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

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(Stanford - SLAC)

A. Vaterlaus(ETH Zürich) ***magnetic imaging***

A. Kashuba(Landau Inst. Moscow) ; A. Dobin(Seagate) ***theory***

G. Woltersdorf, B. Heinrich (S.F.U. Vancouver) ***samples***

Outline

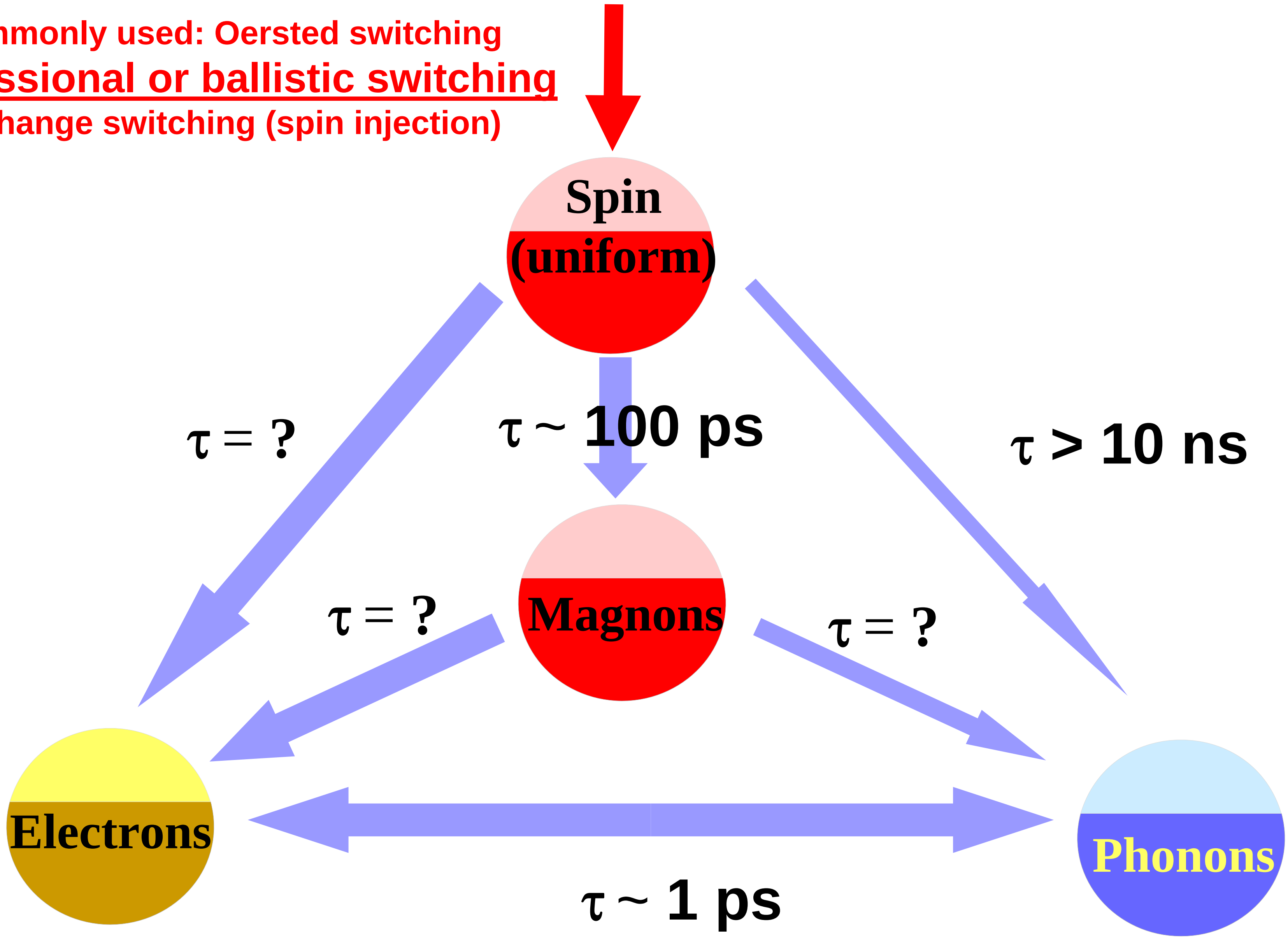
- Overview of magnetic relaxation
- SLAC magneto-dynamic experiments
- Simulations vs. Experiments
- Intrinsic non-linear relaxation theory
- Magnetic recording

Ferromagnetic Relaxation

Commonly used: Oersted switching

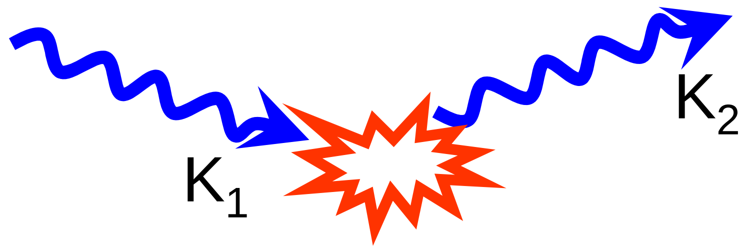
<u>Precessional or ballistic switching</u>

Exchange switching (spin injection)

