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U.S. Department of Commerce

New Directions in Spin Current Research at NIST, Boulder

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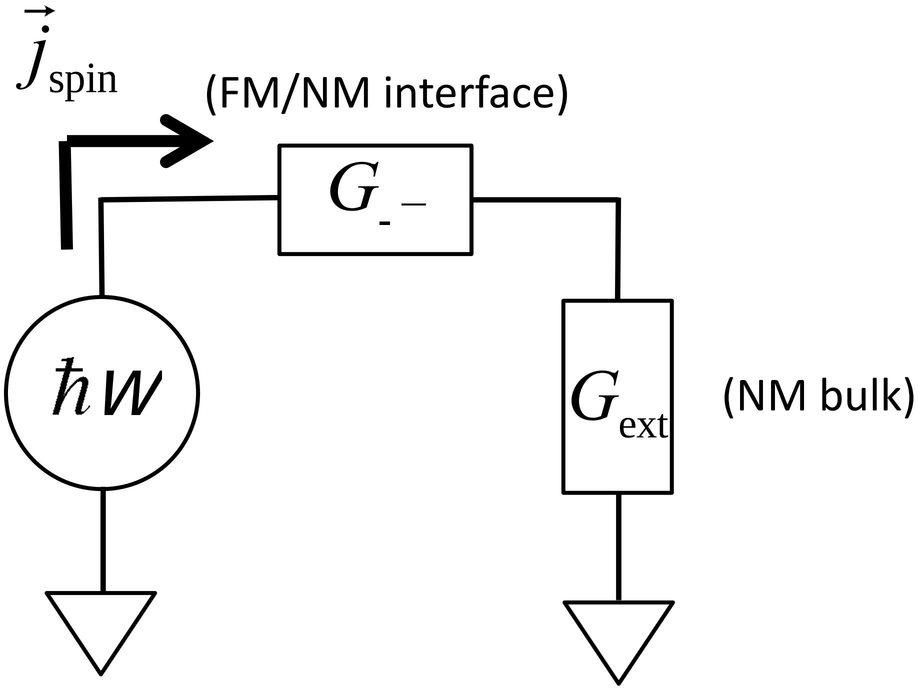
Introduction

- Spin pumping to characterize *interlayer* spin current flow in multilayers: “Spintronic ammeter”.
  - Evidence for *intralayer* transverse spin currents via FMR in individual nanomagnets: Nonlocal damping
    - Giant ultrafast spin currents via optical pumping and high harmonic generation

Spin pumping and spin current metrology: the “spintronic ammeter”

Damping via "spin pumping"



$$\boxed{\left|\vec{j}_{\text{spin}}\right| = \left(\frac{\hbar}{2e}\right)\left(\frac{\hbar\omega}{e}\right)\left(\frac{1}{G_{\uparrow\downarrow}} + \frac{1}{G_{\text{ext}}}\right)^{-1}}$$

$$\alpha_{\text{pump}}\omega = \frac{\text{torque "lost"}}{\text{angular momentum "stored"}} = \frac{j_{\text{spin}}\cdot(\text{area})}{\frac{M_s\cdot(\text{volume})}{\gamma}}$$

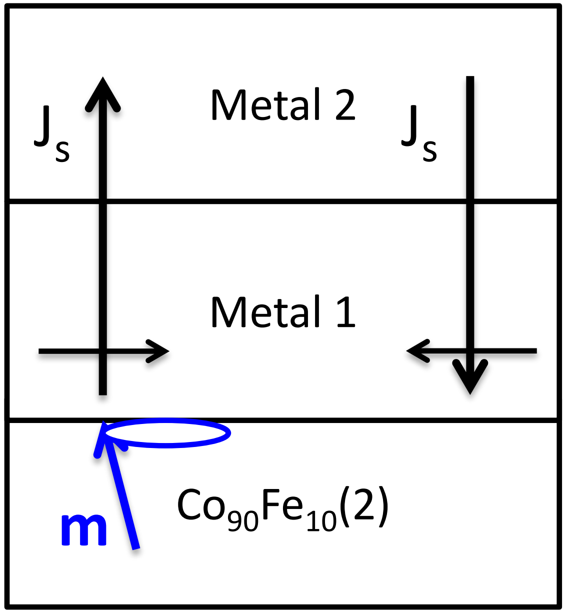
$$= \frac{\gamma\hbar^2\omega}{2e^2 M_s t_{\text{FM}}}\left(\frac{1}{G_{\uparrow\downarrow}} + \frac{1}{G_{\text{ext}}}\right)^{-1}$$

Tserkovnyak, Brataas, Bauer, 2002;
Polianski & Brouwer, 2004

Spin Pumping

- Spin pumping → spin potential at the interface (spin accumulation)

Precessing moment acts as pure spin-voltage source:



$$\frac{d\vec{m}}{dt} \mu \, J_s(0) = - \frac{\hbar}{2e^2} G^{-\,-} [\hbar \vec{m} ´ \frac{d\vec{m}}{dt} + 2 m_s(0)]$$

$$\nabla^2 m_s \equiv \frac{1}{l^2} m_s$$

Final solution depends on boundary conditions at interlayer interface, top interface

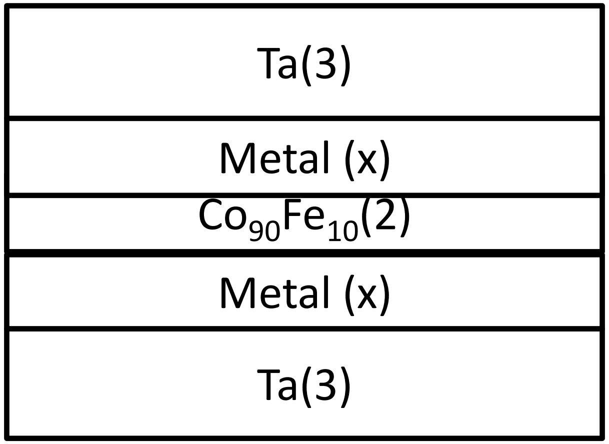
$$J_s = - \frac{\hbar}{2e^2} s \nabla m_s$$

$$m_s^{(i)} \;\mathrm{o}\; A_1^{(i)} e^{x/l} + A_2^{(i)} e^{-x/l}$$

Our large-film, perpendicular geometry allows us to set this up as a 1-D equilibrium transport problem

Experiment

- Use symmetric stacks to make unambiguous measurements
  - Spin pumping equal, in principle, on both sides
  - No oxidation of magnetic layer



Ta(3)

Metal (x)

$Co_{90}Fe_{10}(2)$

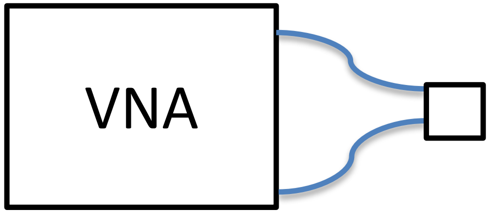
Metal (x)

Ta(3)

Measurement

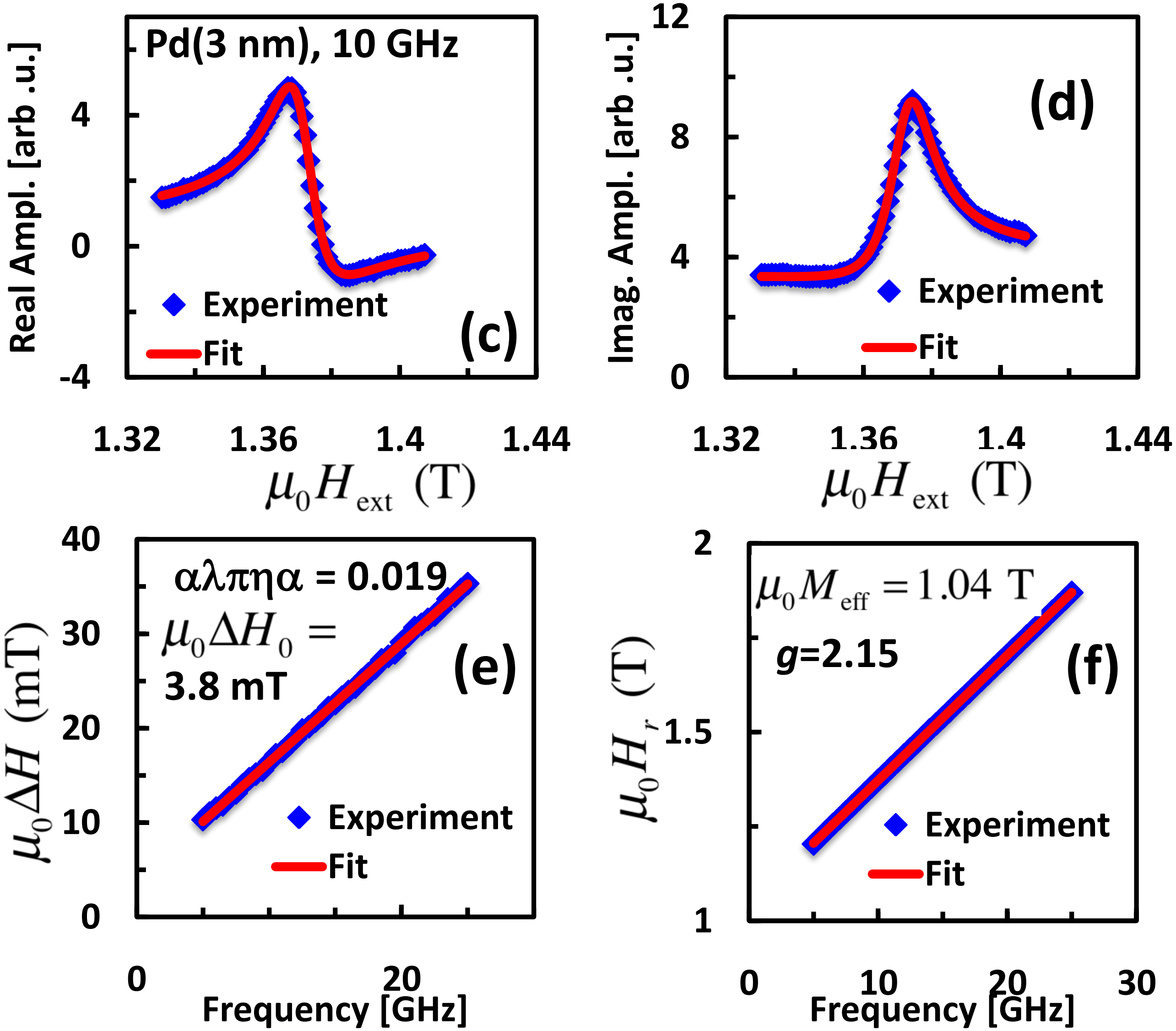
(Nembach, 2008)

