Magnetism with ultra-short magnetic field pulses from highly relativistic electron bunches.

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Outline

- Overview of magnetic relaxation
- SLAC magneto-dynamic experiments
- Simulations vs. Experiments
- Intrinsic non-linear relaxation theory
- Magnetic recording
Ferromagnetic Relaxation

Commonly used: Oersted switching
Precessional or ballistic switching
Exchange switching (spin injection)

Spin (uniform)

Electrons

Magnons

Phonons

τ = ?

τ = ?

τ = ?

τ = ?

τ ~ 100 ps

τ > 10 ns

τ ~ 1 ps

τ ~ 1 ps

τ > 10 ns
Ferromagnetic Relaxation Mechanisms

- **Extrinsic**: scattering
  - off impurities, defects:

- **Intrinsic**: interaction with
  - phonons
  - conduction electrons

- Intrinsic magnon ~ magnon scattering
LLG damping

Gyromagnetic Precession

\[
\frac{d\vec{M}}{dt} = -\gamma \cdot [\vec{M} \times \vec{H}]
\]

Phenomenological Damping

\(-\alpha \cdot \frac{\gamma}{M_s} \cdot [\vec{M} \times [\vec{M} \times \vec{H}]]\)

( Landau~Lifshitz~Gilbert )
Large Angle Switching

- **FMR:**
  - small excitations
  - LLG damping

- **Magnetic Applications:**
  - large angle switching
SLAC experiments

- Magnetic sample
- Electromagnetic field of the beam
- SLAC linac beam 28 GeV
Simulations: $\alpha = 0.004$, no interactions

Time: 900 ps
Simulations: $\alpha=0.02$, no interactions
Spin Waves = Magnons

- $k=0$ magnons are excited when average magnetization deviates from equilibrium direction.

- $k \neq 0$ magnons at $t=0$ are thermally excited: $E_k = \hbar \omega_k \cdot N_k \approx \hbar \omega_k \cdot \frac{T}{\hbar \omega_k}$

- Zeeman and Demag Energy of $k=0$ magnons is transferred into Exchange, Zeeman and Demag Energy of $k \neq 0$ magnons.
Simulations with interactions, $\alpha=0.004$
Pattern along the horizontal center line

- Easy Axis direction X, μm
- Experiment
- 0D, $\alpha=0.017$, no magnons
- 1D, $\alpha=0.017$, no magnons

$\frac{M_x}{M_s}$
Pattern along the horizontal center line

- **Experiment**
- 0D, $\alpha=0.004$, no magnons
- 1D, $\alpha=0.004$, no magnons

Graph showing the ratio $M_x/M_s$ along the Easy Axis direction $X, \mu m$.
Pattern along the horizontal center line

\[ M_x / M_s \]

- Experiment
- 2D, \( \alpha = 0.004 \), +magnons

Easy Axis direction \( X, \mu m \)
New SLAC experiments on thin Fe films

2.3 ps Gaussian pulse, $H=4.2\text{kOe}$

Average magnetization projection on Easy Axis

- $\alpha=0.004$, no magnons
- $\alpha=0.017$, no magnons
- $\alpha=0.004$, + magnons
Spin wave generation

Magnitude of the average magnetization

Time, ns

no magnons

$\alpha=0.004$, + magnons
Siegmann Experiment

Co, 200Å-thick, $H_K=2$ kOe

- Short (10ps) pulse non-uniform field
- In LLG calculation, reversal pattern strongly depends on damping $\alpha$
- Required $\alpha=0.037$ to explain results

Siegmann Experiment: Simulations

\[ \alpha = 0.037 \]

Magnon excitations NOT allowed

\[ \alpha = 0.005 \]  

Magnon scattering \[ \downarrow \]  
increased damping

\[ \approx 8 \cdot 10^6 \] elements
Analytic Theory: 3,4-magnon scattering

○ H. Suhl Hamiltonian:

\[ \mathcal{H} = \sum_k (\omega_k + \Lambda_k N_0) \cdot b_k b_k^\dagger \]

\[ + \Phi_k \cdot \left\{ b_0 b_k^\dagger b_{-k}^\dagger + b_{-k}^\dagger b_k b_{-k} \right\} + \Psi_k \cdot \left\{ b_0 b_0 b_k^\dagger b_{-k}^\dagger + b_{-k}^\dagger b_0^\dagger b_k b_{-k} \right\} \]

3-magnon

4-magnon
Simulations: Magnon Numbers Dynamics

$N_k \quad 10^3 \quad 10^4 \quad 10^5 \quad 10^6$

$k_x \quad k_y$
Chaotic switching

uniform Pulse field 
$H_{\text{pulse}} = 15$ kOe

with current beam at ~ 60 um from the center

a few chaotic domains appear
Chaos onset

**uniform** pulse field
\[ H_{\text{pulse}} = 20 \text{ kOe} \]
at \( \sim 40 \text{ um} \) from the center

full chaos after 1 ns

chaotic domains slowly disappear after \( \sim 5 \text{ ns} \) -
high magnetic temperature?
Chaos onset

Uniform pulse field
$H_{\text{pulse}} = 20 \text{ kOe}$
at $\sim 40 \text{ um}$ from the center

$\alpha = 0.02$
chaos does not develop
Magnetic recording
Write process

simulations for realistic heads and media,
but with high damping
distances in nano-meters
bit length ~25nm, velocity ~50m/s
Importance for Magnetic Recording

- FeCo, 500A-thick
- Rise Time: 50ps
- Data Rate: 4 Gb/s

Magnon excitations NOT allowed

Magnon scattering ↓ reduces noise
Time-resolved magneto-optic Kerr effect

Disadvantages:

- very low field (<100 Oe)
- longe rise time (>50 ps)
- stroboscopic technique
- requires mounting or growing samples on the stripe line
Summary

- Ultra-fast magneto-dynamics with highly relativistic electrons at SLAC is a very powerful and unique technique for studying ferromagnetic relaxation.

- Very interesting non-linear physical phenomena are being discovered in these experiments and are not fully understood at the moment.