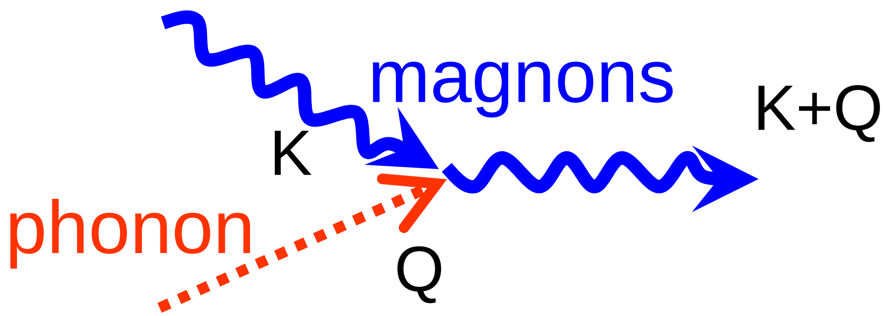


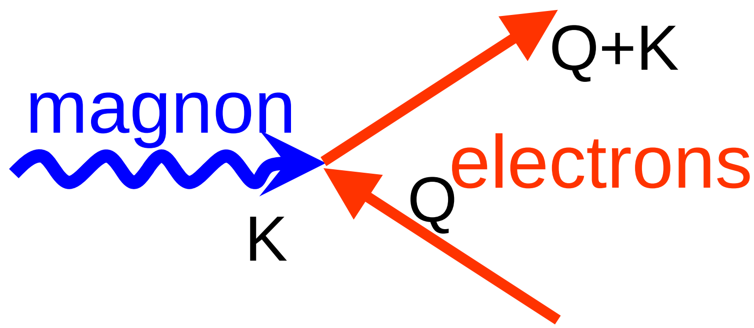
Ferromagnetic Relaxation Mechanisms

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

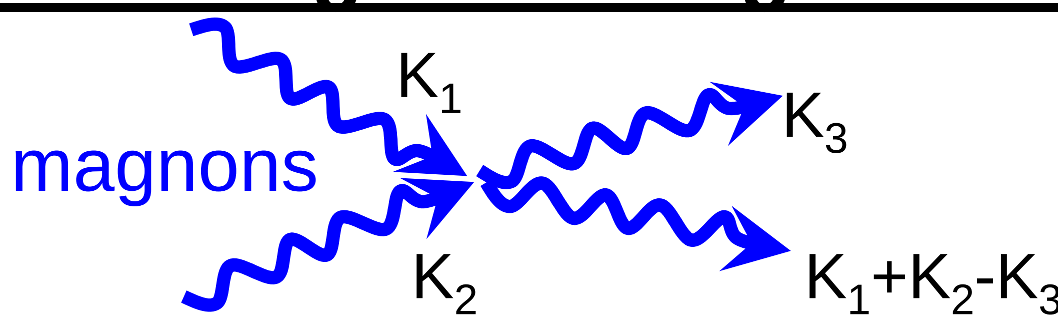


- ***Intrinsic:*** interaction with
  - phonons
  - conduction electrons

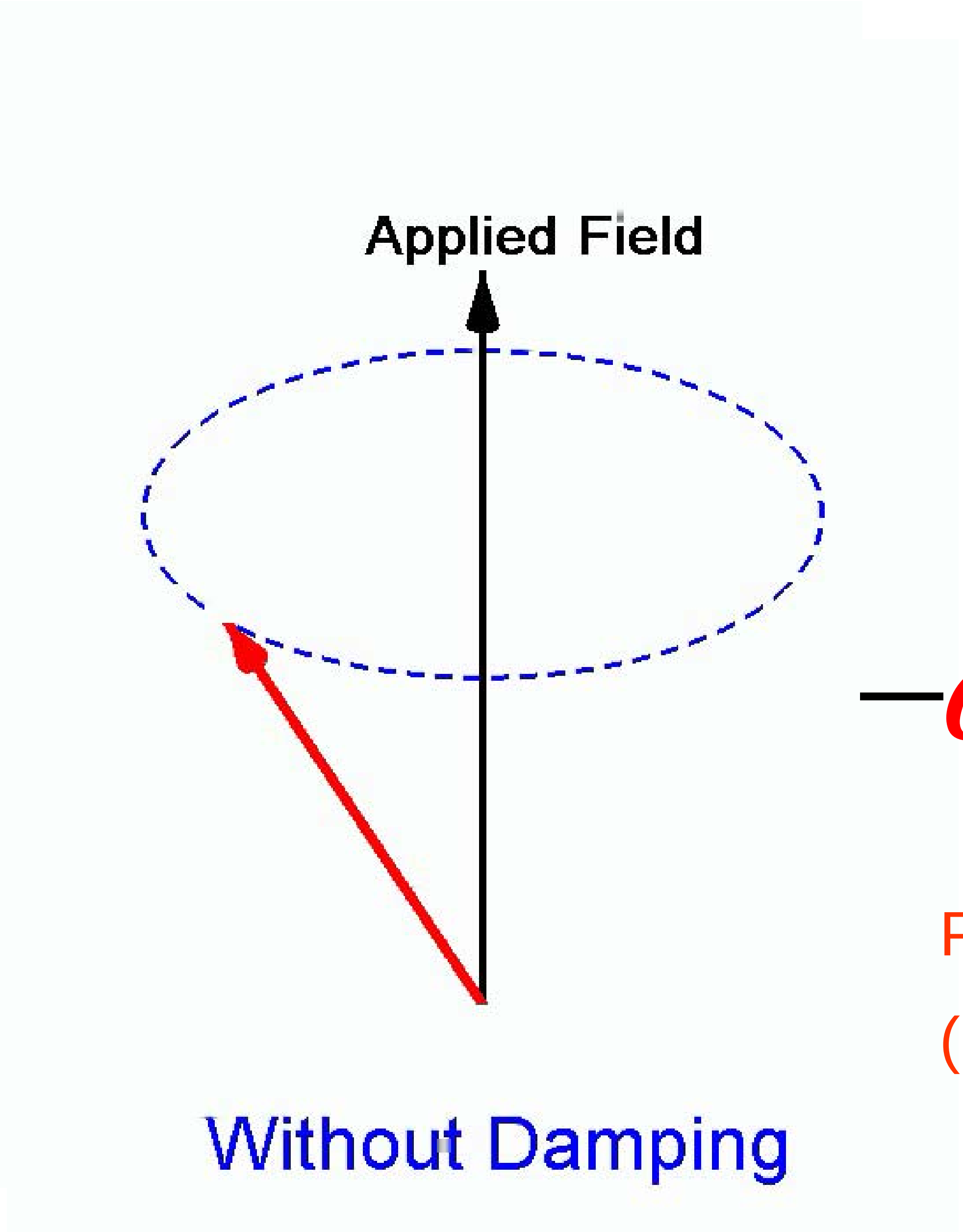




- **Intrinsic magnon ~ magnon scattering**



LLG damping



Gyromagnetic Precession

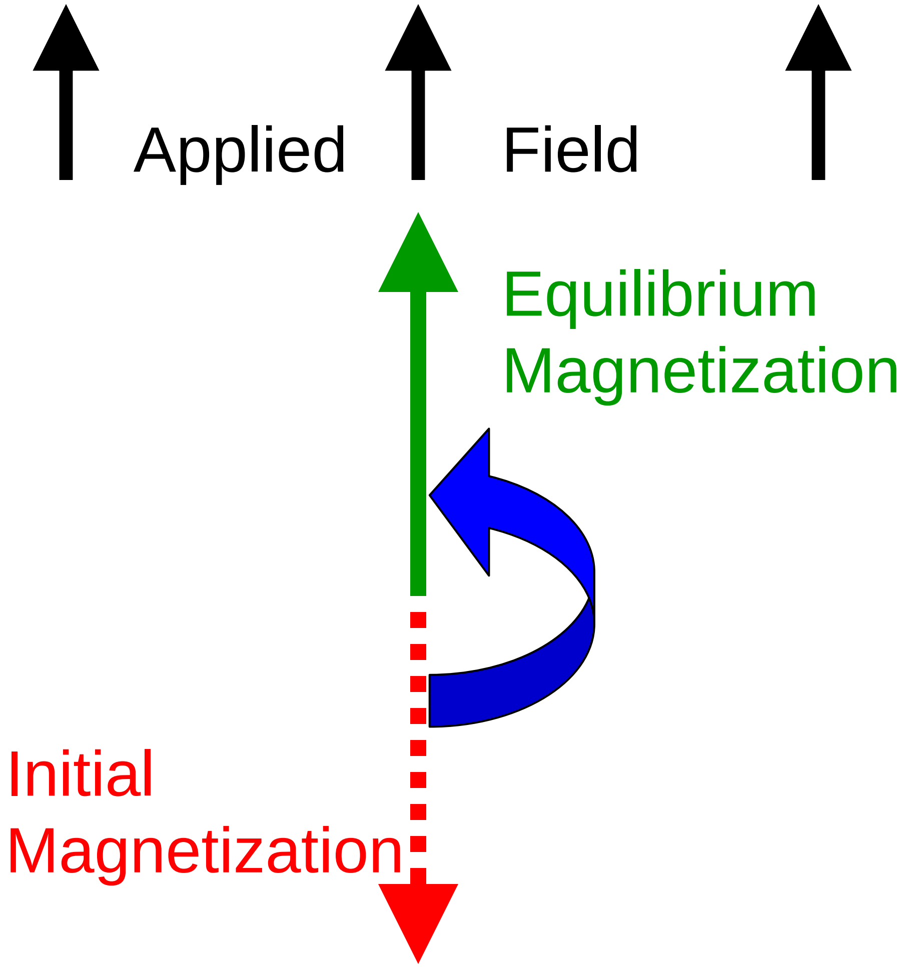
$$\frac{d\vec{M}}{dt} = -\gamma \cdot [\vec{M} \times \vec{H}]$$

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

Phenomenological Damping

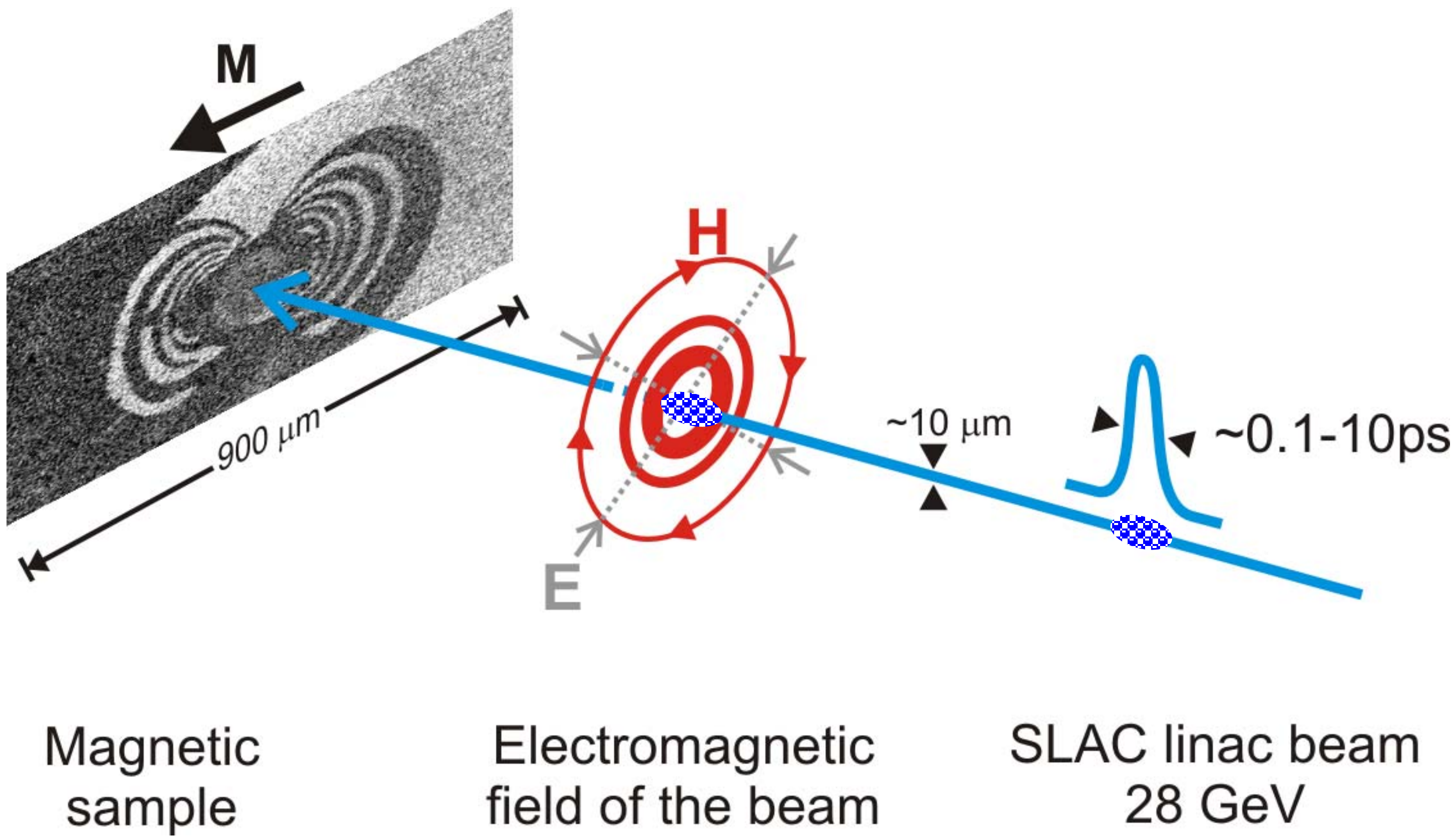
(Landau~Lifshitz~Gilbert)

Large Angle Switching

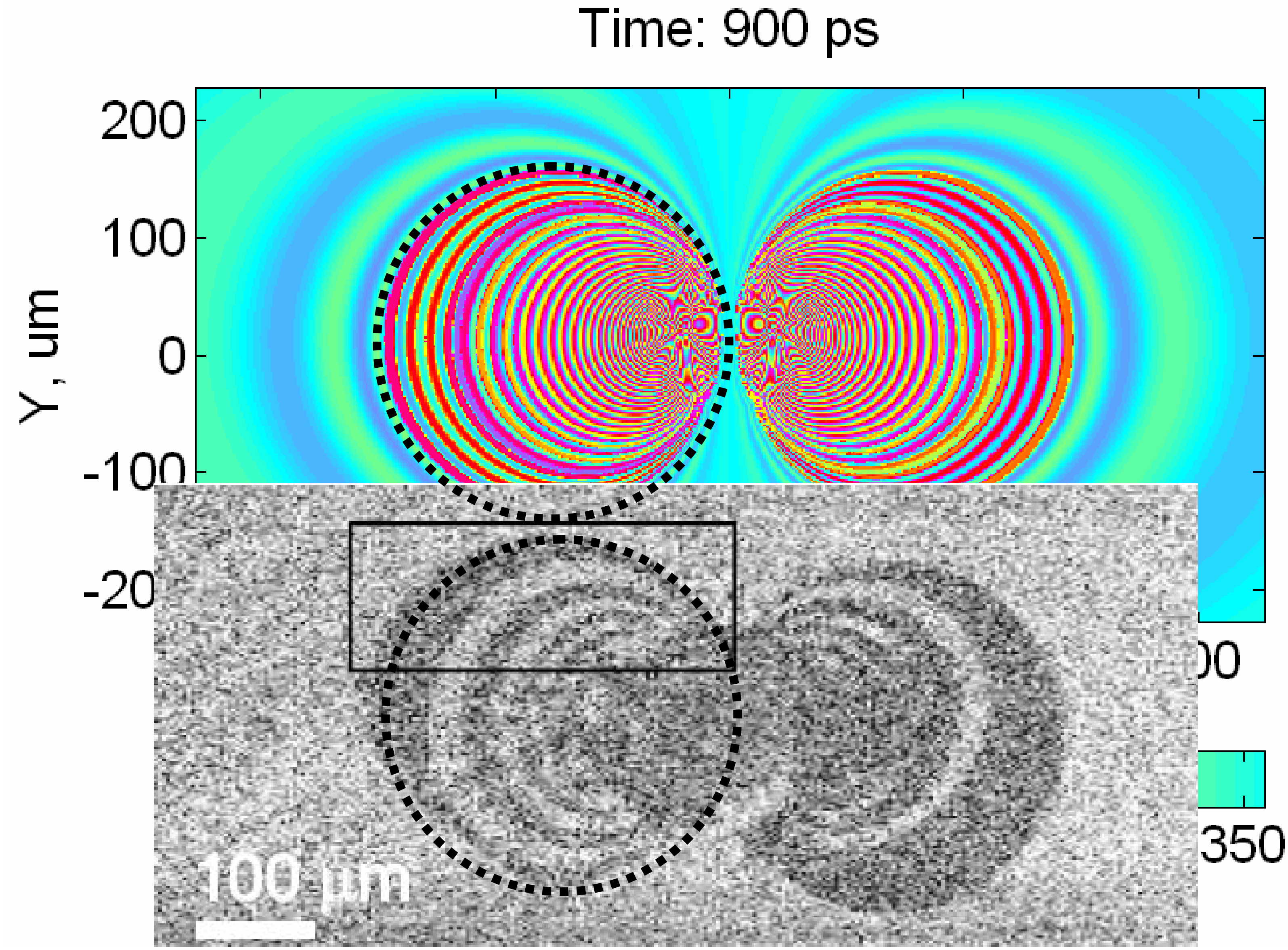


- ***FMR:***
  - small excitations
  - LLG damping
- ***Magnetic Applications:***
  - large angle switching