- VNA-FMR
  - Get damping constant αλπηα, M_{eff}, g, ΔH_0



Measure absorption and reflection as function of field

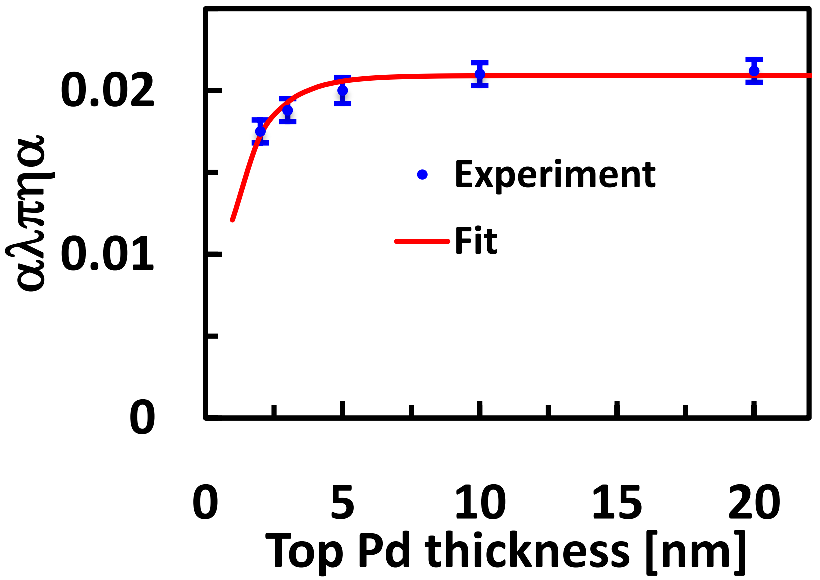
Analyze resonance structure



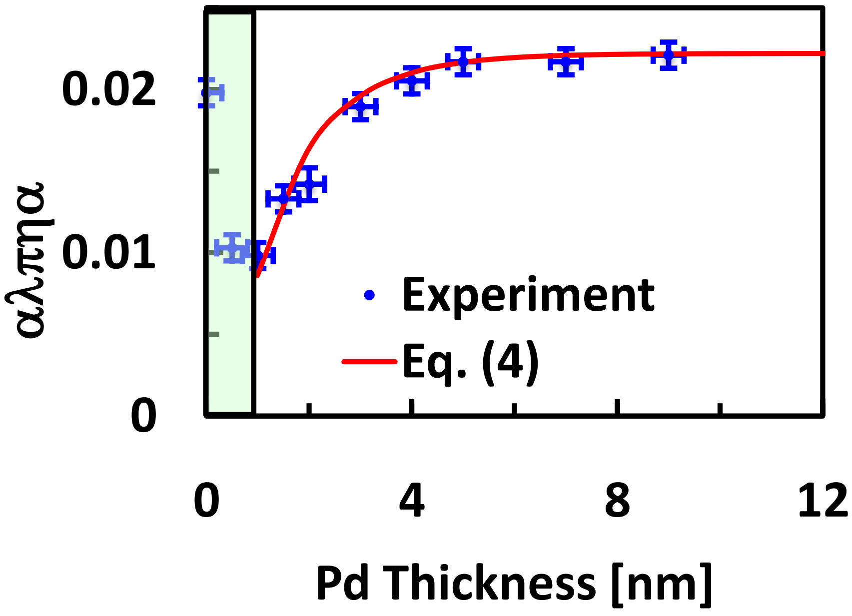
Parameter Extraction

Require offset of t_{Pd} ~ 1 nm to account for polarization of Pd

Assume bulk conductivity of Pd, $\sigma_{Pd} = 49.5 \times 10^{6}\,\Omega^{-1}m^{-1}$
Measure our Ta conductivity $\sigma_{Ta} = 4.1 \times 10^{5}\,\Omega^{-1}m^{-1}$



No Ta cap, Ta(3)Pd(3) underlayer



Symmetric Ta(3)Pd(x)

- C. T. Boone, et al., J. Appl. Phys. 113, 153906 (2013)

Parameter Extraction

Know properties of Ta and Pd, can then extract all other material parameters

Metal	$G^{\uparrow\downarrow}_{CoFe\text{-}X}$ [$10^{15}(\Omega\text{-m}^2)^{--1}$]	Spin diffusion length λ [nm]	Conductivity $(\Omega\text{-m})^{-1}$	Spin Conductivity σ/λ [$10^{-15}(\Omega\text{-m}^2)^{-1}$]
Pd	1.26 ± 0.17	2.6 ± 1.2	9.5×10^6 [1]	3.65 ± 0.49
Ta		1.0 ± 0.18	4.1×10^5	0.41 ± 0.074
Cu	2.6	170 [2]	5.8×10^7 [1]	0.34
Nb		8.0 ± 2.5	6.6×10^6 [1]	0.26 ± 0.05
Pt		0.5 ± 0.3	9.4×10^6 [1]	19 ± 13

- C. T. Boone, et al., J. Appl. Phys. 113, 153906 (2013)

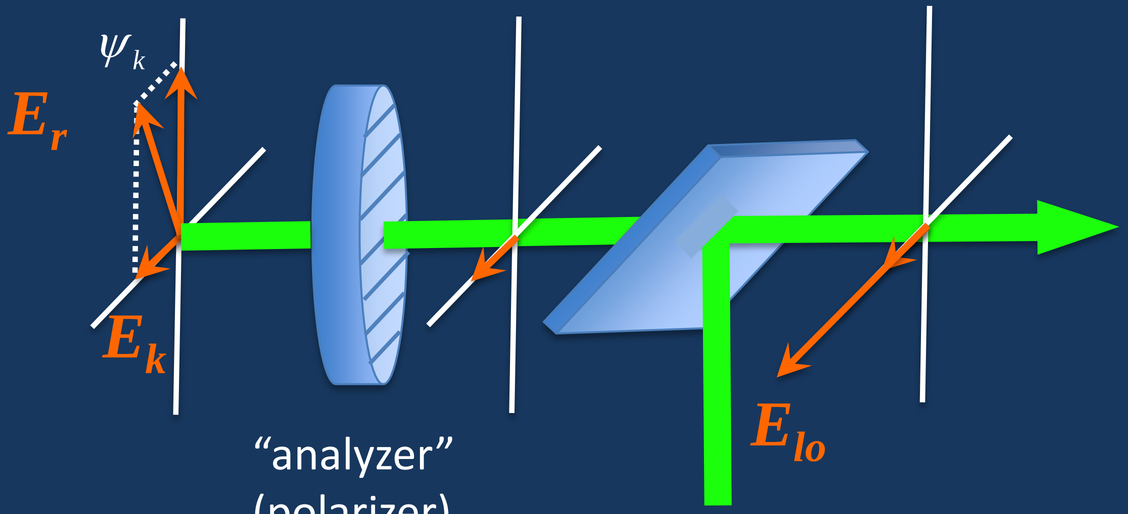
(Lengths appear short, but comparable to newer data [Kondou, et al, Appl. Phys Express. 5, 073002 (1012)] (Pd~2nm, Pt~1.2nm))

Problem #1

When the spin diffusion length is less than the mean free path, there is something wrong with our understanding of spin-flip processes in normal metals.

Intralayer spin currents and non-local damping

Heterodyne MOKE: Concept



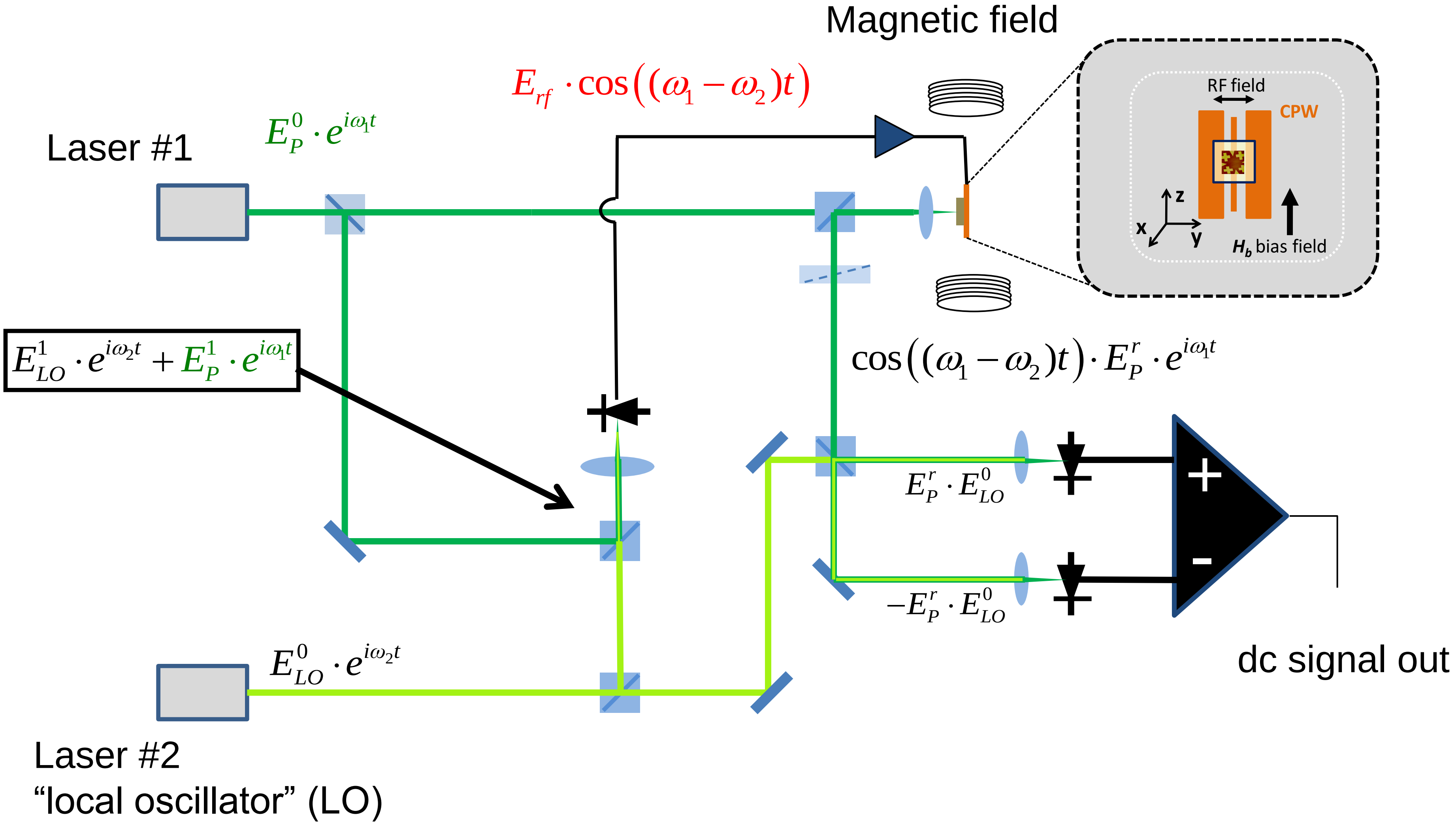
“analyzer”
(polarizer)

“local oscillator”

