Concepts of magnetic 3D and multilayer recording

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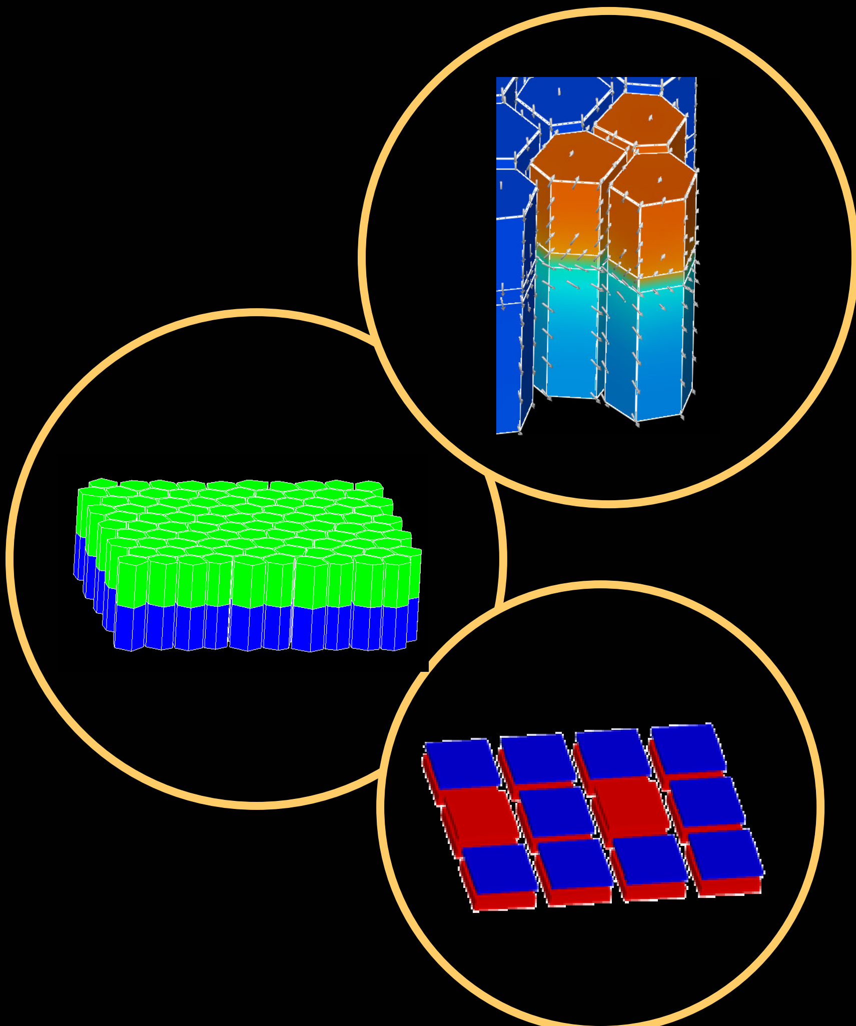
Outlook