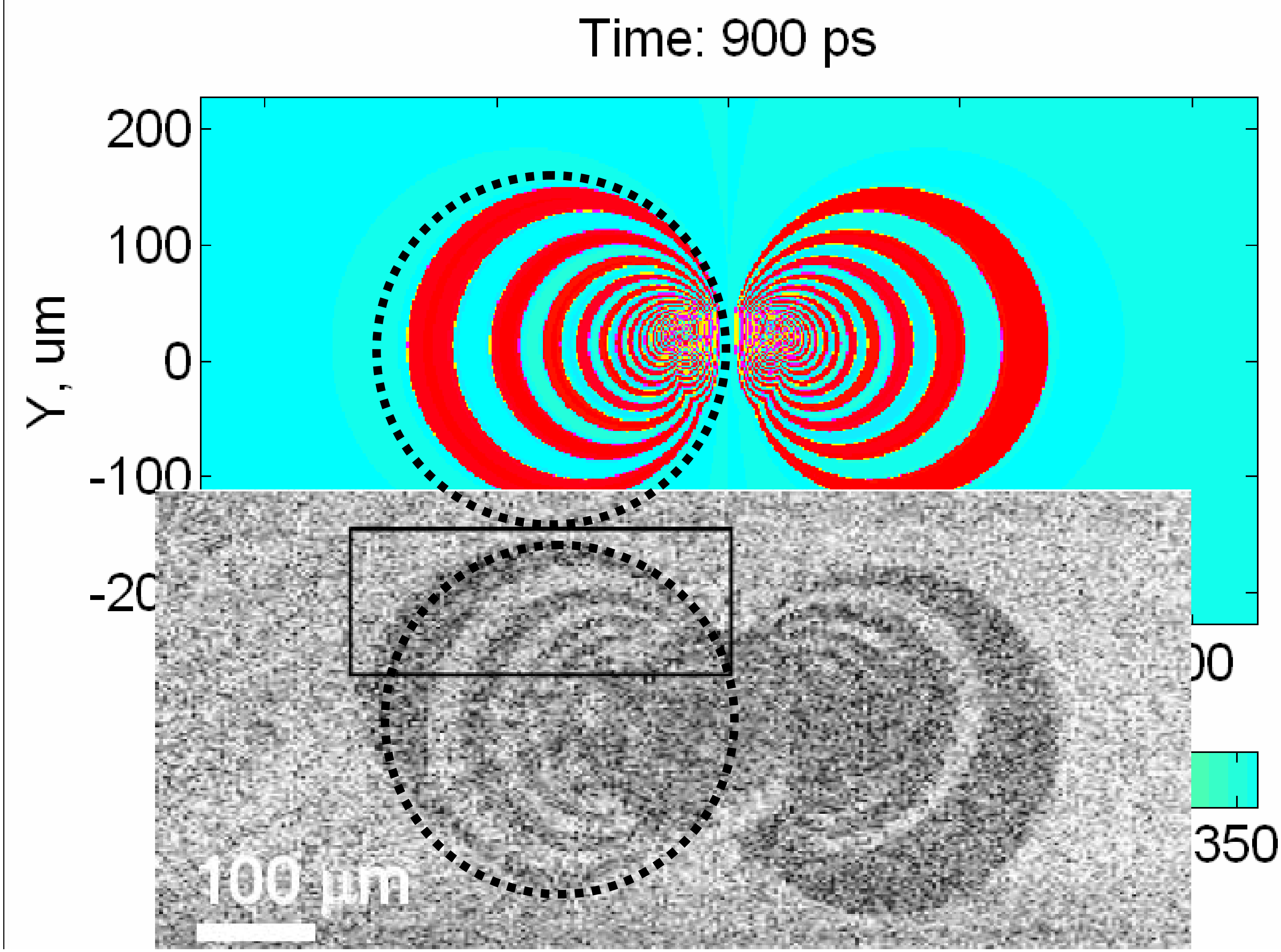
SLAC experiments



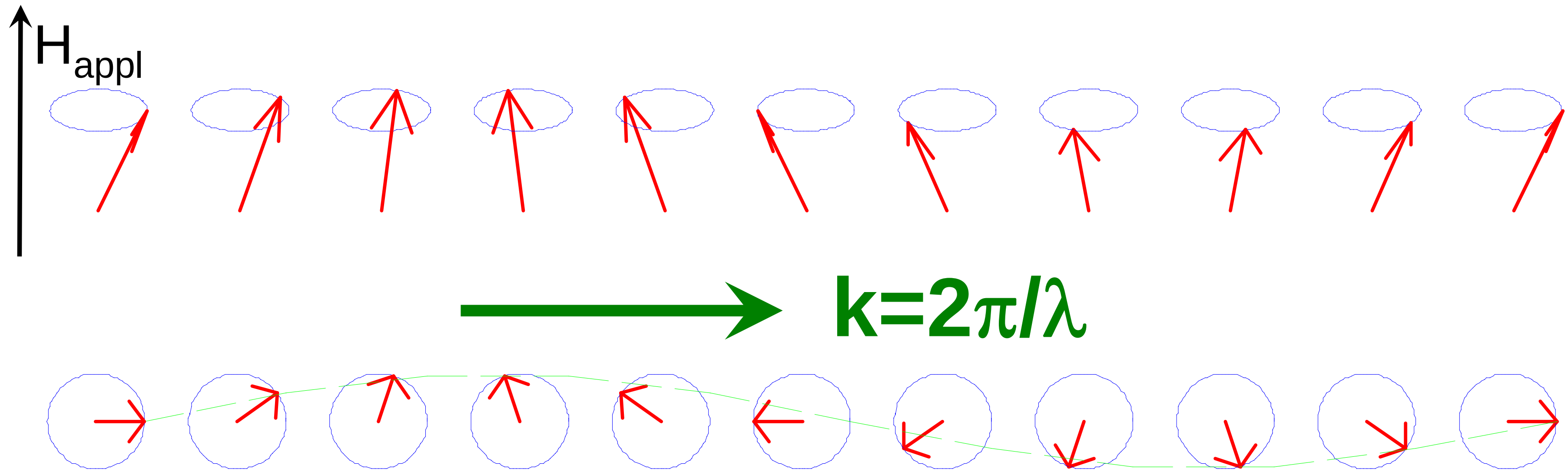
Simulations: α=0.004, no interactions



Simulations: α=0.02, no interactions



Spin Waves = Magnons

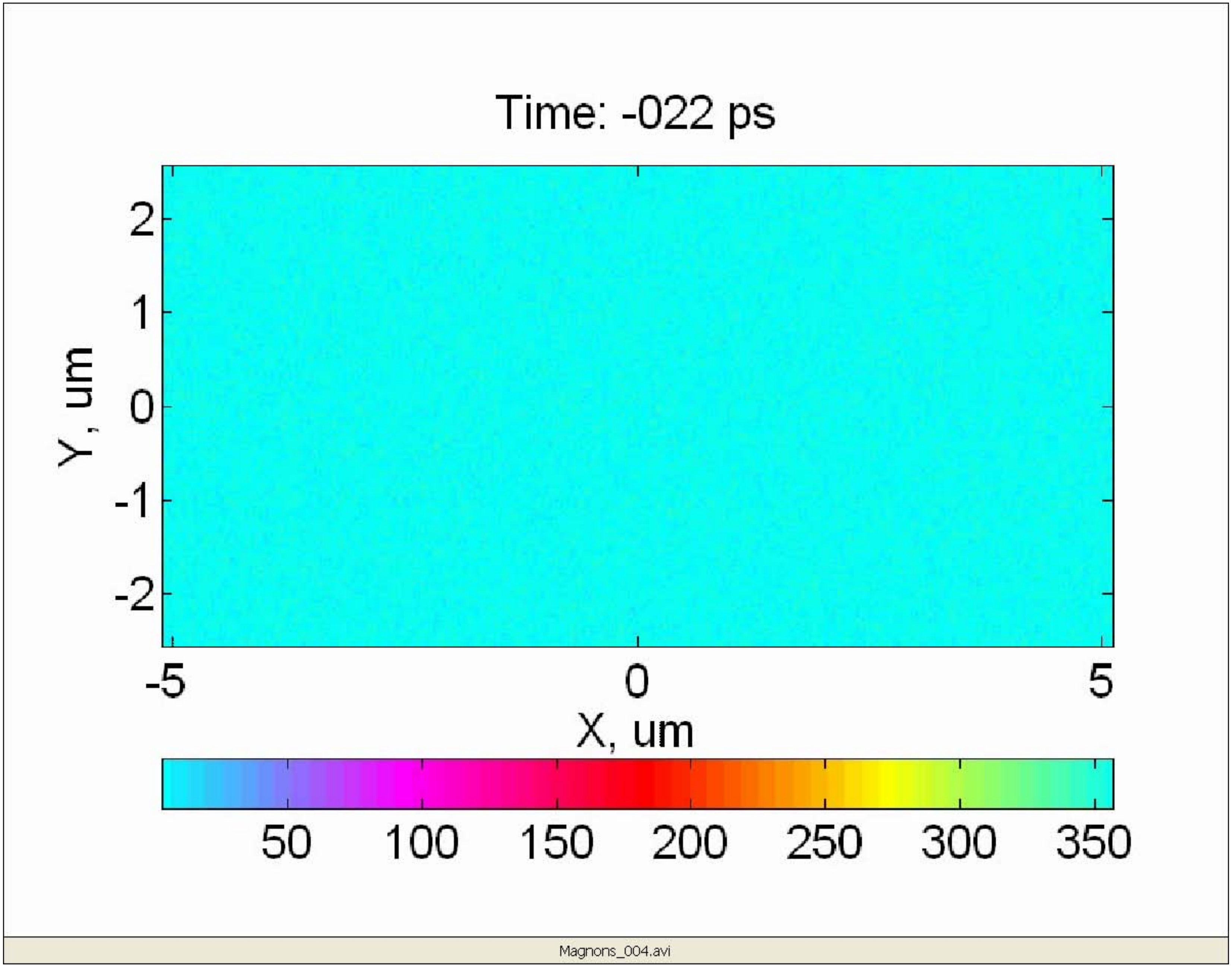


- **k=0** magnons are excited when average magnetization deviates from equilibrium direction

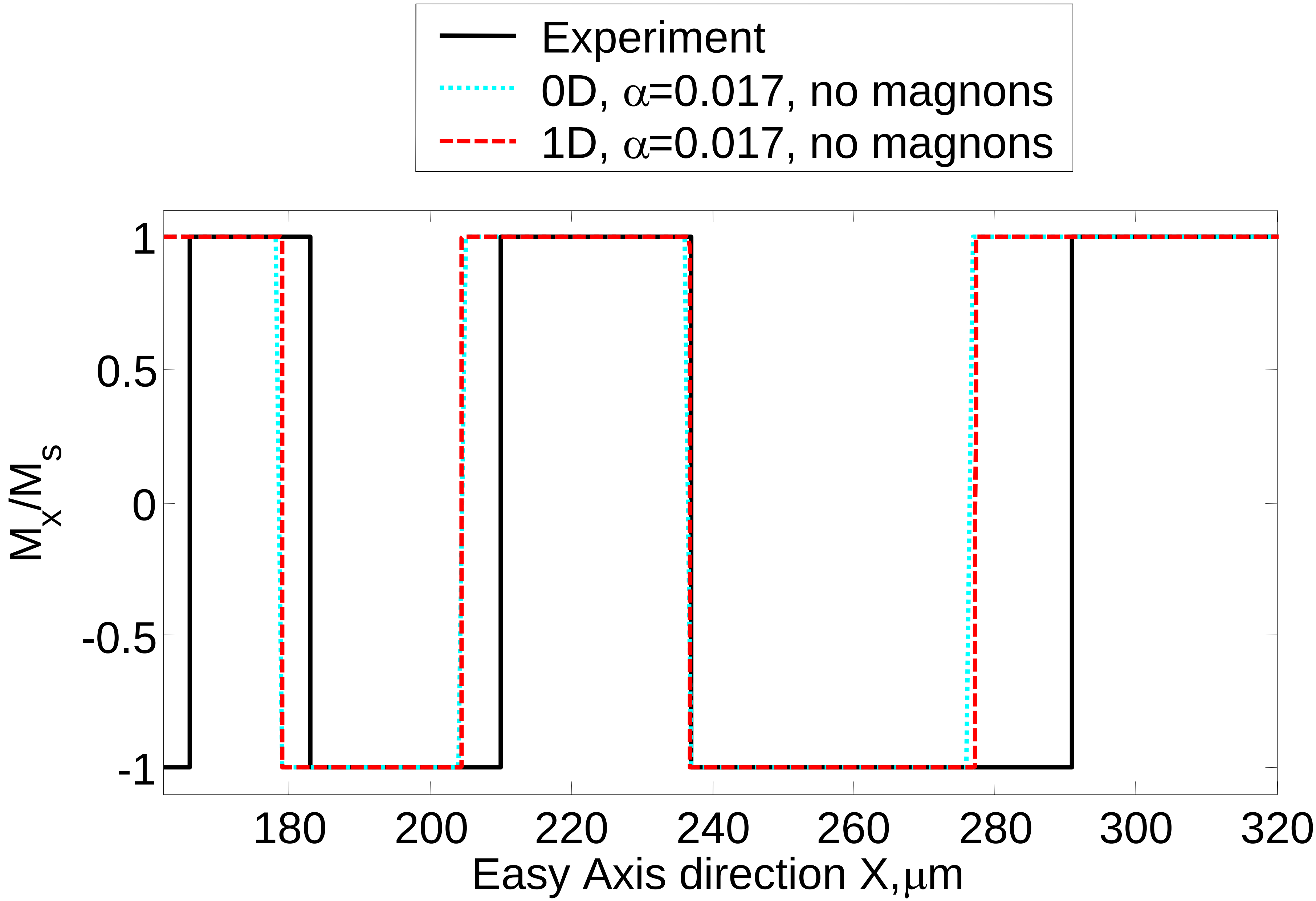
- **k≠0** magnons at **t=0** are thermally excited: $E_k = \hbar\omega_k \cdot N_k \approx \hbar\omega_k \cdot \frac{T}{\hbar\omega_k}$

