Scattering Geometry: ALICE Diffractometer @ BESSY-II







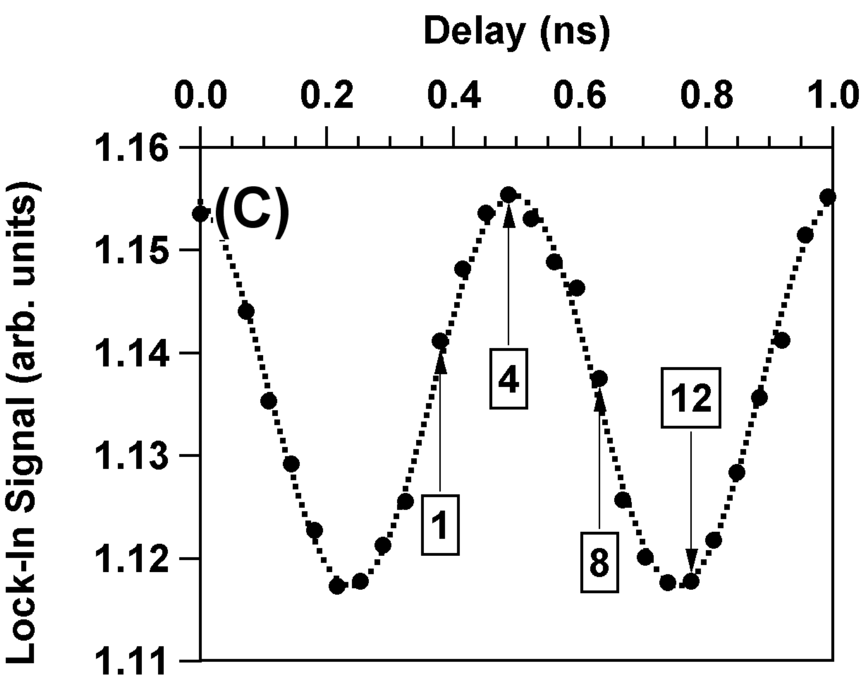


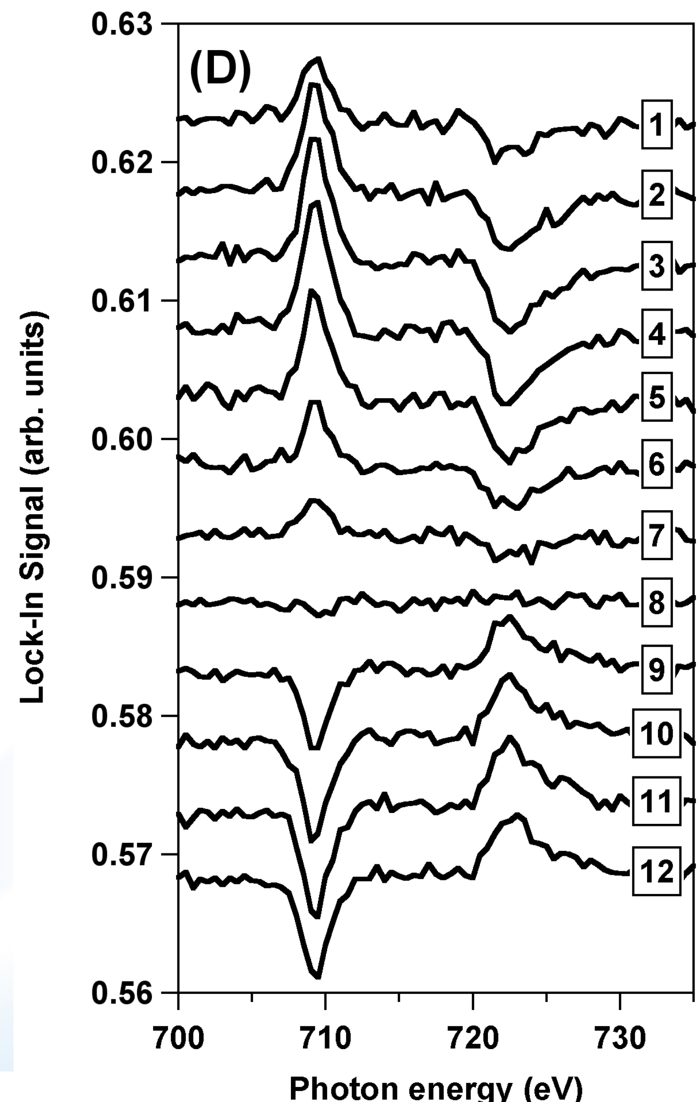
- **XRMS under pulsed excitation on proper diffractometer**
- **Large angle excitations (~30 deg.)**
- **Opens up dynamical studies of multi-layer structures, superlattices etc.**