Introduction

- Micromagnetics
- Limits in recording

Multilayer Media

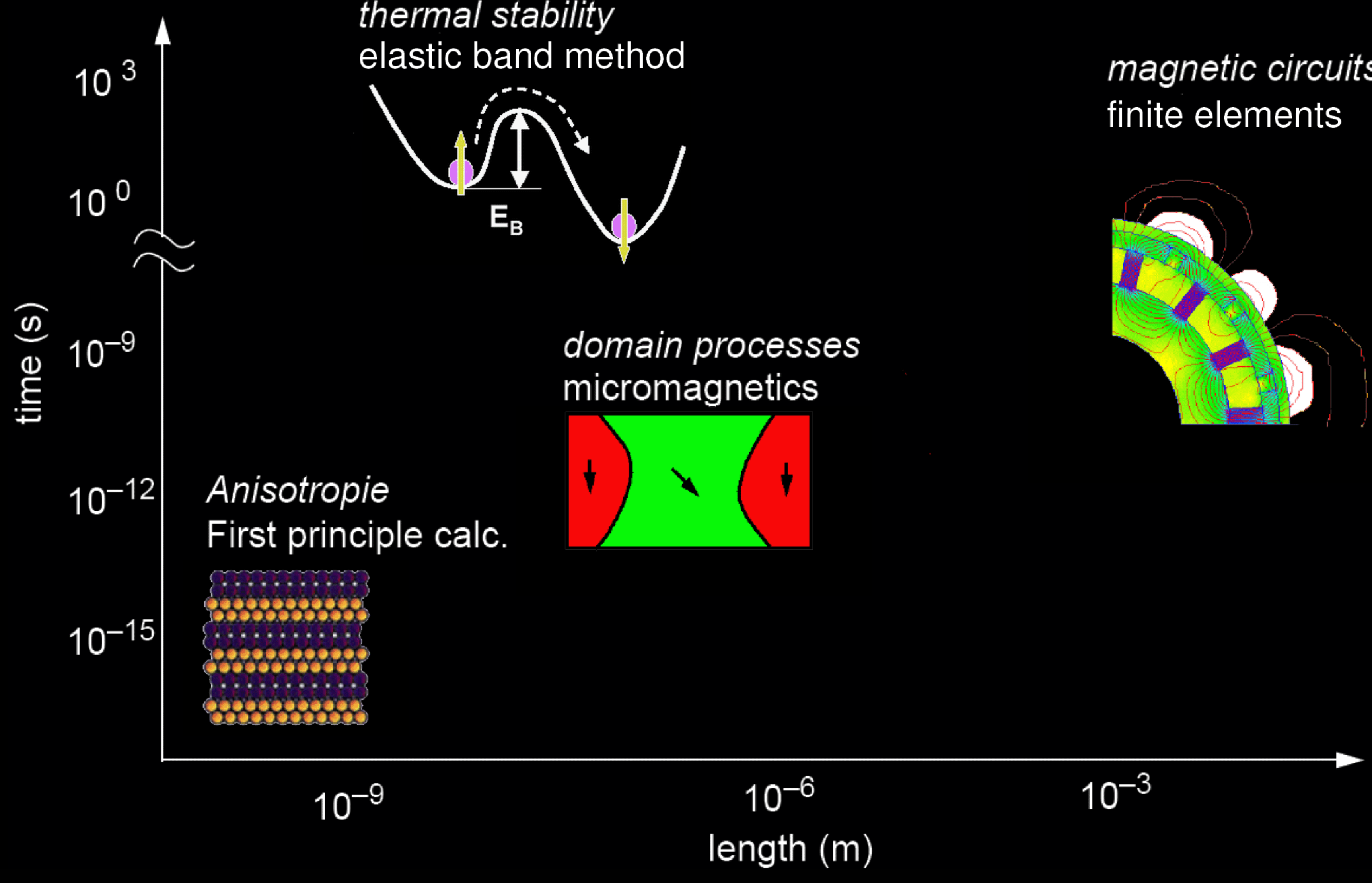
- overcoming limits
- exchange spring media