- Zeeman and Demag Energy of **k=0** magnons is transferred into Exchange, Zeeman and Demag Energy of **k≠0** magnons

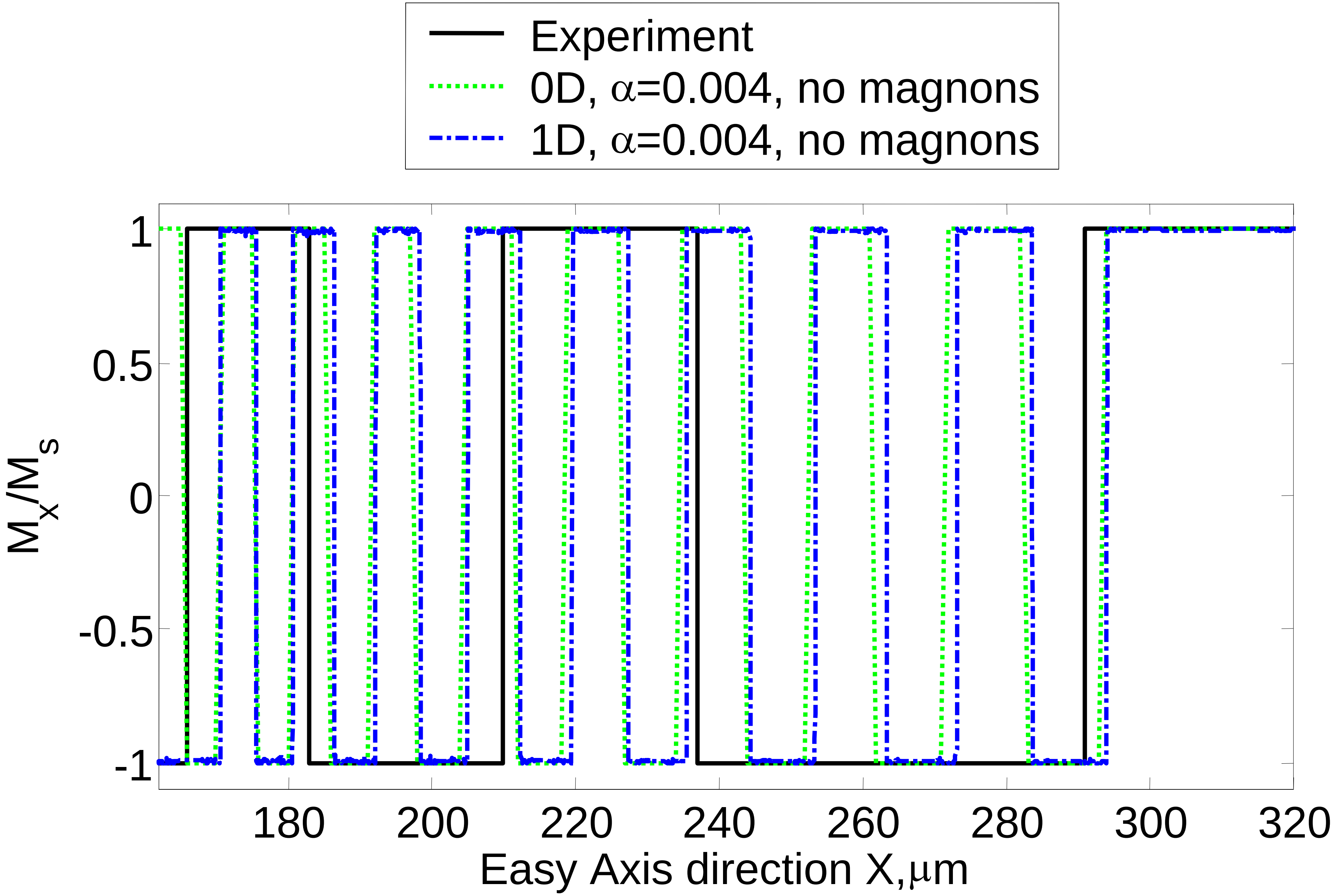
Simulations with interactions, α=0.004



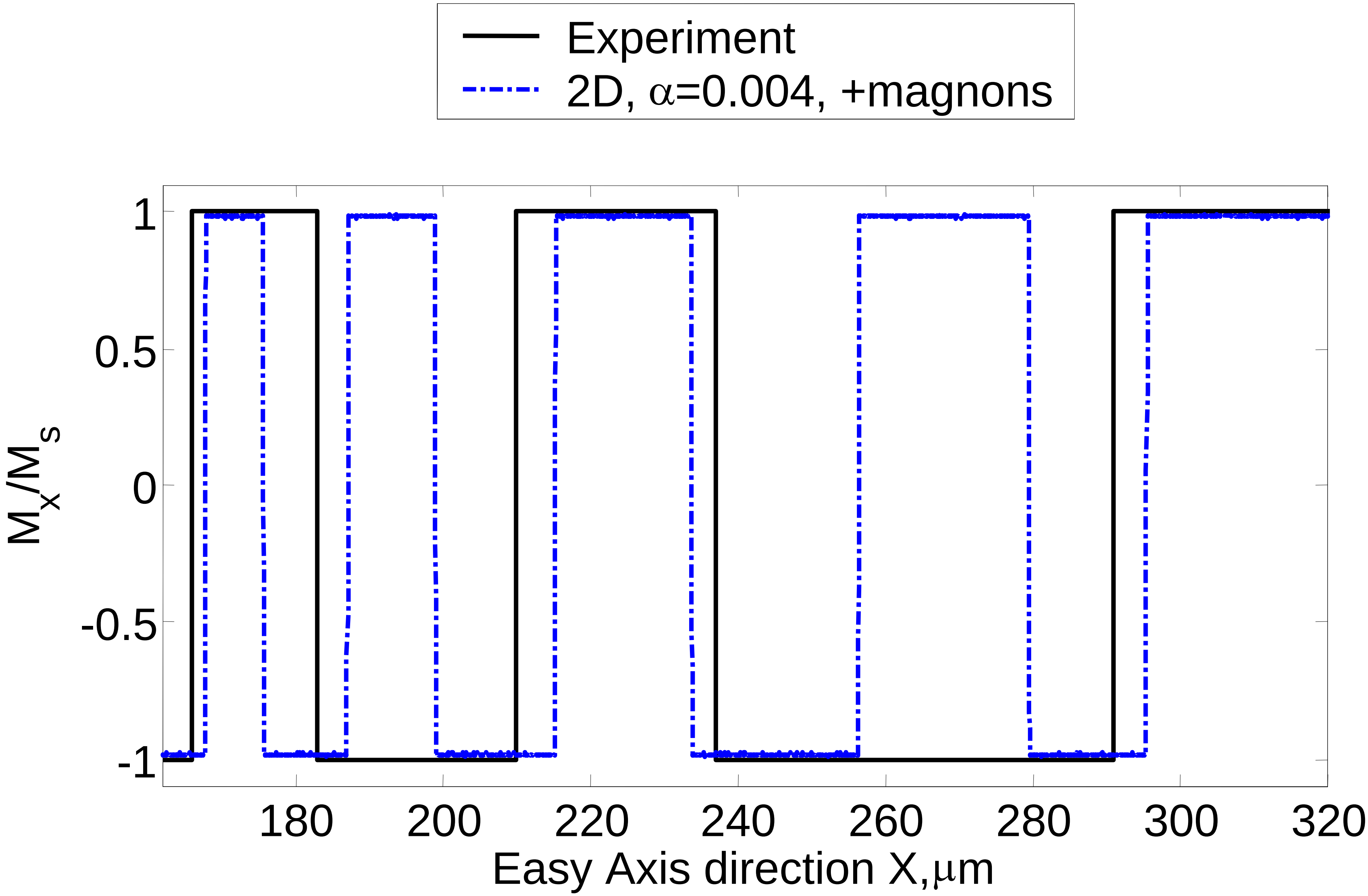
Pattern along the horizontal center line



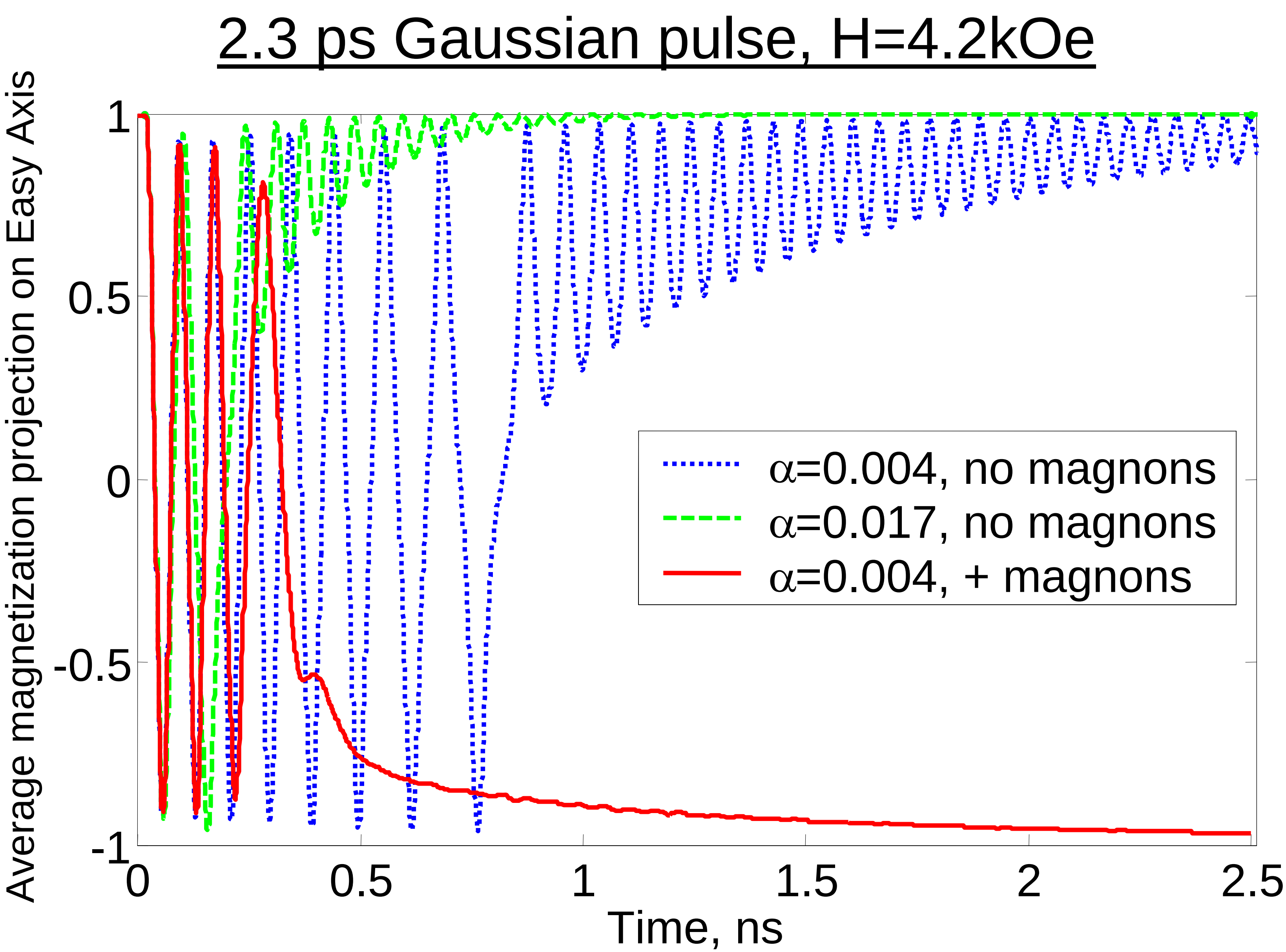
Pattern along the horizontal center line