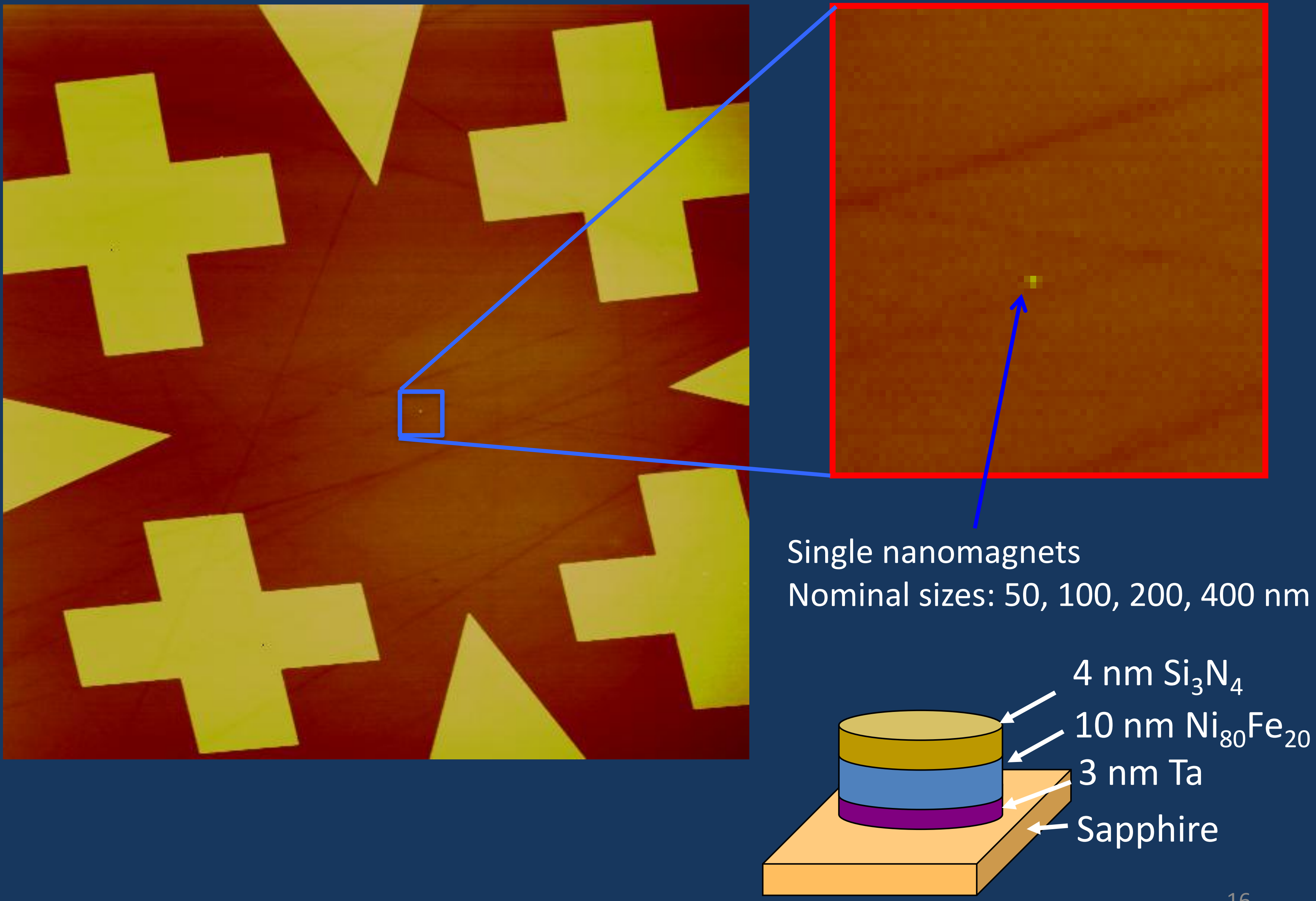
Signal depends on
square-root of
reflected intensity!!

signal ~ $|E_{lo}|^2 + 2|E_{lo}||E_k||\cos f| = |E_{lo}|^2 + 2|E_{lo}||E_r||\cos f| \times y_k$

Heterodyne microscopy



Sample Design

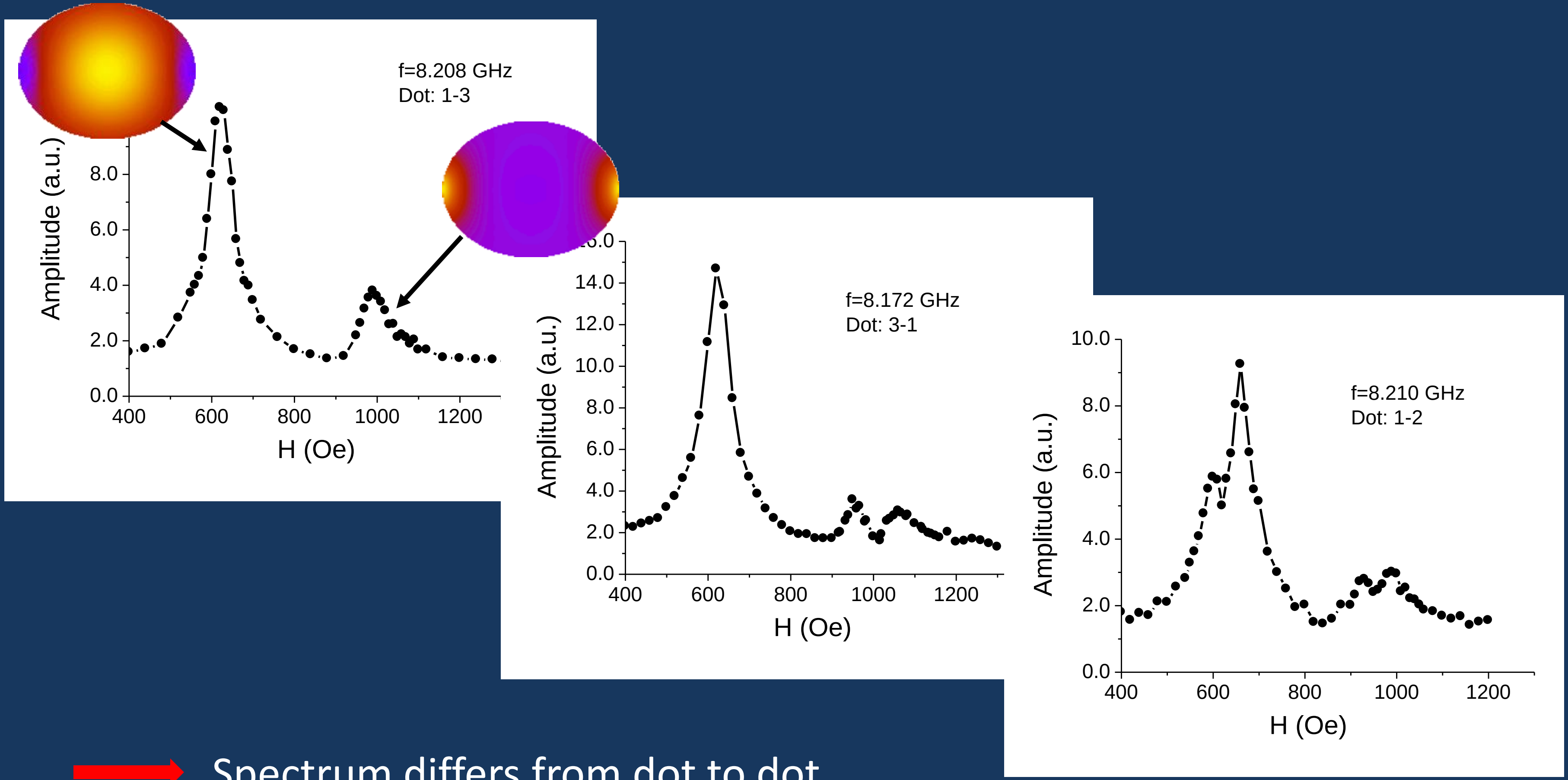


Single nanomagnets
Nominal sizes: 50, 100, 200, 400 nm

Dynamics in a single nanomagnet

Single nanomagnet:

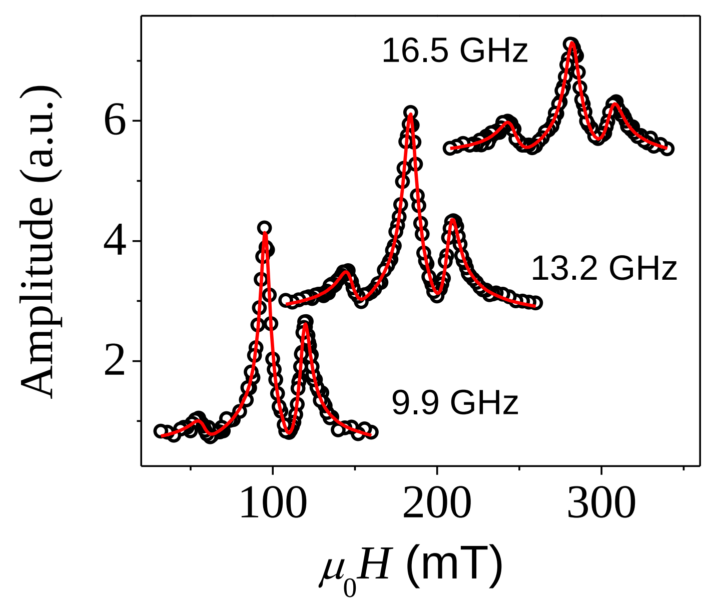
Nominal size: 240 nm x 200 nm

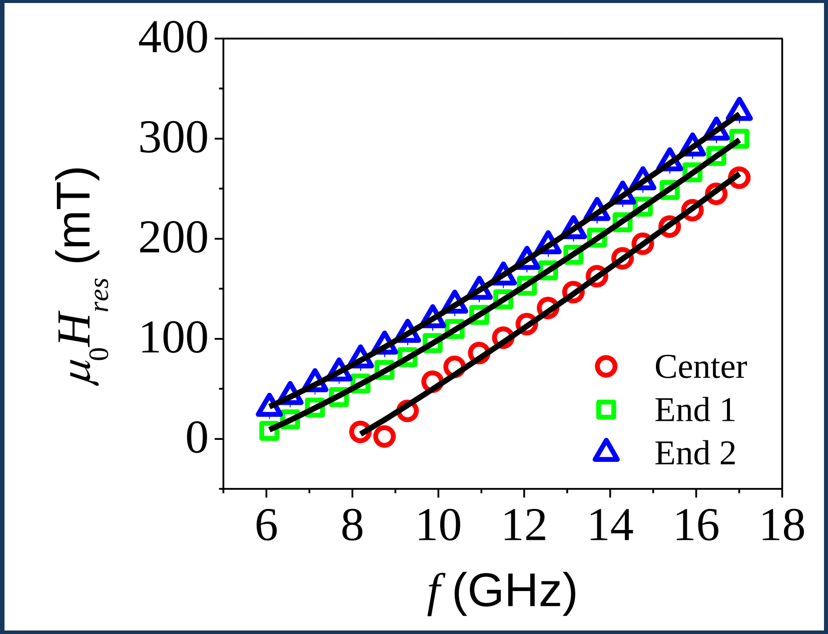


→ Spectrum differs from dot to dot

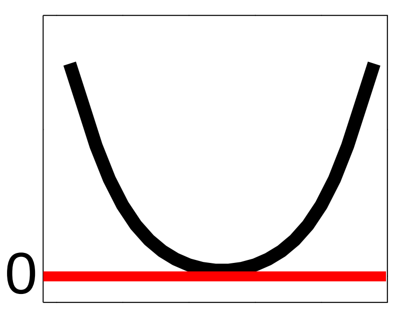
Dynamics in a single nanomagnet

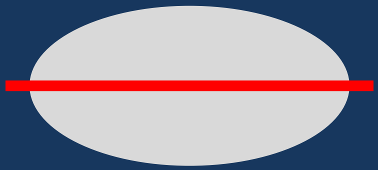
100 nm nanomagnets



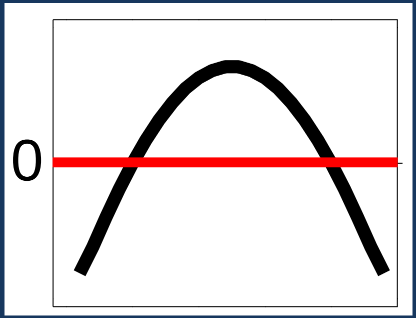


End-Mode

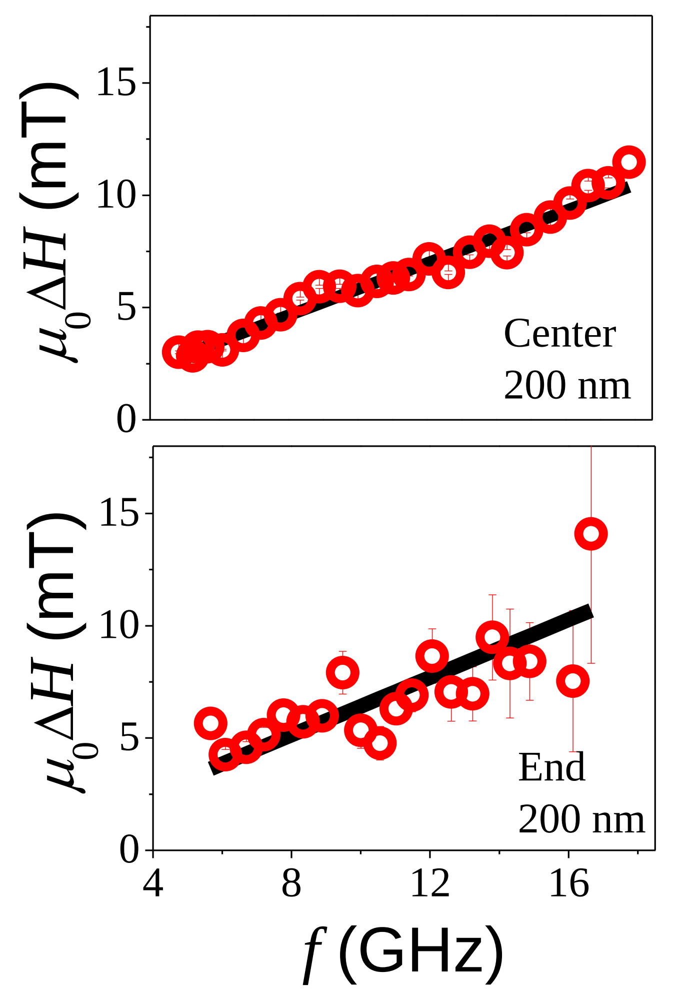




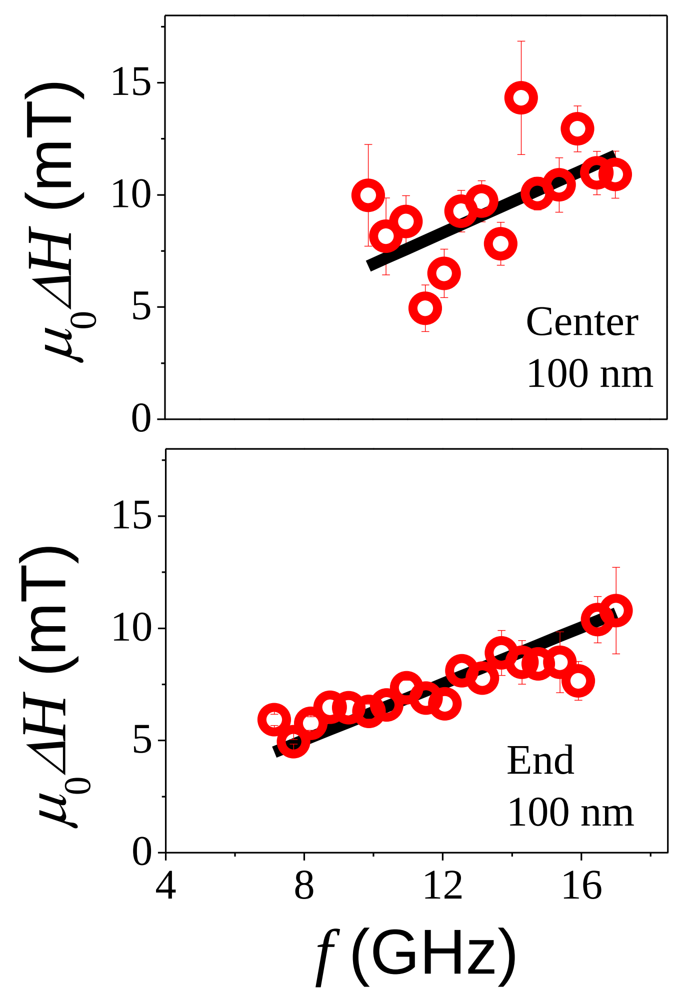
Center-Mode



Linewidth

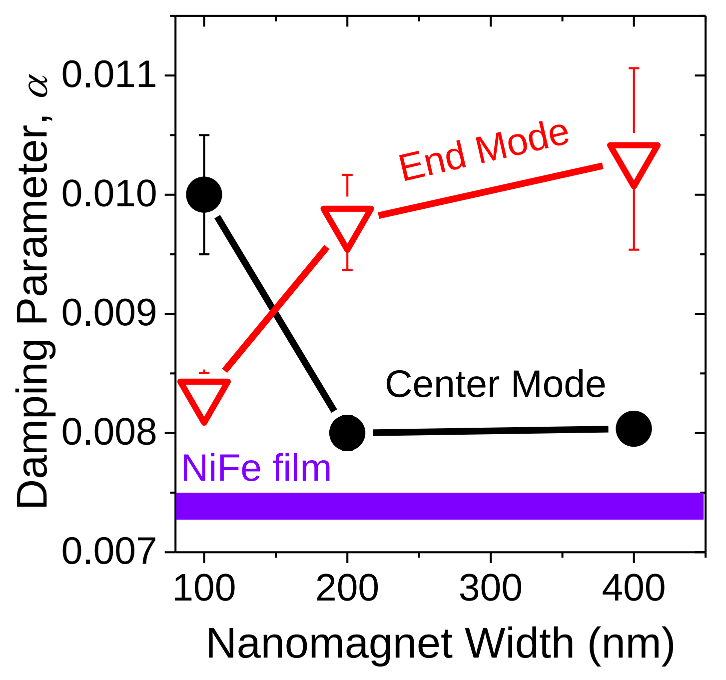


$$\Delta H \equiv \frac{4\pi\alpha f}{\gamma\mu_0}$$



- No inhomogenous linewidth broadening in individual nanomagnets (Expected)
- “Bowing” of linewidth at lower frequencies due to “field-dragging” effect (Also expected)

Damping in nanomagnets



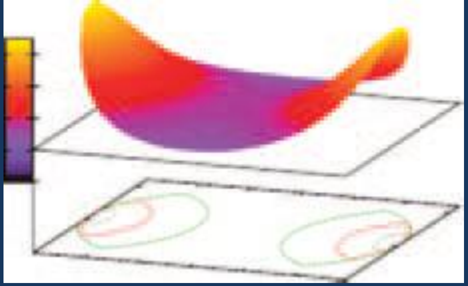
Average results for repeated measurements on 8 nanomagnets: 2 x 400 nm, 3 x 200 nm, 3 x 100 nm.

- Damping is increased compared to thin film
- Damping increases with size for center-mode
- Damping decreases with size for end-mode

Non-local damping

Theory:

Spatial variation of the magnetization profile gives rise to intralayer spin-currents, which contribute to the damping.



Y. Tserkovnyak et al.: Phys. Rev. B 79, 094415 (2009)
J. Forros et al.: Phys. Rev. B 78, 140402(R) (2008)
S. Zhang et al.: Phys. Rev. Lett., 102, 086601 (2009)

$$\frac{\partial \vec{m}}{\partial t} = -\mu_0 |\gamma| \vec{m} \times \vec{H}_{eff} - \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} - \frac{|\gamma|}{M_s} \frac{\partial \vec{j}_i}{\partial x_i}$$

Only the transversal spin-current has a contribution linear in the excitation amplitude:

$$\vec{j}_i = -\sigma_T \vec{m} \times \frac{\partial^2 \vec{m}}{\partial x_i \partial t}$$

(Specific case of exchange-driven damping in Bar'yakhtar equation. Sov. Phys. JETP 60, 863 (1984). General result of s-d model. *Spin-orbit is not required!*)

Non-local damping

Additional damping:

$$\mathrm{Da} = \frac{s_{\wedge}|g|}{M_s} \cdot \frac{\int k^2 \left|dm\left(\vec{k}\right)\right|^2 d^2k}{\int_{Area} \left|dm\left(\vec{k}\right)\right|^2 d^2k}$$

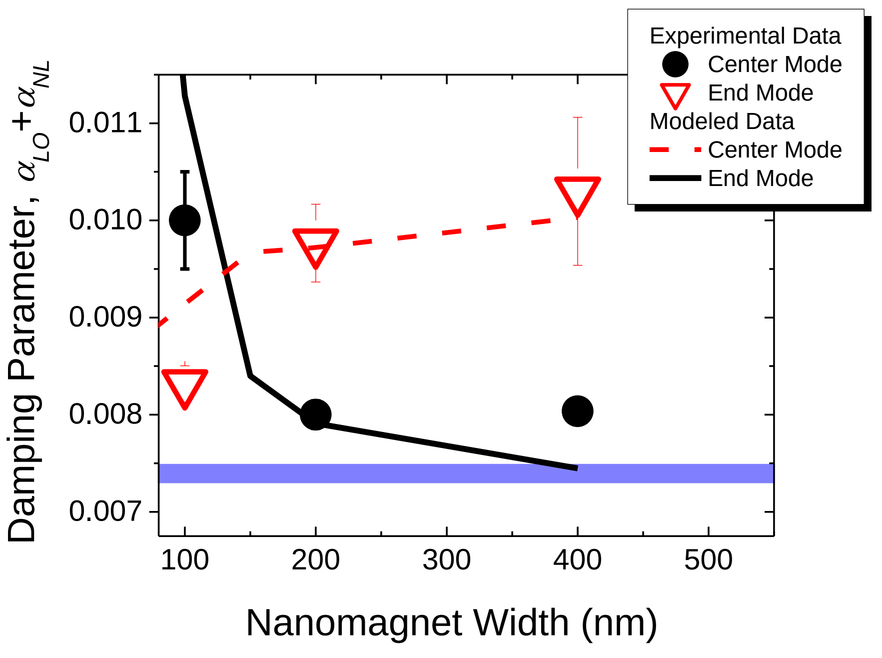
with: $s_{\wedge} = \left(\frac{\hbar}{2}\right)^2 \frac{n_e t_{\wedge}}{m^*}$

$n_e = 3.9 \cdot 10^{28}\,\mathrm{m}^{-3}$: electron density

$m^* = m_e$: effective mass

$t_{\wedge}$: transverse spin scattering time

Fit data with $t_{\wedge}$ as the only fitting parameter:



$t_{\wedge}$ = 49 fs, which is within limits based on a spin-diffusion length of 3-8 nm

($T_2 = 2T_1$ = 26-74 fs)

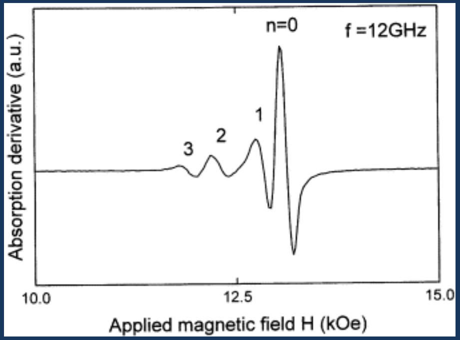
D.Y. Petrovyhk et al.: Appl. Phys. Lett 73, 3459 (1998)
T. Kimura et al.: Phys. Rev. B 72, 014461 (2005)
F.J. Jedema et al.: Phys. Rev. B 67, 085319 (2003)