Stefan Buschhorn et al., J. Synchrotron Rad. (2011). 18, 212–216

Time-Resolved XMCD Spectroscopy

Py sample (25nm); 2 GHz excitation
Fixed Field
Vary Photon Energy





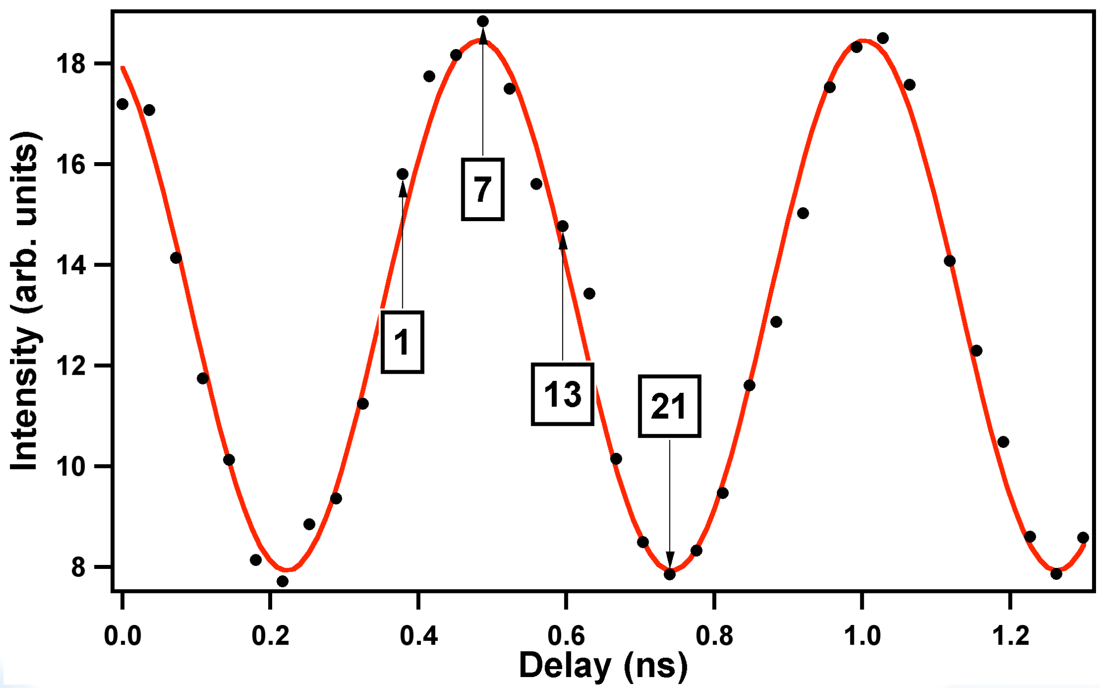
Recall: small angle excitation (~1° or less)

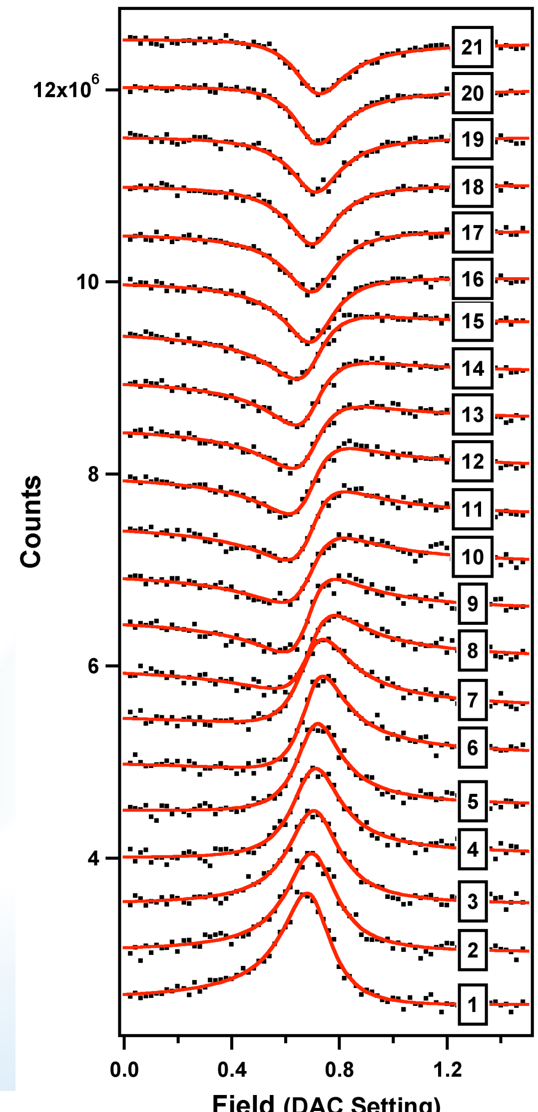
Measurement of XMCD spectra under dynamic (low-energy) excitation