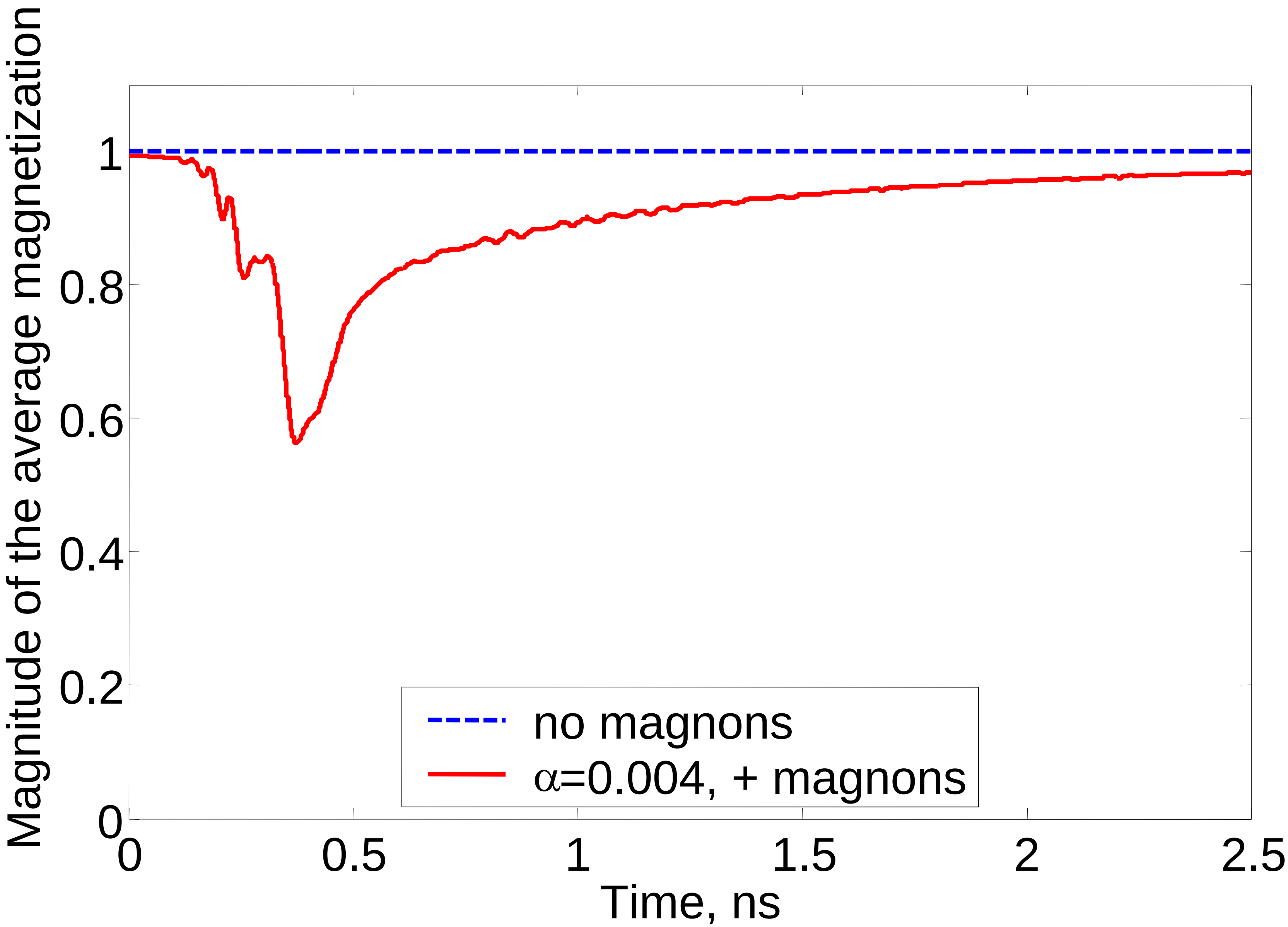
Pattern along the horizontal center line

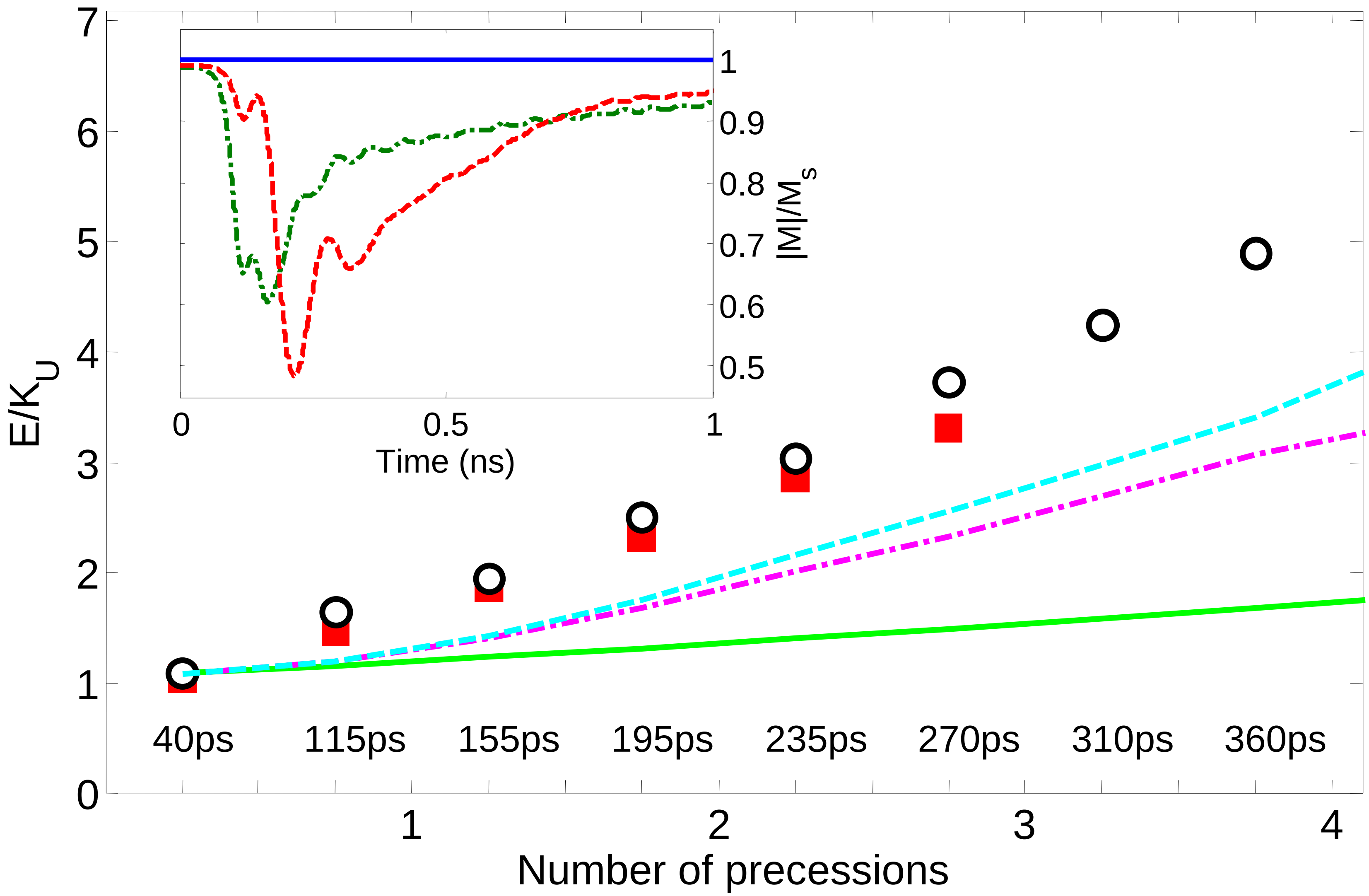


New SLAC experiments on thin Fe films



Spin wave generation

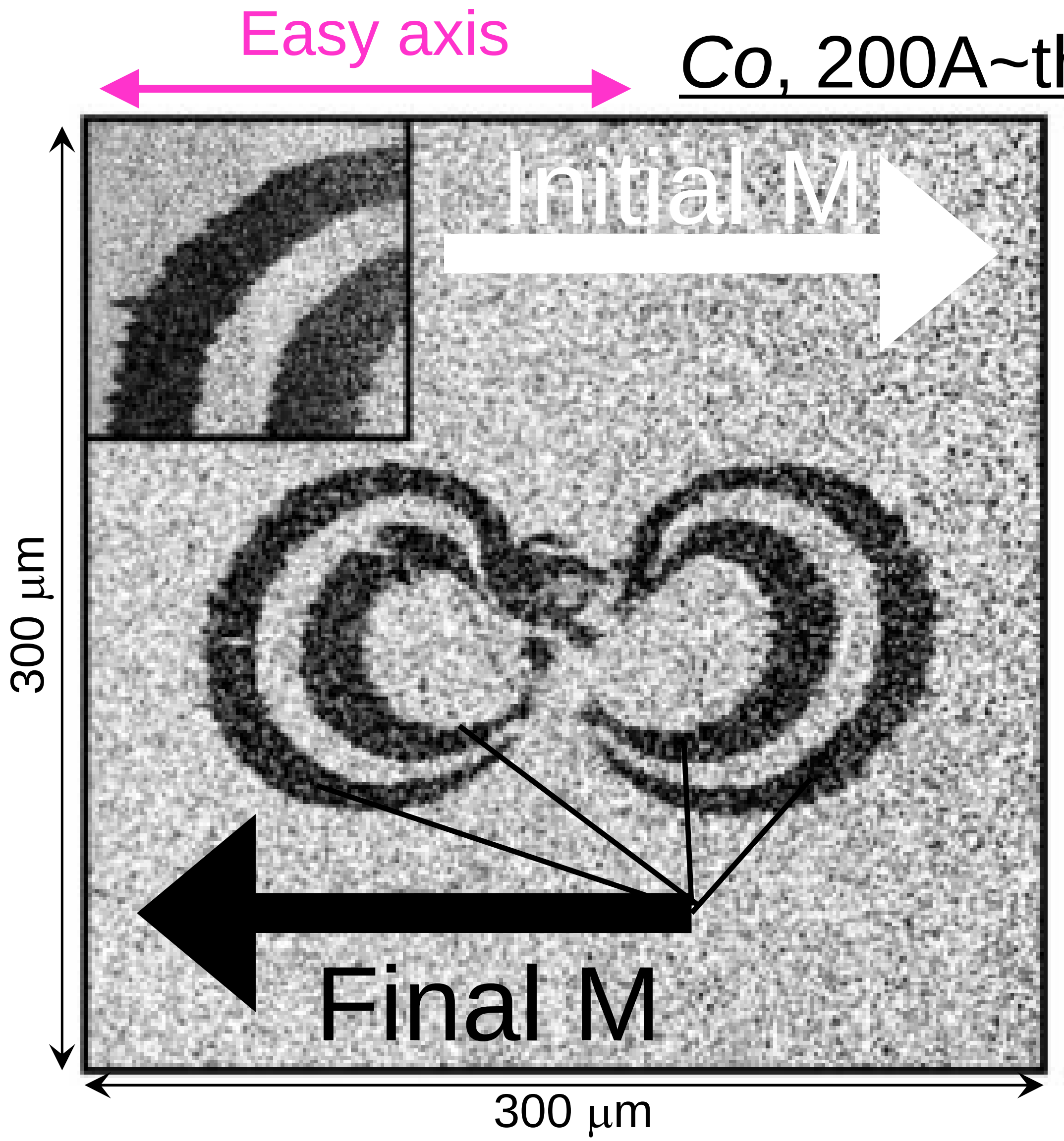




E/K_U
Number of precessions
40ps
115ps
155ps
195ps
235ps
270ps
310ps
360ps
0
1
2
3
4
5
6
7
1
2
3
4
Time (ns)
0
0.5
1
|M|/M_s
0.5
0.6
0.7
0.8
0.9
1