Nembach et al., Phys. Rev. Lett. 110, 117201 (2013)
Highlight in Nature Nanotechnology, 8, 227 (2013)

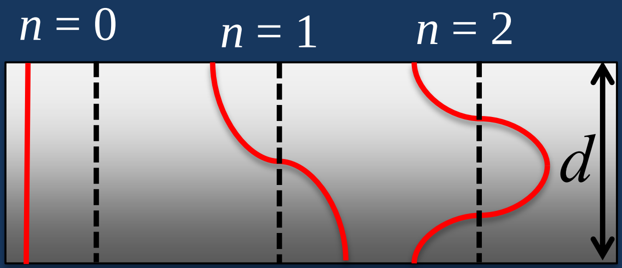
Problem #2

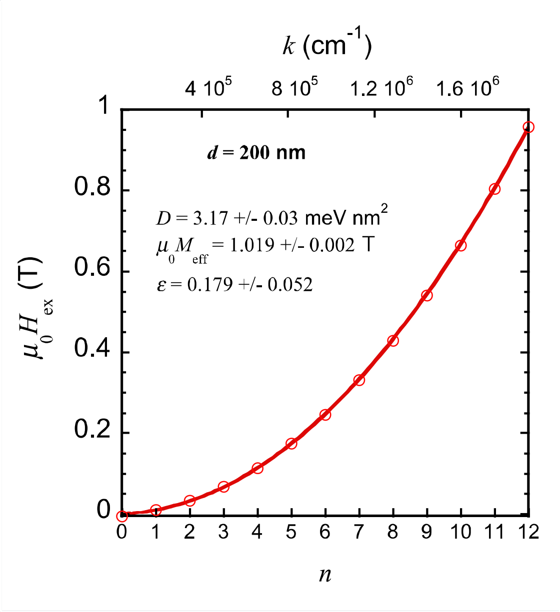
What we observed for eigenmodes in nanomagnets must be an extrinsic effect!

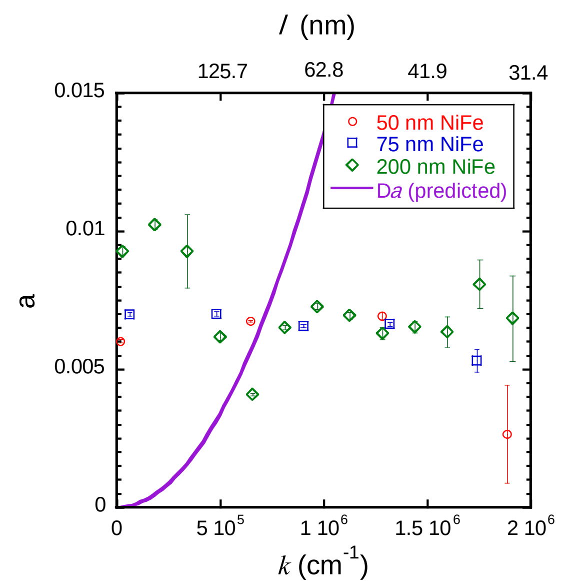
1. k^2 damping not observed in perpendicular standing spin waves by others* or ourselves.



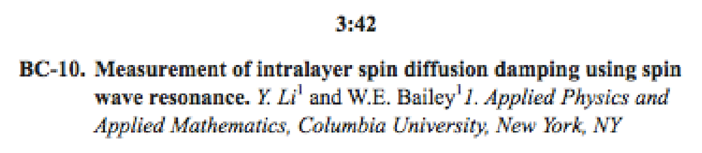
Quantized spin waves observed via FMR in thin films







*Y. Li and W. E. Bailey, Talk BC-10, MMM Denver Nov. 4-8 2013



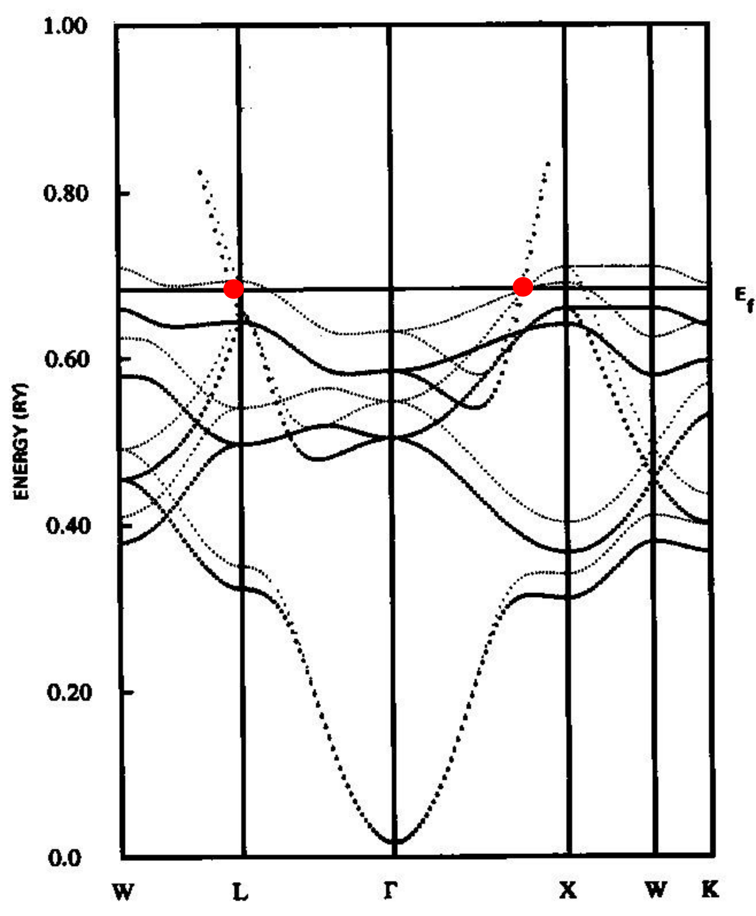
3:42

BC-10. Measurement of intralayer spin diffusion damping using spin wave resonance. *Y. Li*[1] and W.E. Bailey[1] *1. Applied Physics and Applied Mathematics, Columbia University, New York, NY*

Problem #2, continued

Ni and Permalloy are "strong" ferromagnets. *Low (zero) energy Stoner excitations do not exist*.

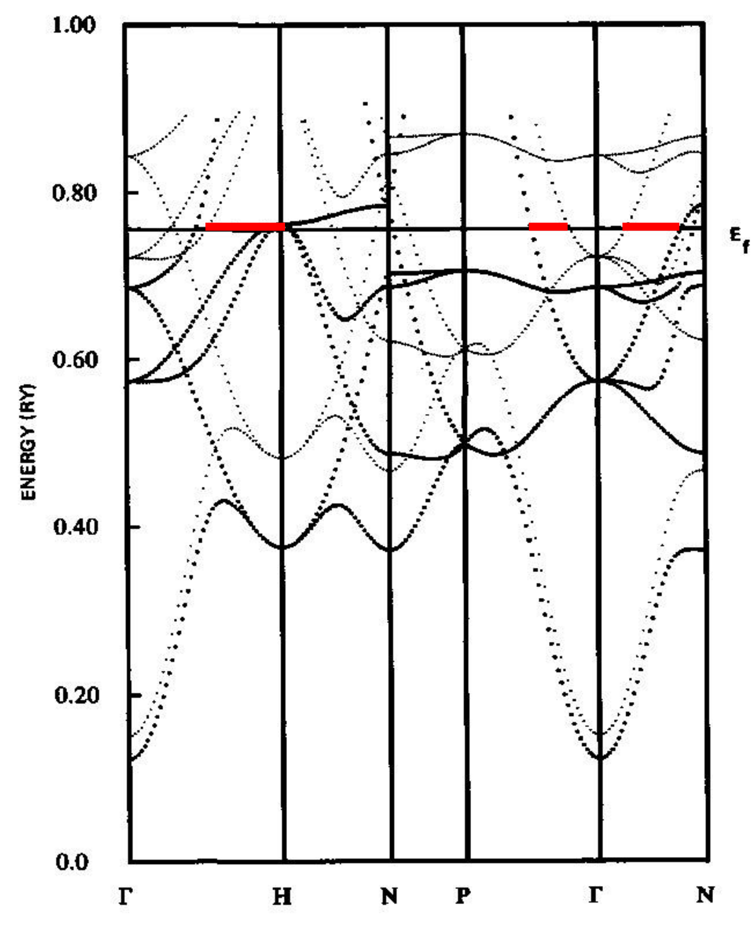
Ni



Dark points for majority spin, light points for minority spin.

Z=28

Fe

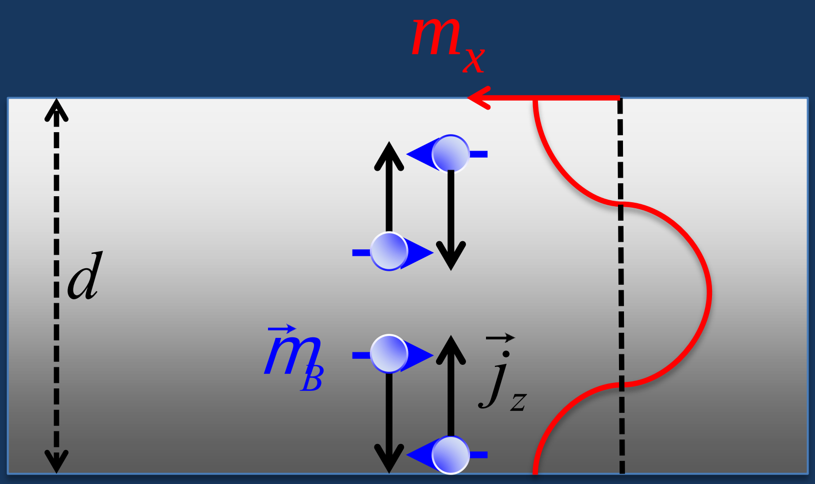


Dark points for majority spin, light points for minority spin.

Z=26

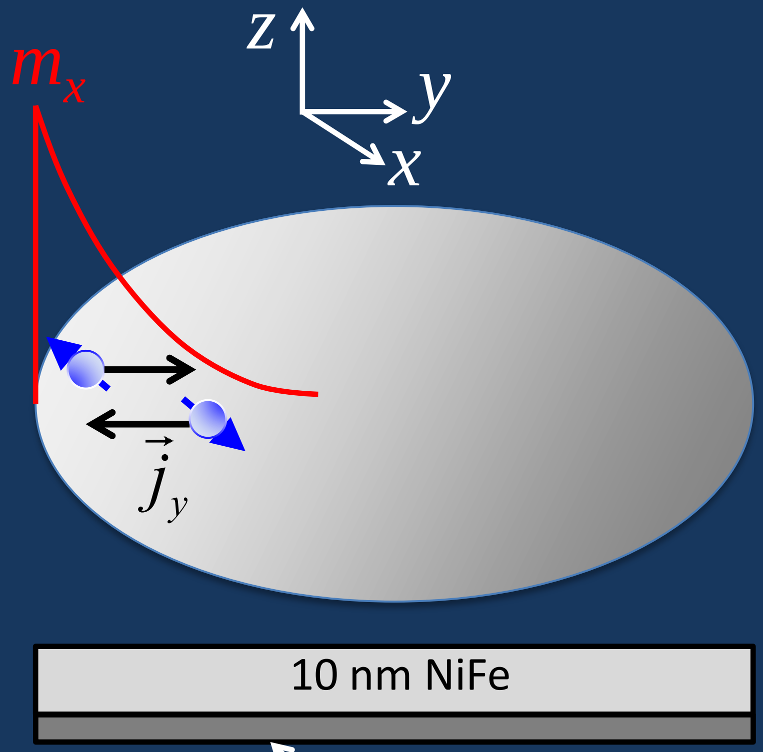
Does intralayer spin current flow direction matter?