3-d recording

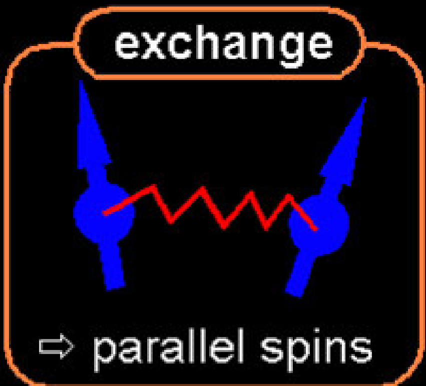
- Microwave assisted
- patterned media

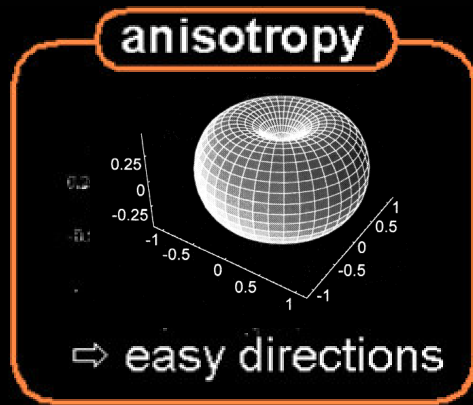
Summary

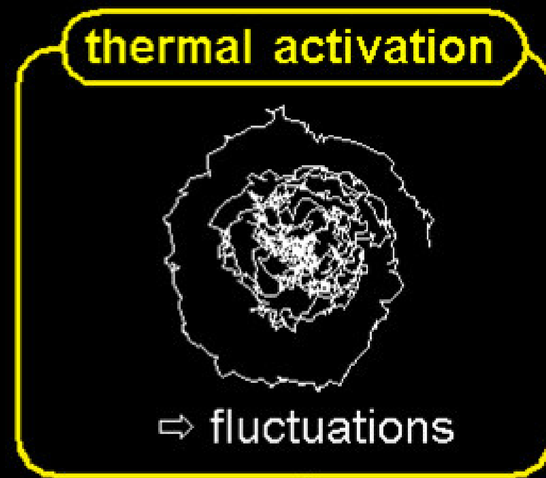
Length and Time Scales



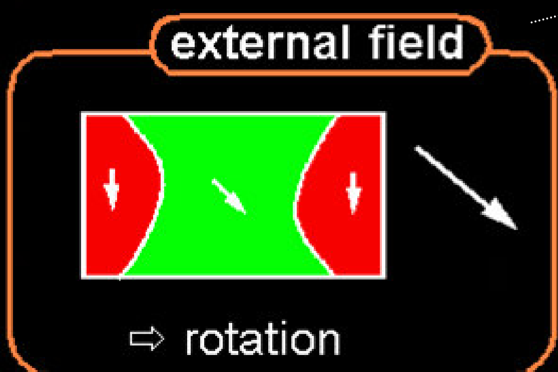
Micromagnetis

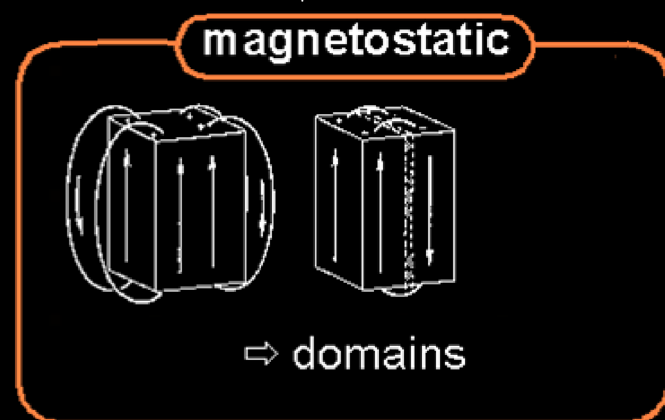




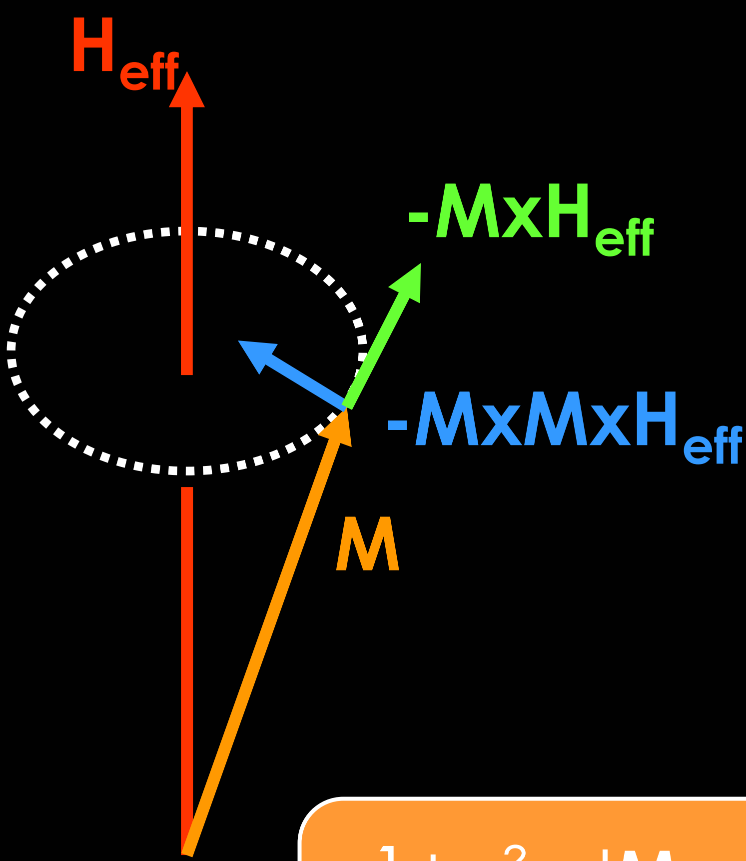


$$\Phi_{tot}(\mathbf{J}) = \int \left[\frac{A}{J_s^2}(\nabla \mathbf{J})^2 - K_1 \left(\mathbf{u}_c \cdot \frac{\mathbf{J}}{J_s} \right)^2 - \mathbf{J} \cdot \mathbf{H}_{ext} - \mathbf{J} \cdot \mathbf{H}_d \right] dV$$