Siegmann Experiment

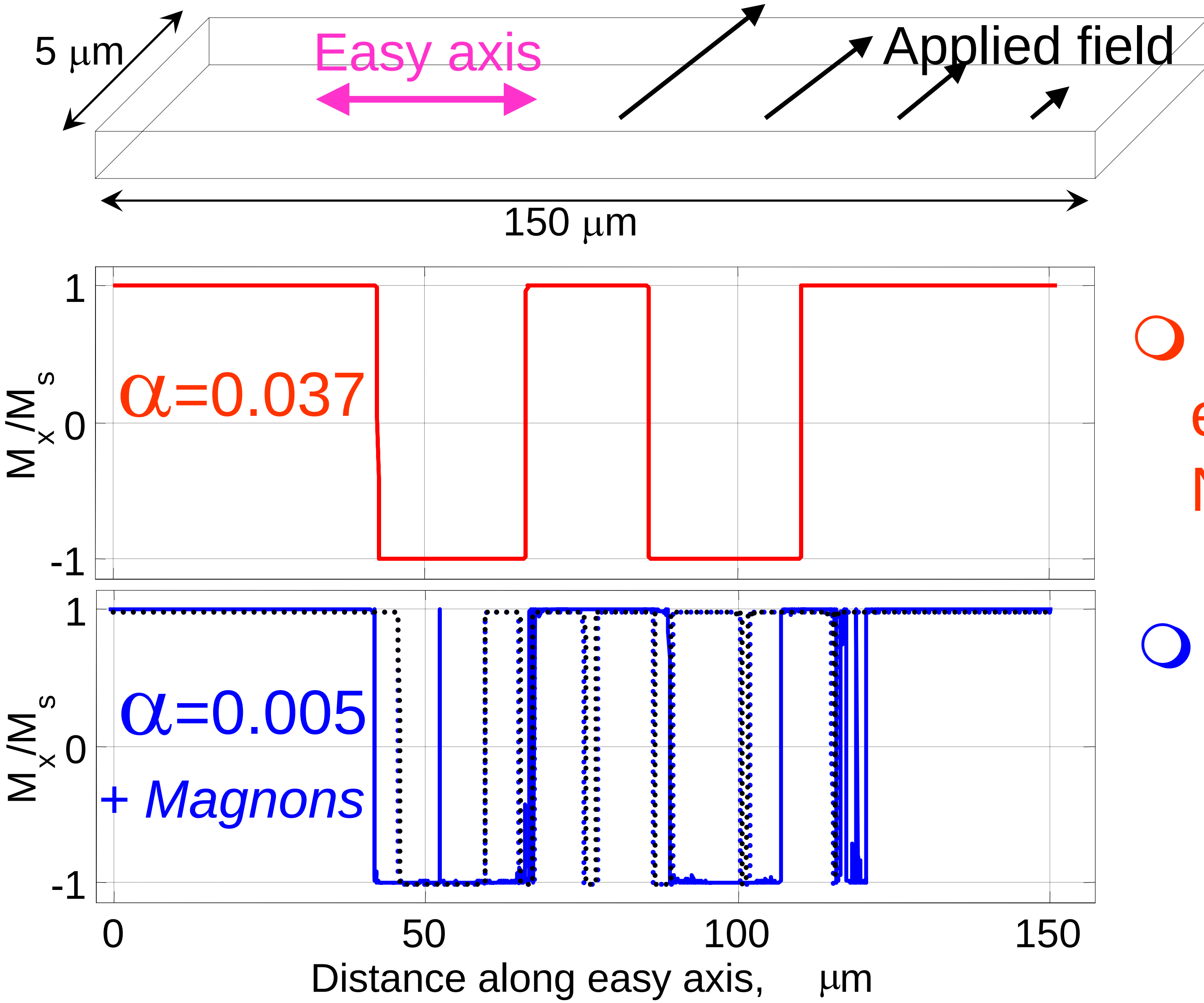
Back, Allenspach, Weber, Parkin, Weller, Garwin, Siegmann: *Science*, 1999.



Co, 200A~thick, H_K=2 kOe

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

Siegmann Experiment: Simulations



≈ $8 \cdot 10^6$ elements

- Magnon excitations NOT allowed
- Magnon scattering ⇓ increased damping

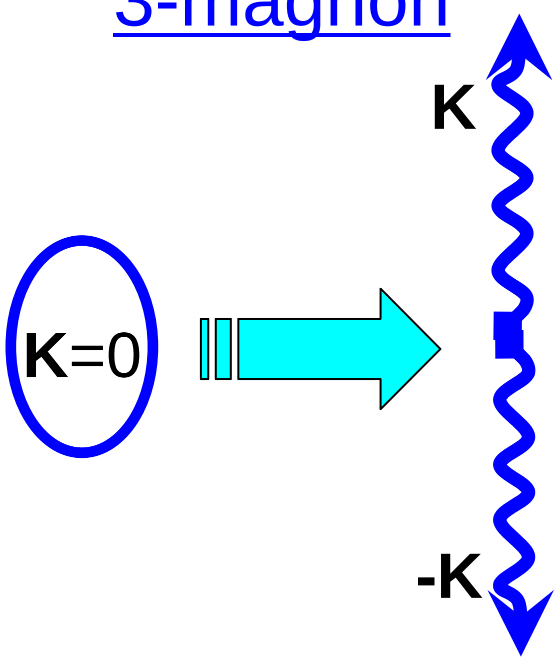
Analytic Theory: 3,4~magnon scattering

- **H. Suhl Hamiltonian:**

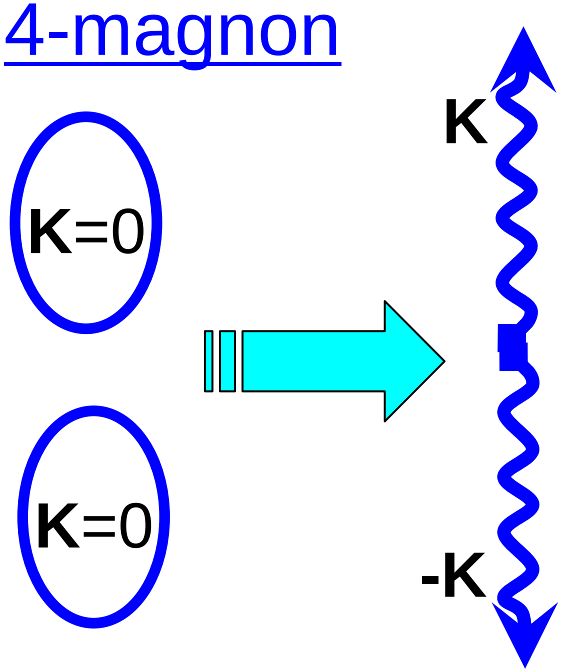
$$\mathcal{H} = \sum_{\mathbf{k}} (\omega_{\mathbf{k}} + \Lambda_{\mathbf{k}} N_0) \cdot b_{\mathbf{k}} b_{\mathbf{k}}^{\dagger}$$

$$+ \Phi_{\mathbf{k}} \cdot \left\{ b_0 b_{\mathbf{k}}^{\dagger} b_{-\mathbf{k}}^{\dagger} + b_0^{\dagger} b_{\mathbf{k}} b_{-\mathbf{k}} \right\} + \Psi_{\mathbf{k}} \cdot \left\{ b_0 b_0 b_{\mathbf{k}}^{\dagger} b_{-\mathbf{k}}^{\dagger} + b_0^{\dagger} b_0^{\dagger} b_{\mathbf{k}} b_{-\mathbf{k}} \right\}$$