PSSWs in thin films



Spin currents flow within bulk of thin film.

Eigenmodes in nanomagnets



2 nm Ta

Spin currents flow parallel to surfaces and interfaces.

High harmonic generation and giant ultrafast spin currents

High Harmonic Generation (HHG): A primer

Conversion efficiency:

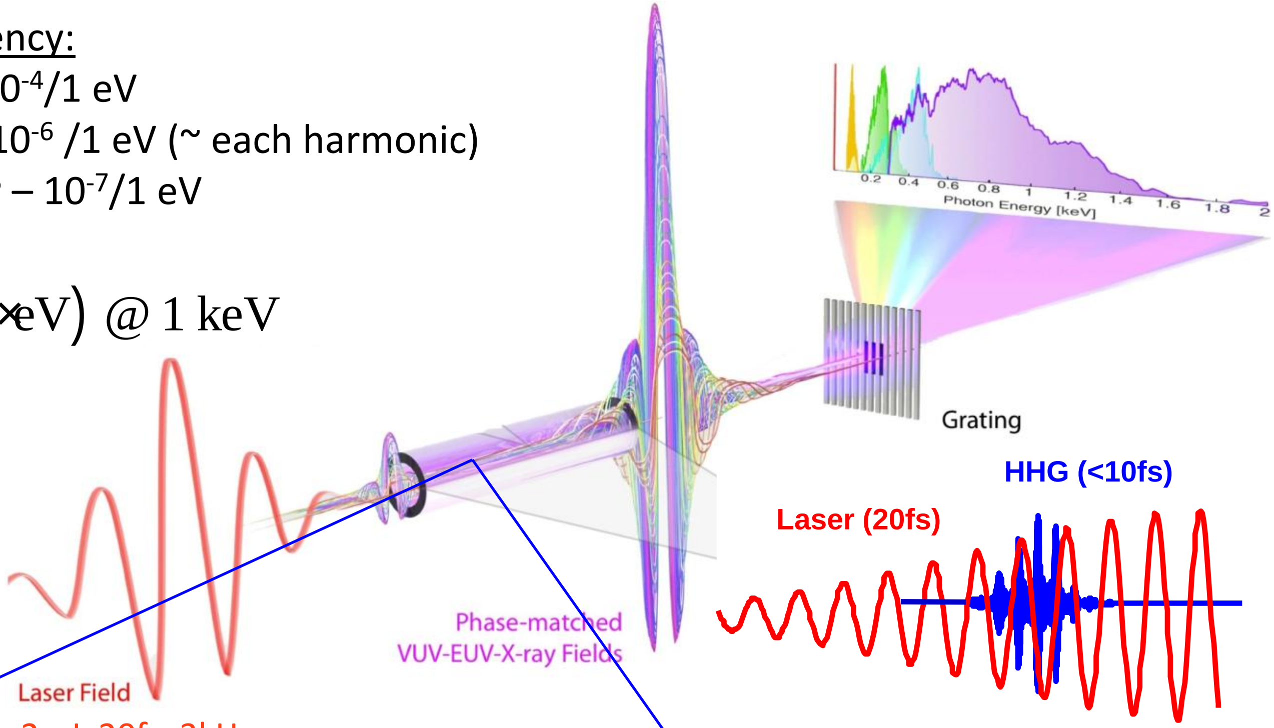
10-50 eV: $10^{-3} – 10^{-4}$/1 eV

50-100 eV: 10^{-5} - 10^{-6} /1 eV (~ each harmonic)

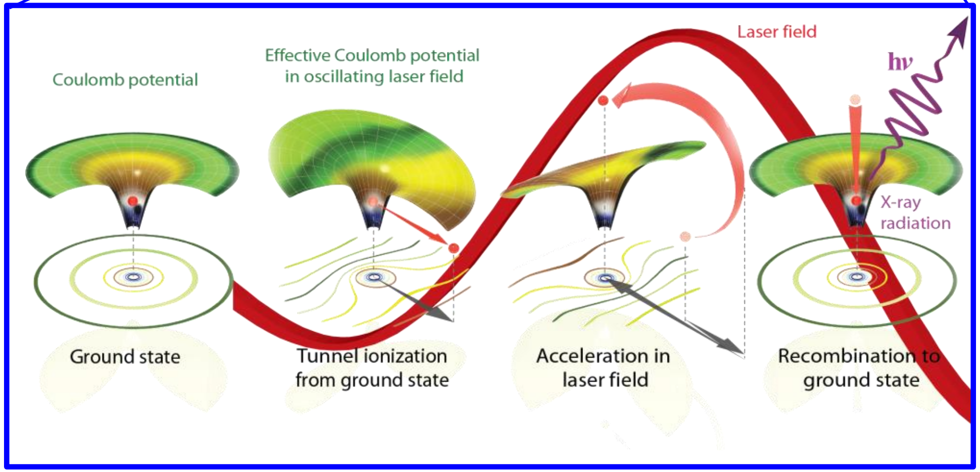
300-1000 eV: $10^{-6} – 10^{-7}$/1 eV

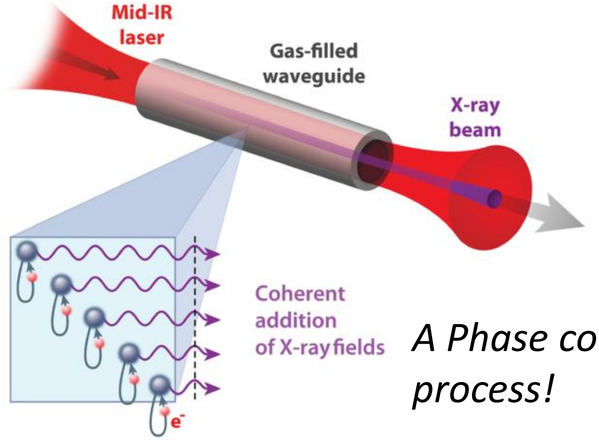
Ex:

$$10^5 \text{ photons}/(\text{s} \times \text{eV}) \text{ @ } 1 \text{ keV}$$



2mJ, 20fs, 3kHz



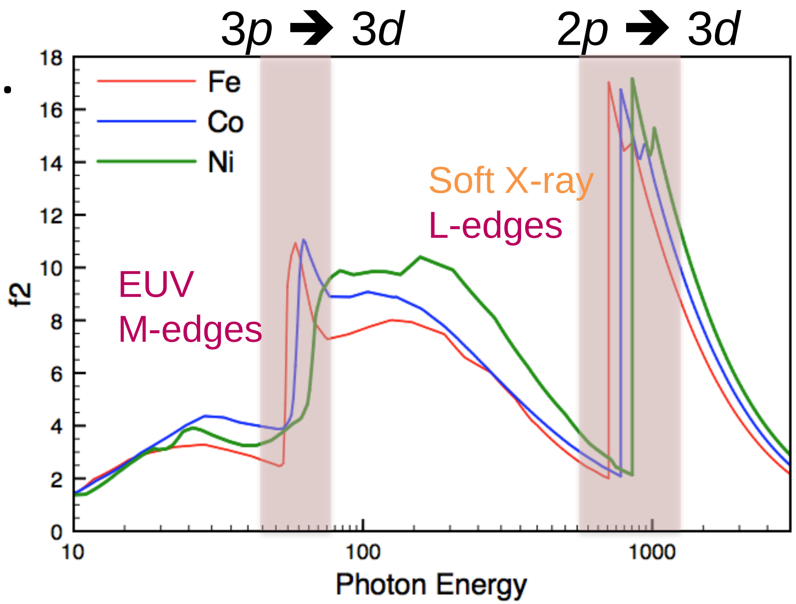


A Phase coherent process!

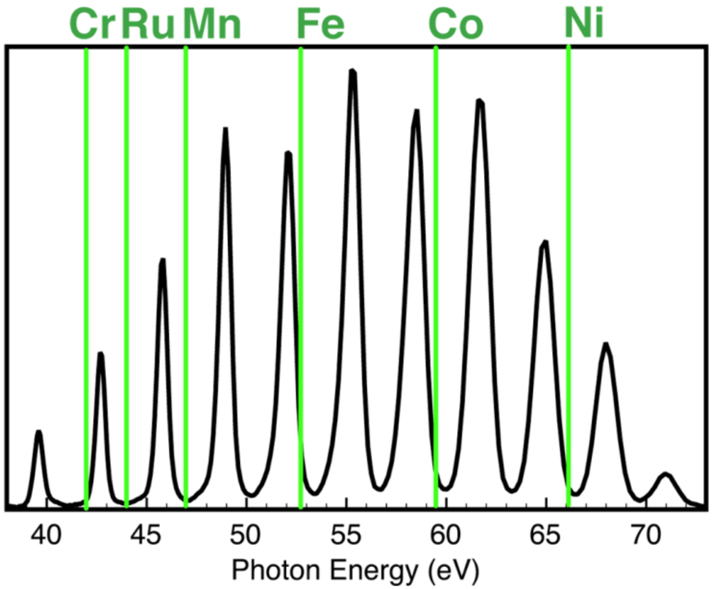
Popmintchev, et al., Science 336, 1287 (2012)

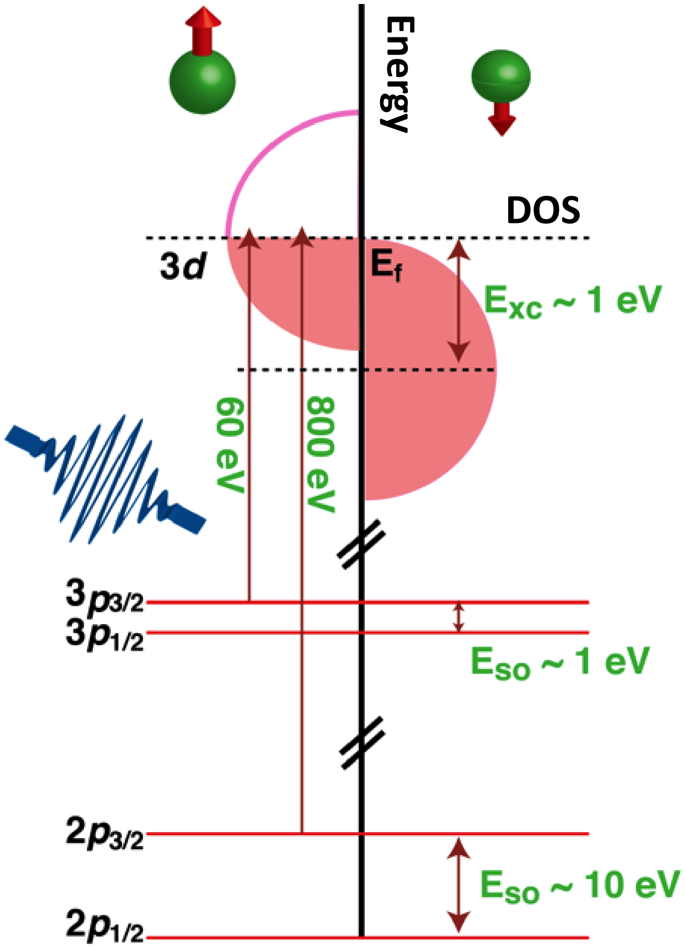
M-edge magnetic spectroscopy with HHG

EUV abs.