D. A. Arena et al., Rev. Sci. Inst. 80, 083903 (2009)

Element-Resolved Magnetic Susceptibility

Py sample (25nm); 2 GHz excitation
Fixed Energy (Fe L3 edge)
Vary Applied Bias Field



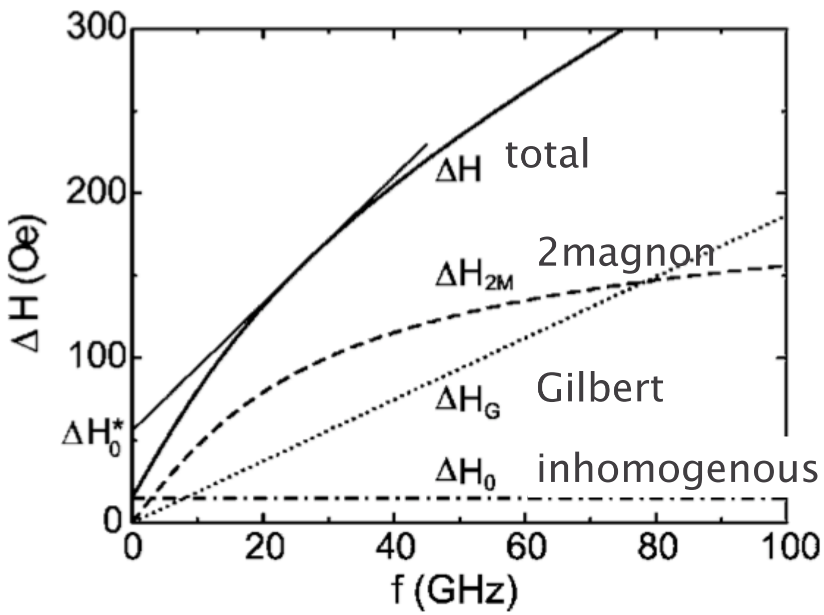


By choosing phase appropriately, we can measure the element-resolved Re χ or Im χ

D. A. Arena et al., Rev. Sci. Inst. 80, 083903 (2009)

Non-Gilbert Damping:
Contribution at high frequencies

PHYSICAL REVIEW B **73**, 144424 (2006)



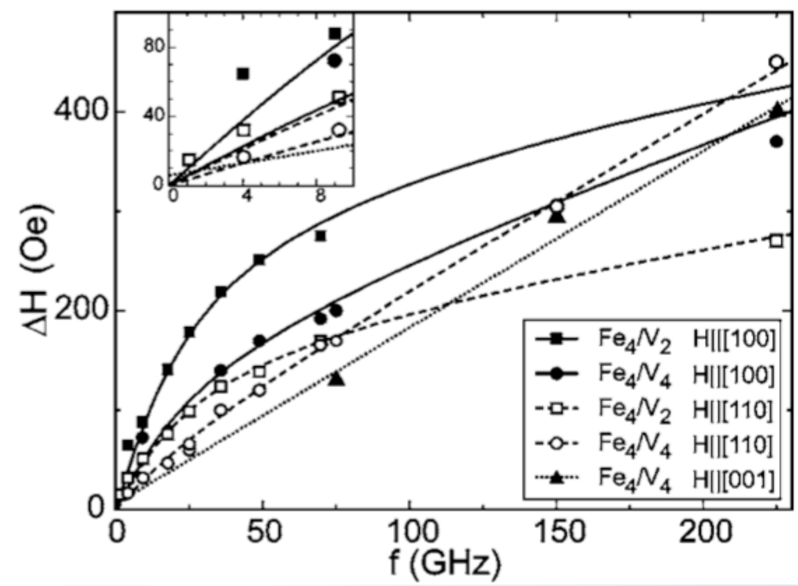


FIG. 3. Schematic diagram of the frequency dependence of the various linewidth contributions.

K. Lenz, K Baberschke PRB (2006)