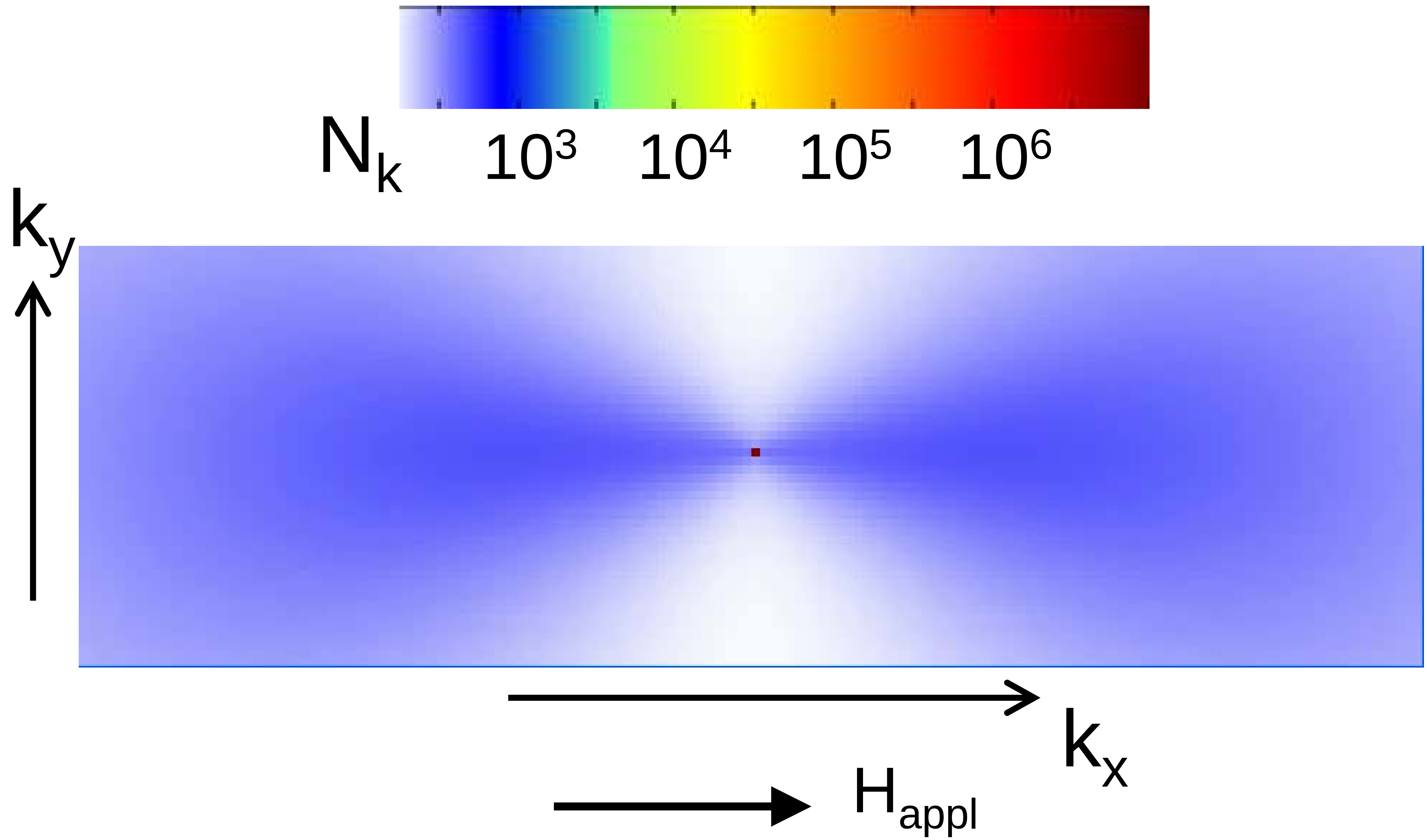
3-magnon



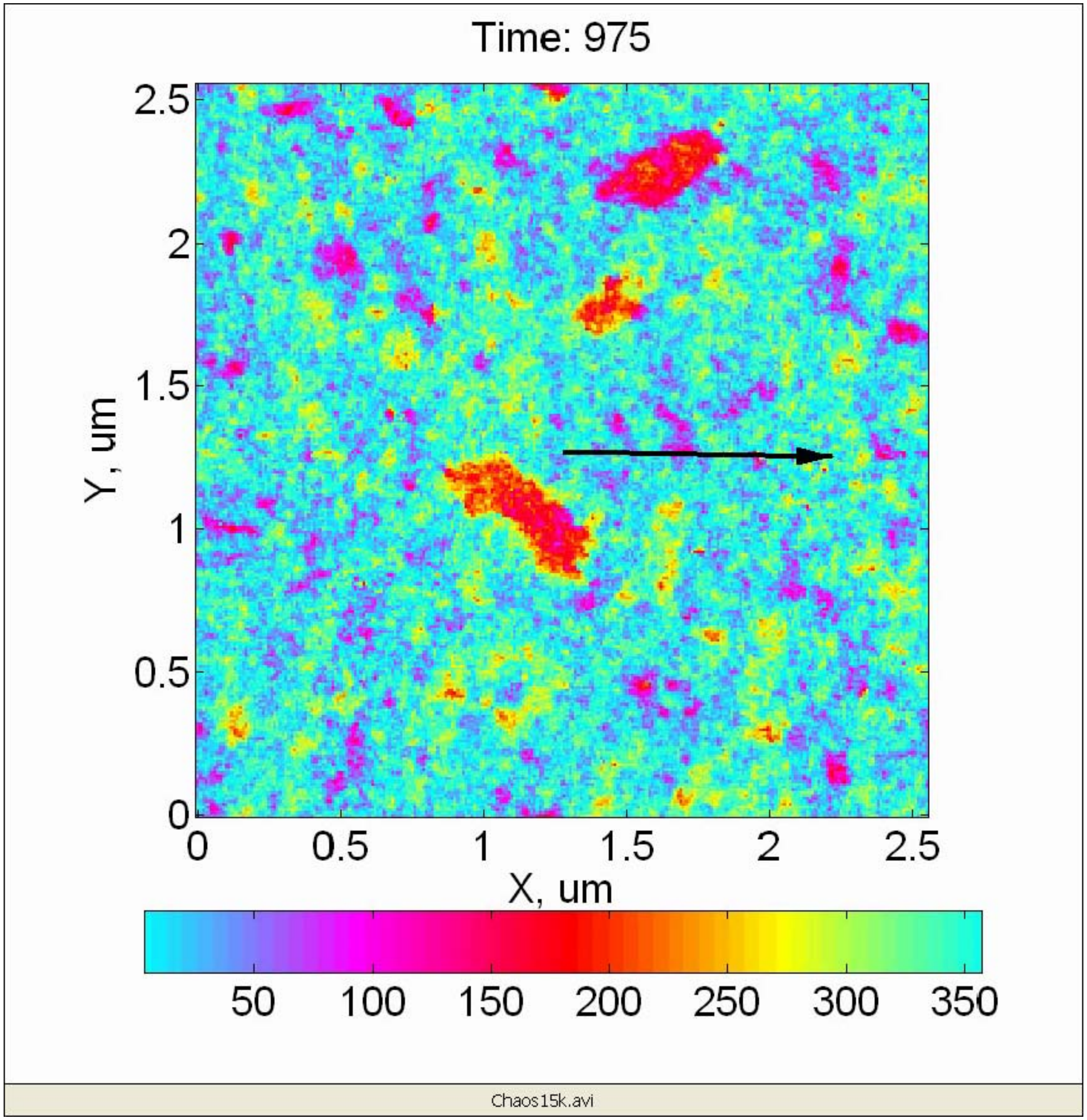
4-magnon



Simulations: Magnon Numbers Dynamics



Chaotic switching



uniform Pulse field

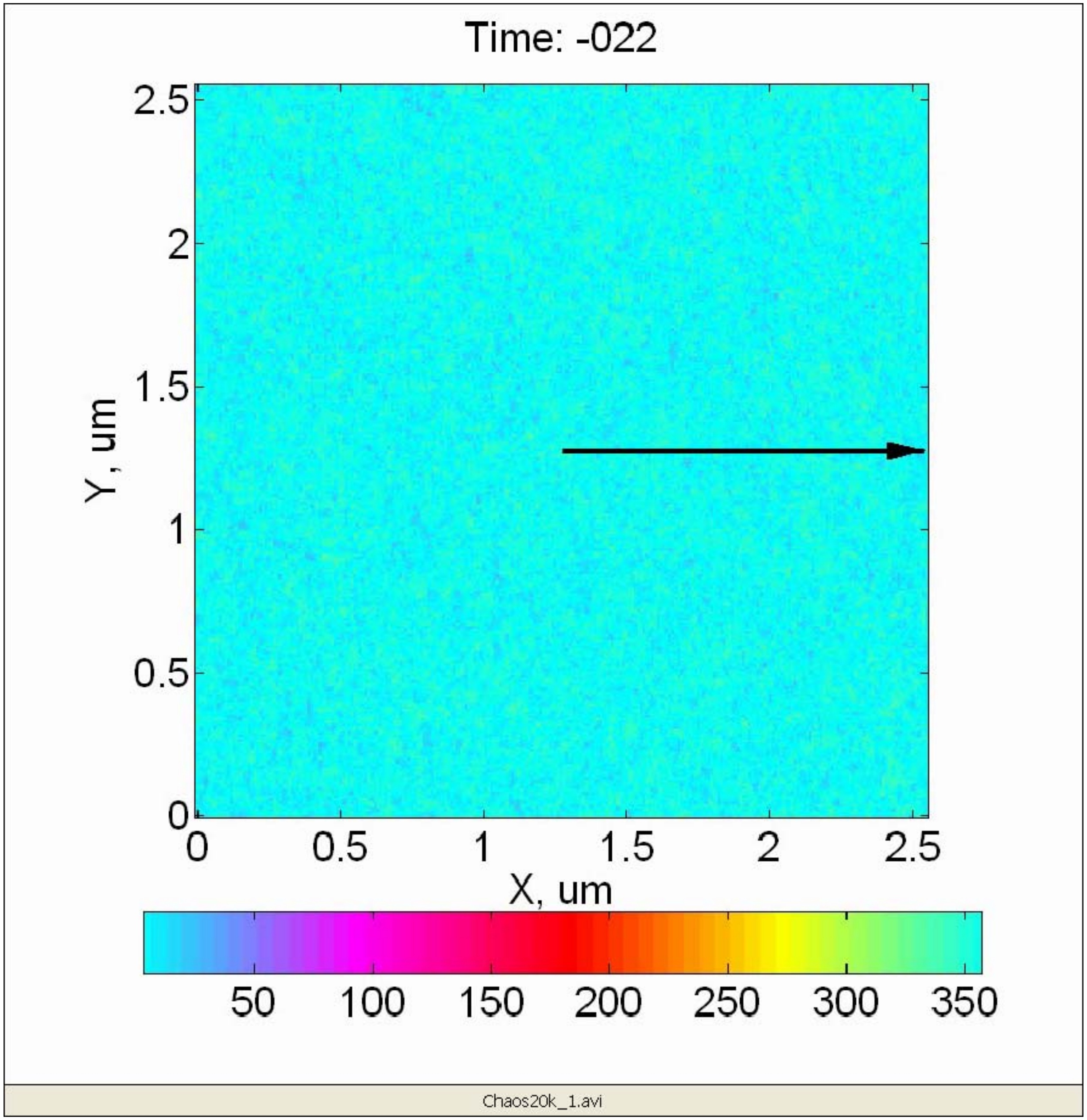
H_{pulse}=15 kOe

with current beam

at ~ 60 um from the center

a few chaotic domains appear

Chaos onset



uniform pulse field

H_{pulse}=20 kOe

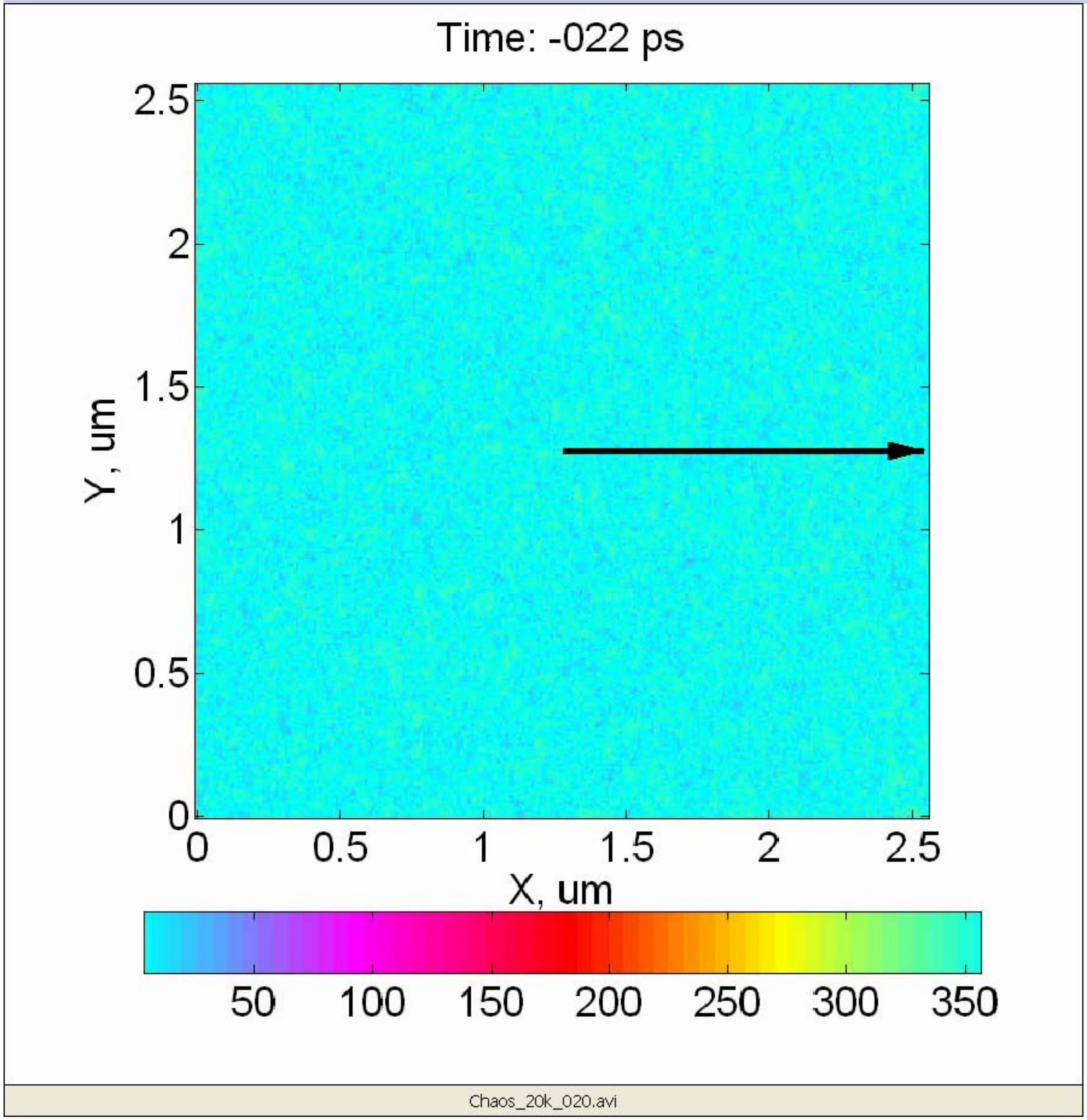
at ~ 40 um from the center

full chaos after 1ns

chaotic domains slowly disappear after ~ 5ns -

high magnetic temperature?