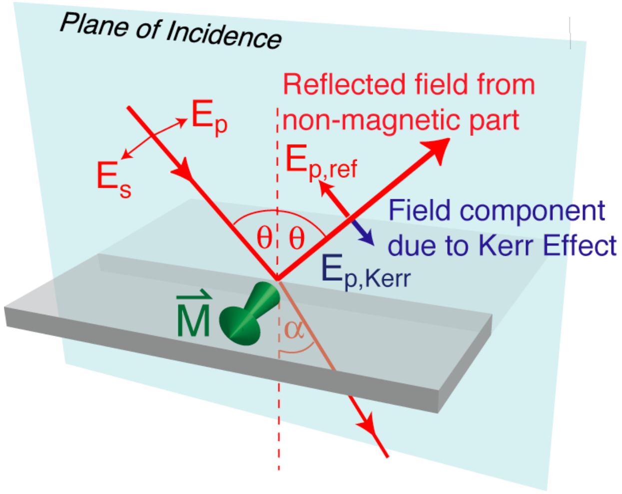
EUV HHG





Pump-probe magnetic spectroscopy with HHG

Transverse-MOKE contrast



$$R_{\pm}^{\mathrm{p}} = \left| \frac{n\cos\theta_i - \cos\theta_t}{n\cos\theta_i + \cos\theta_t} \pm \frac{\sin 2\theta_i \varepsilon_{xy}\left[M_{\perp}/M_s\right]}{n^2\left(n\cos\theta_i + \cos\theta_t\right)^2} \right|^2$$

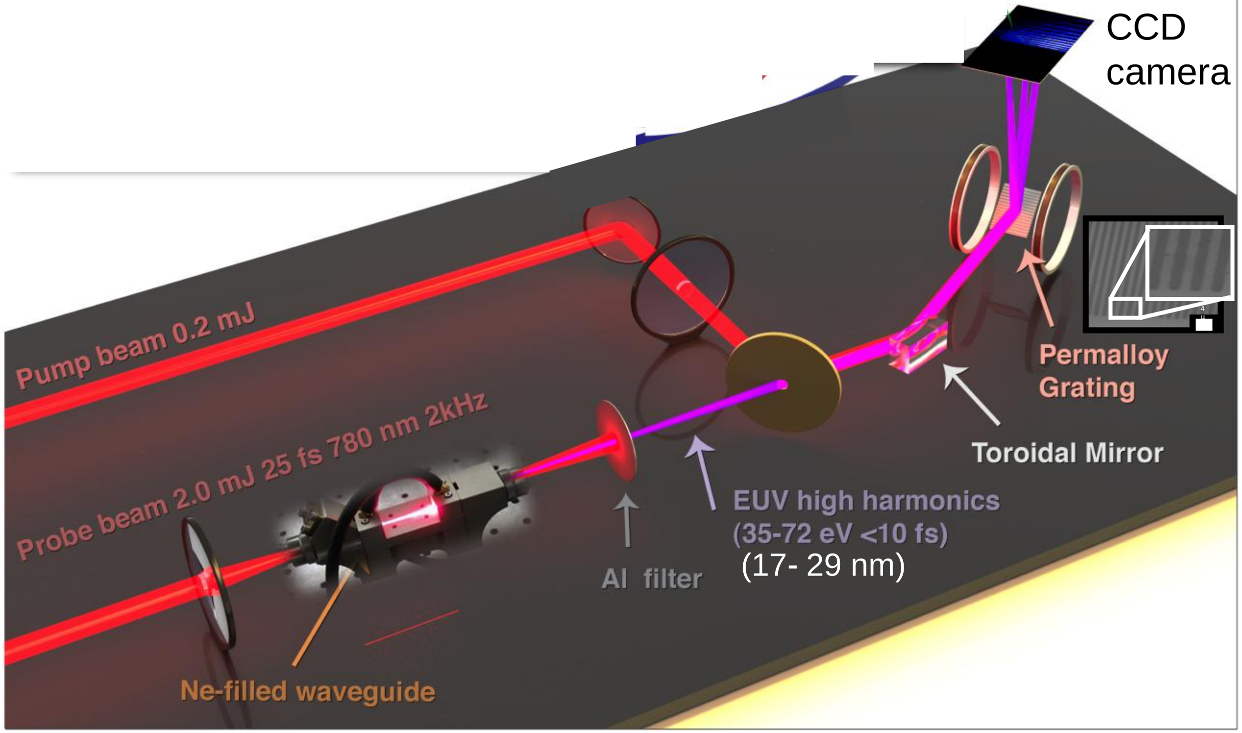
$$= \left| r_{\mathrm{NM}} \pm r_{\mathrm{M}} m_{\perp} \right|^2$$

Near Brewster's angle, $r_{\mathrm{NM}} \approx 10^{-2}$

$\approx 5 r_{\mathrm{M}}$

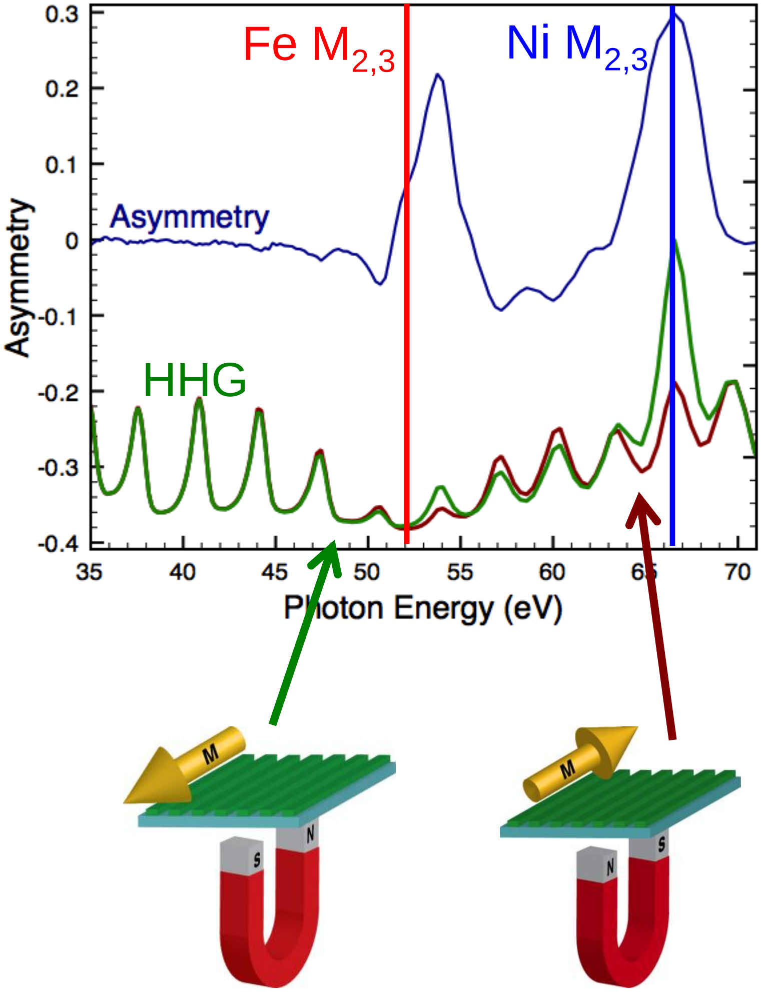
Magnetic asymmetry parameter:

$$A = \frac{R_{+}^{\mathrm{p}} - R_{-}^{\mathrm{p}}}{R_{+}^{\mathrm{p}} + R_{-}^{\mathrm{p}}} \propto m_{\perp}$$

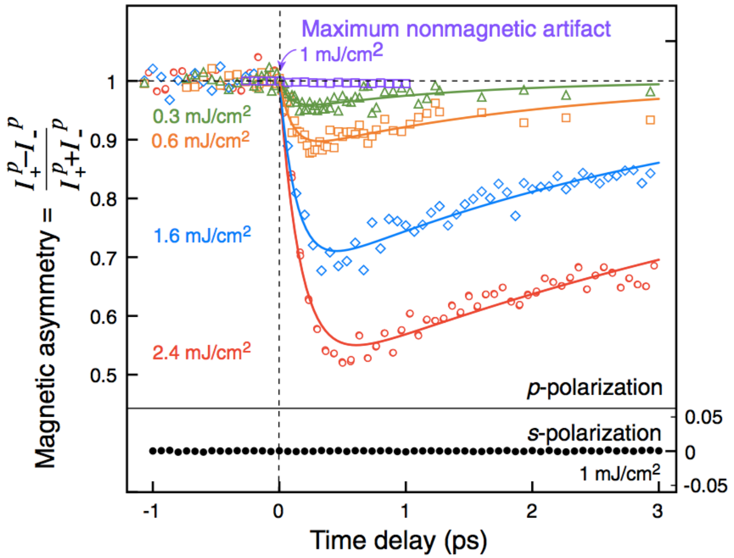


T-MOKE primarily sensitive to changes in magnetic state

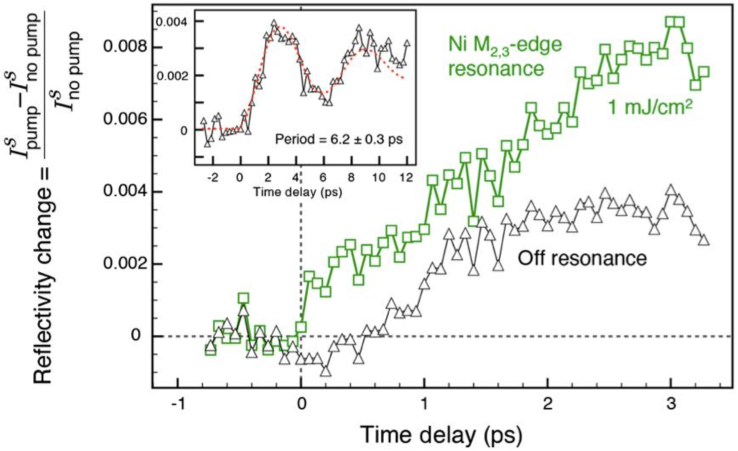
$$Asymmetry = \frac{I_+ - I_-}{I_+ + I_-} \propto \epsilon_{xy}$$



p-pol data

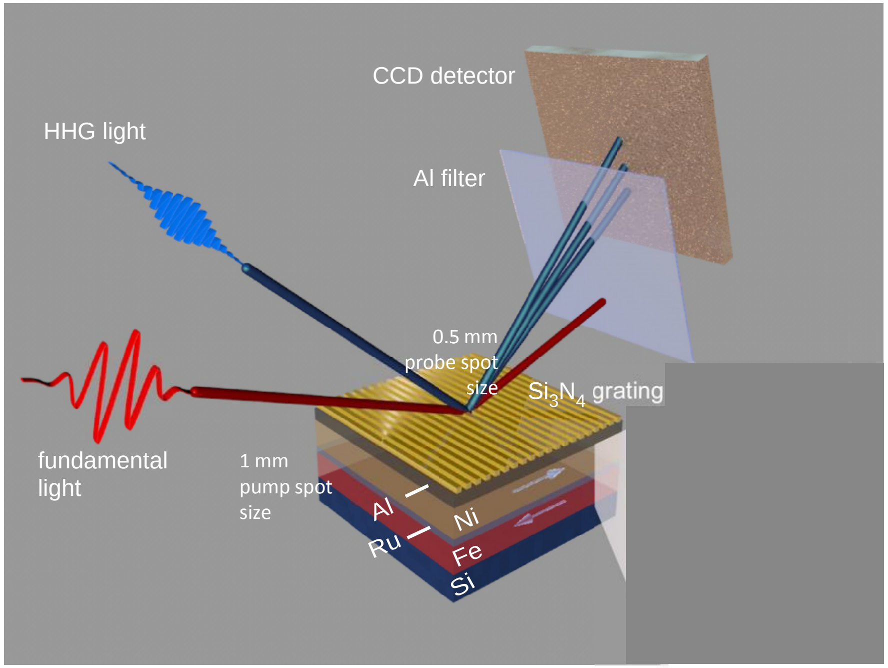


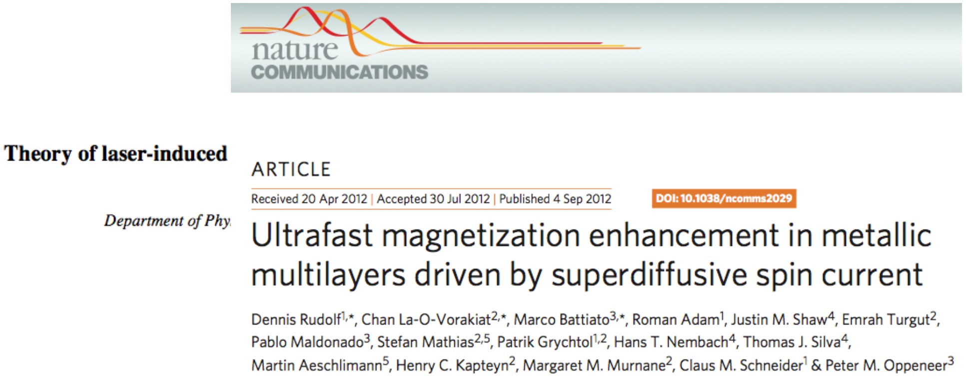
s-pol data



Phys. Rev. Lett. ***103***, *257402 (2009); PRX* ***2***, *011005 (2012); Physics* ***5***, *11 (2012)*

Ultrafast spin dynamics in Ni/Ru/Fe multilayers





Theory of laser-induced

Department of Phy

ARTICLE

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Ultrafast magnetization enhancement in metallic multilayers driven by superdiffusive spin current

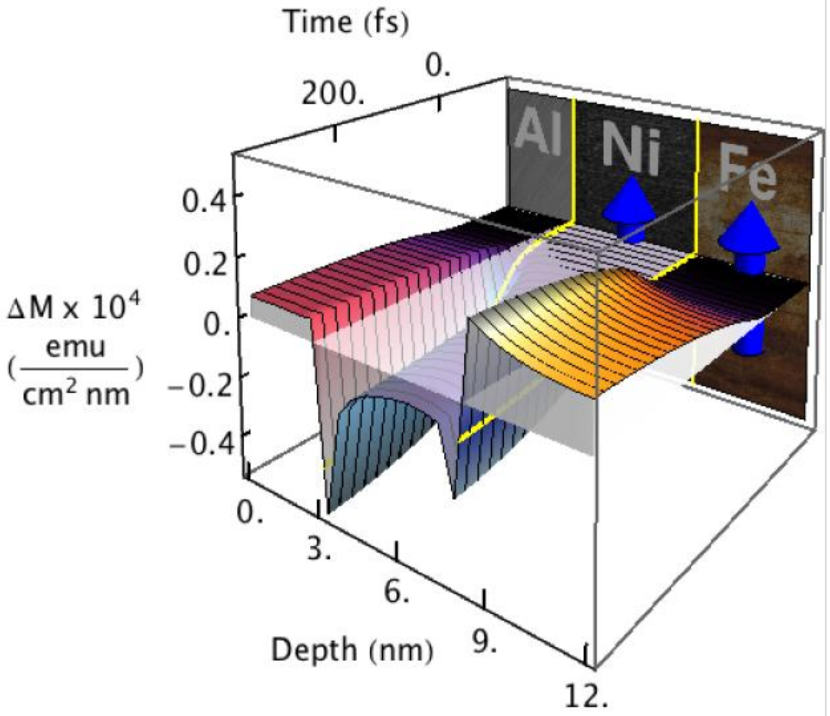
Dennis Rudolf[1,*], Chan La-O-Vorakiat[2,*], Marco Battiato[3,*], Roman Adam[1], Justin M. Shaw[4], Emrah Turgut[2], Pablo Maldonado[3], Stefan Mathias[2,5], Patrik Grychtol[1,2], Hans T. Nembach[4], Thomas J. Silva[4], Martin Aeschlimann[5], Henry C. Kapteyn[2], Margaret M. Murnane[2], Claus M. Schneider[1] & Peter M. Oppeneer[3]

THEORY

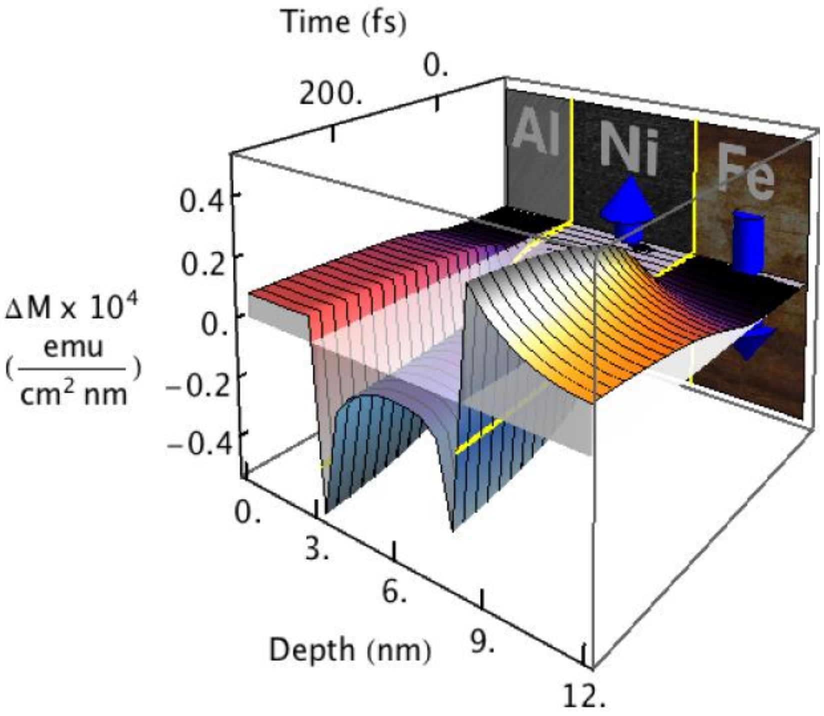
Theory: Interlayer "hot" spin transport

Spin accumulation in metallic layers:

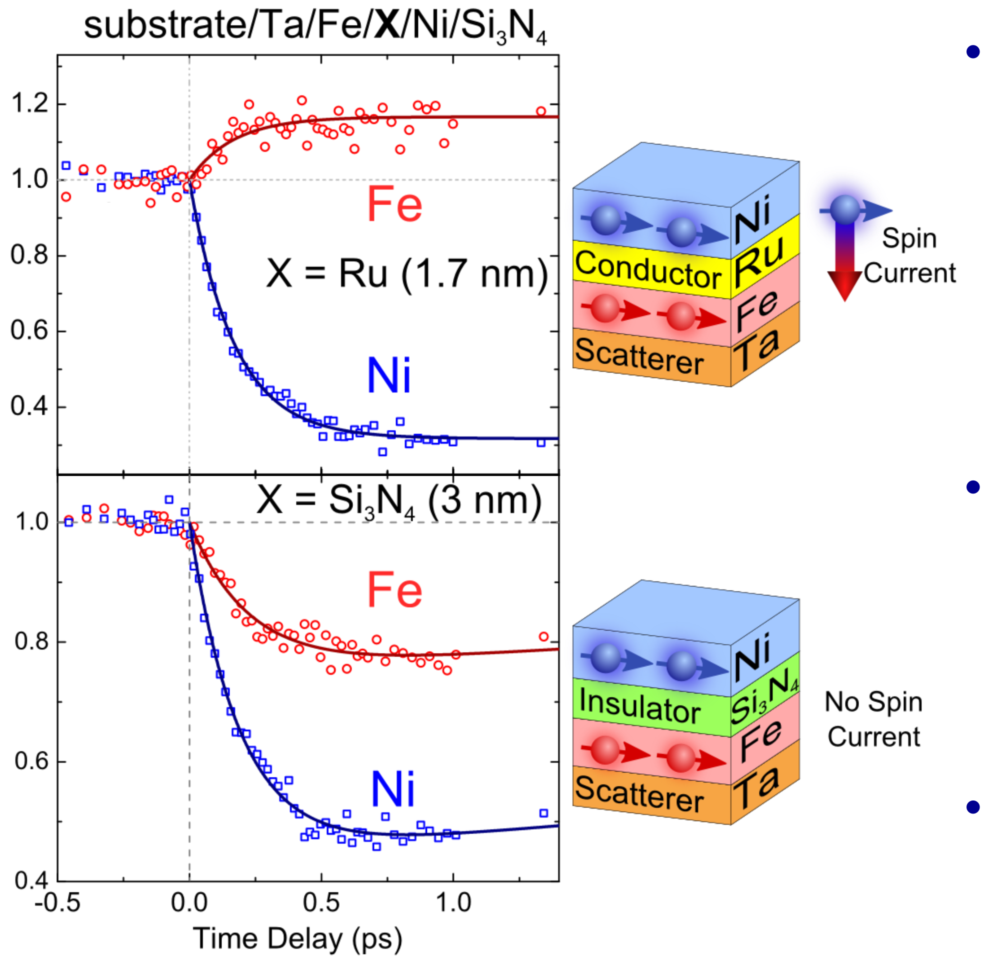
Parallel magnetism



Antiparallel magnetism



Two microscopic processes at work on fast timescales



- All theory to date assumed fast demagnetization due to **either**
  - **Non-local spin currents** *(e.g., PRB **86**, 024404 (2012))*
  - **Local spin-flip scattering** *(e.g., Nature Materials **9**, 259 (2010))*
- Our data show that **local and non-local** processes are important and comparable in magnitude for certain systems.
- Complete theory will need to include both spin-flips and spin-currents

E. Turgut, et al., Phys. Rev. Lett. **110** 197201 (2013). *(2013)*

Conclusions

- Spin pumping in multilayers (“spin ammeter”)
    1. Short spin diffusion lengths for Pd (2.6 nm) and Pt (0.5). Shorter than mean free path!
    2. “Spin conductivity” figure of merit: $s//_{\mathrm{sd}}$. Though $/_{\mathrm{sd}}$ is small (1 nm), Ta is still a poor spin conductor.

- Damping of individual eigenmodes in individual nanomagnets
    1. “True” FMR measurements (microwave field excitation, non-perturbative detection) on structures as small as 100 nm are possible.
    2. Dependence of damping on curvature can be explained by invocation of transverse *intralayer* spin current theory.
    3. k^2 damping not seen for perpendicular standing spin waves. *Extrinsic effect?*

- Ultrafast detection of layer-specific dynamics for optical pumping
    1. First observation that magnetization can be enhanced.
    2. Can be partly explained by theory of non-local giant “superdiffusive” spin currents… local spin-flip is still required for full understanding. Can both mechanisms be reconciled with each other?