Chaos onset



uniform pulse field

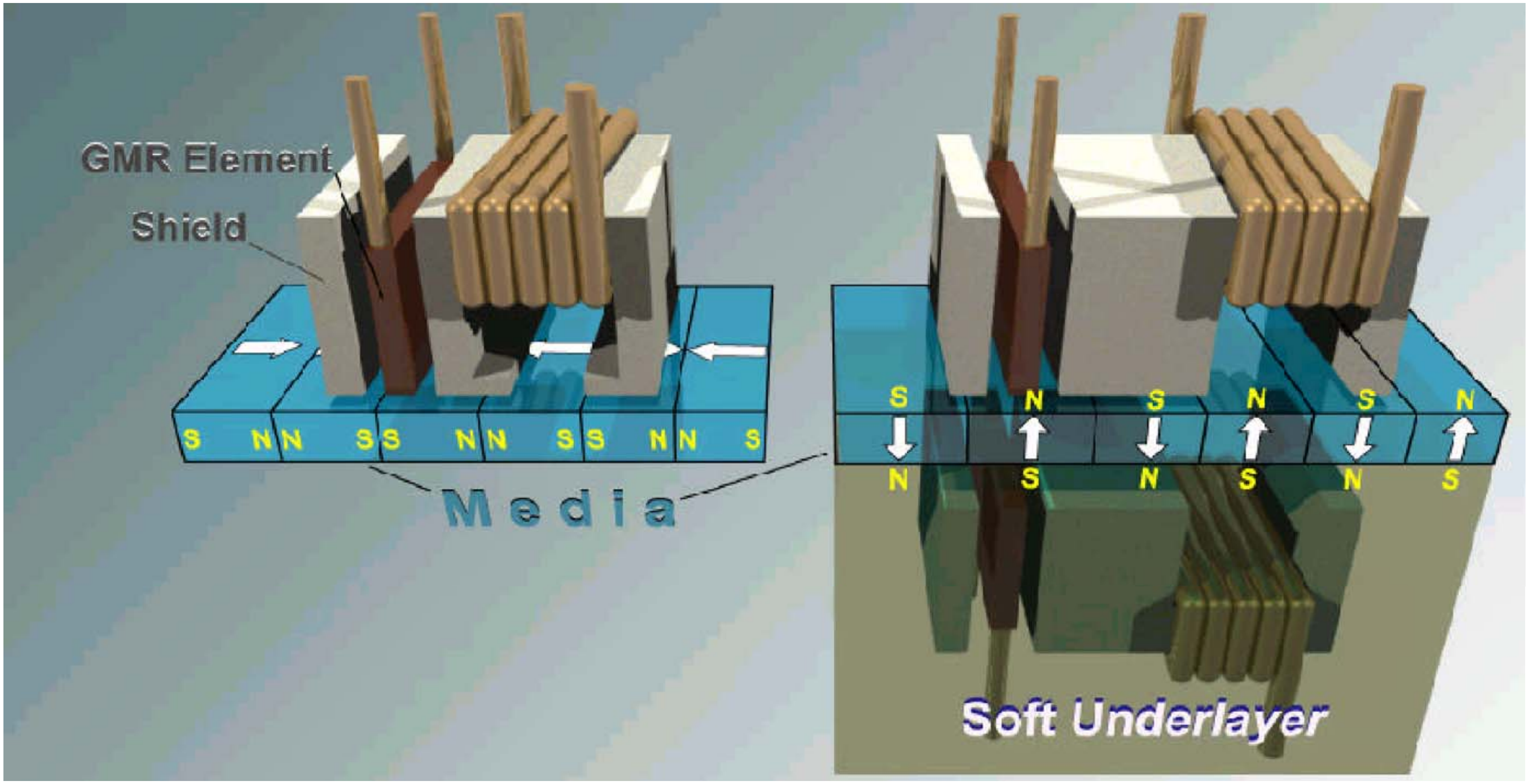
H_{pulse}=20 kOe

at ~ 40 um from the center

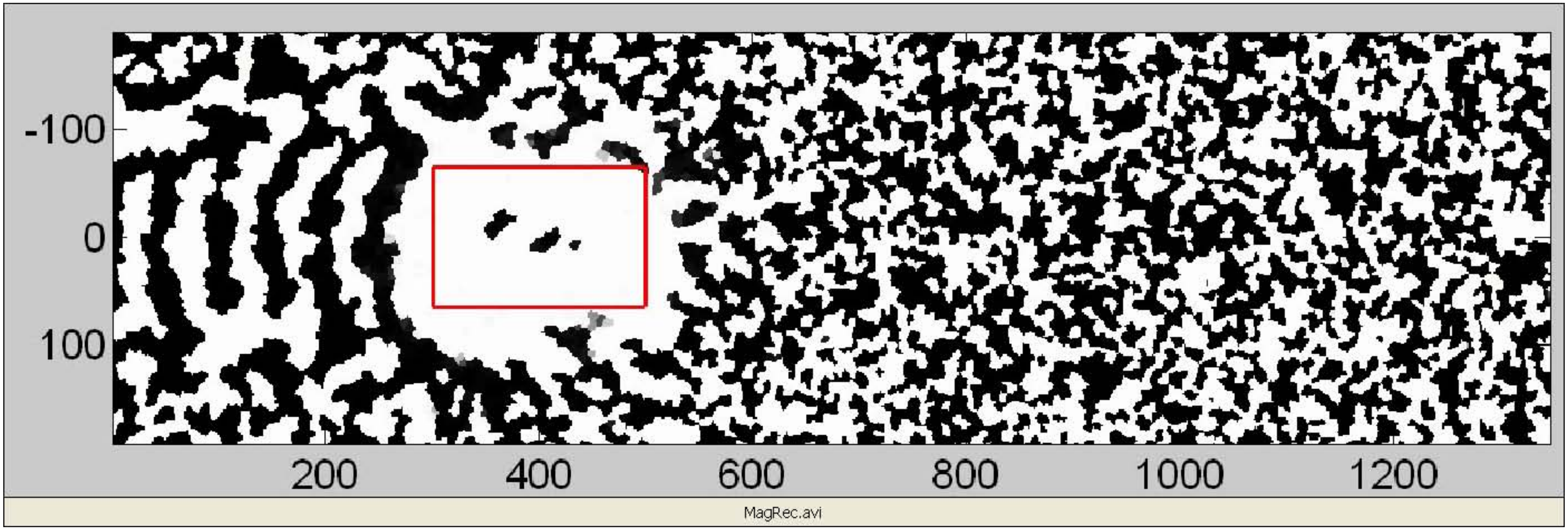
α=0.02

chaos does not develop

Magnetic recording



Write process

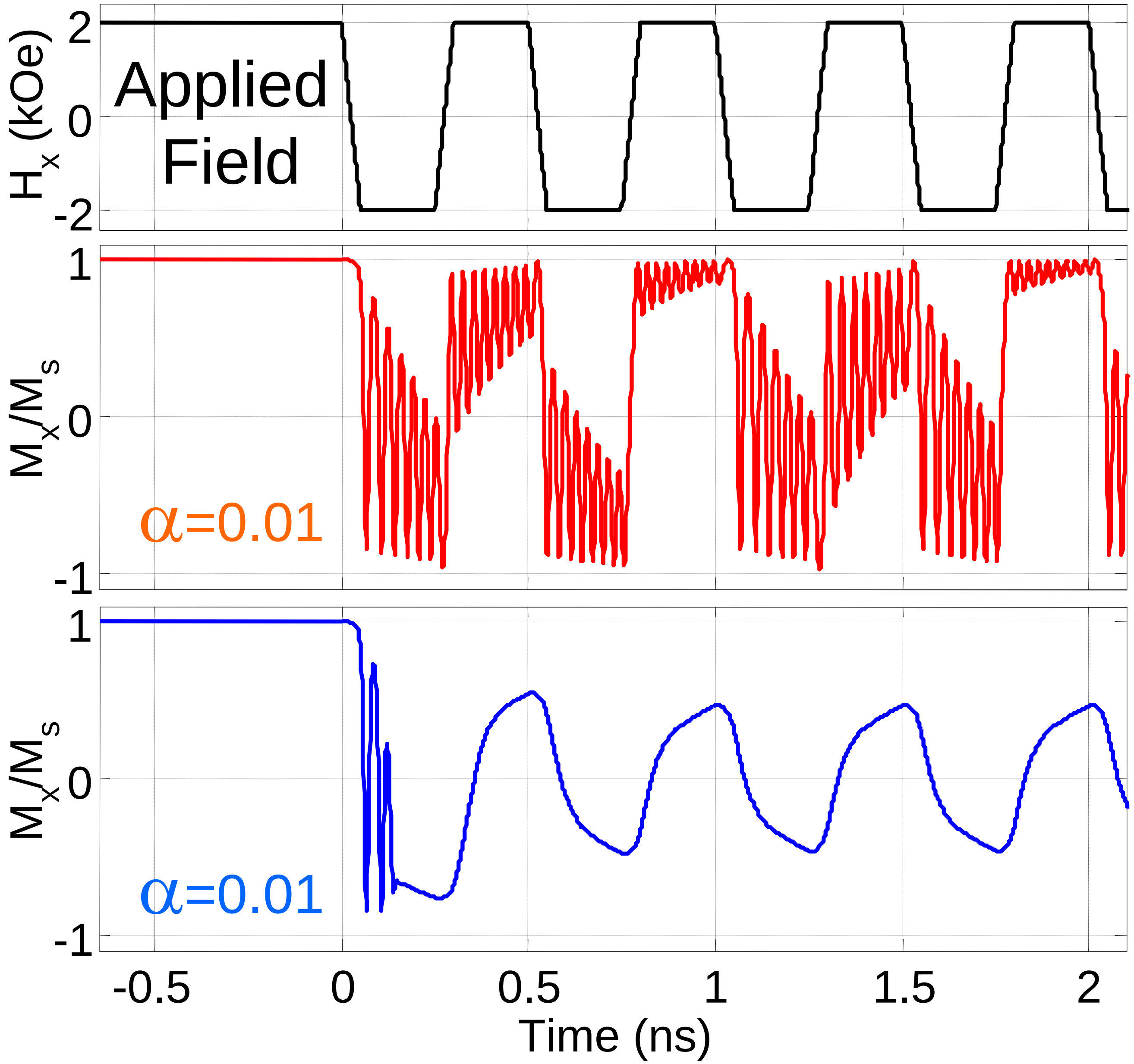


simulations for realistic heads and media,
but with high damping

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

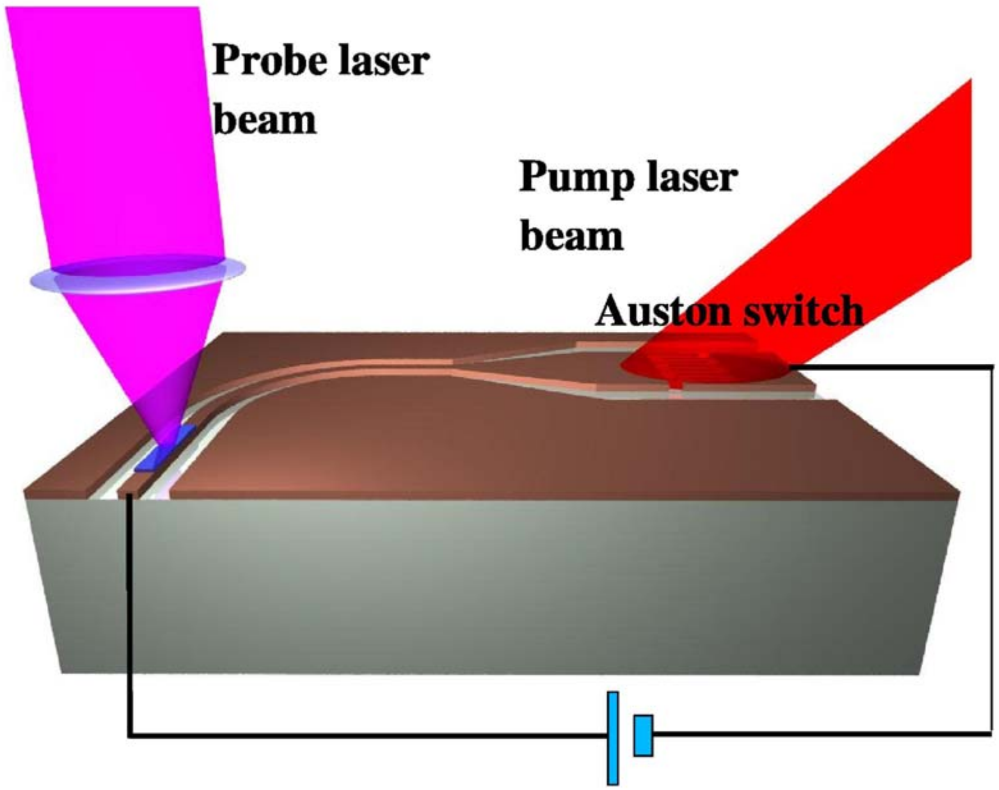
- Magnon excitations NOT allowed

- 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