Magnetization Dynamics



Gyromagnetic precession

M rotates around H_{eff}

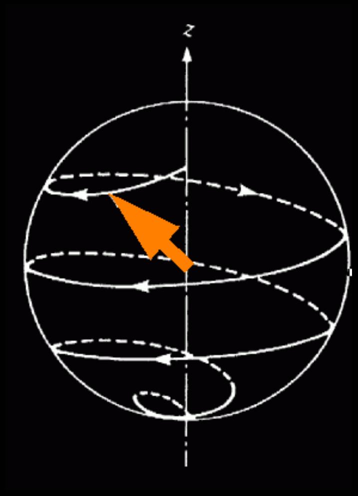
Dissipative term

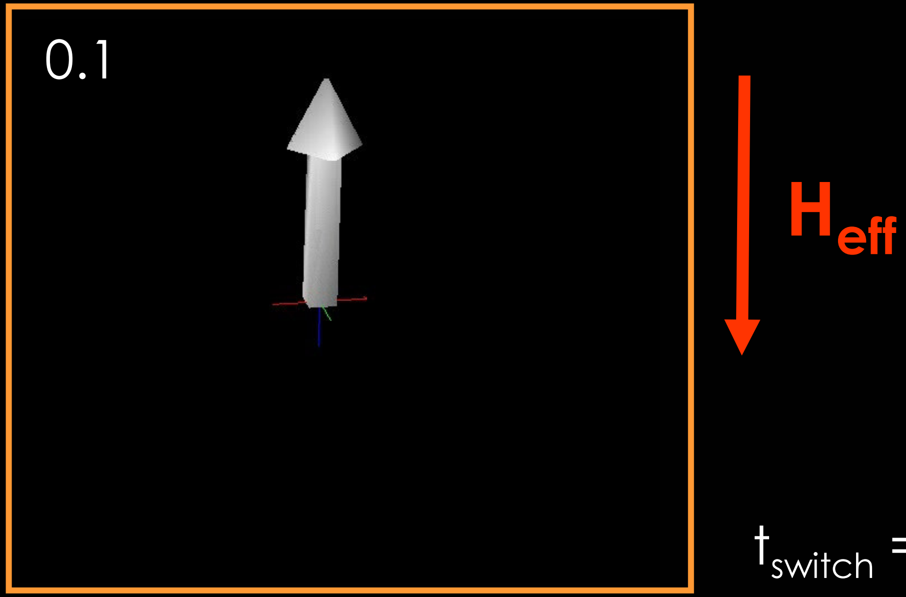
"force" proportional
to generalized velocity

$$\mathbf{H}_{eff} = -\frac{\delta E}{\delta \mathbf{M}}$$

$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\times\mathbf{H}_{eff} - \frac{\alpha}{M_s}\mathbf{M}\times\mathbf{M}\times\mathbf{H}_{eff}$$

Reversal of Single Spin

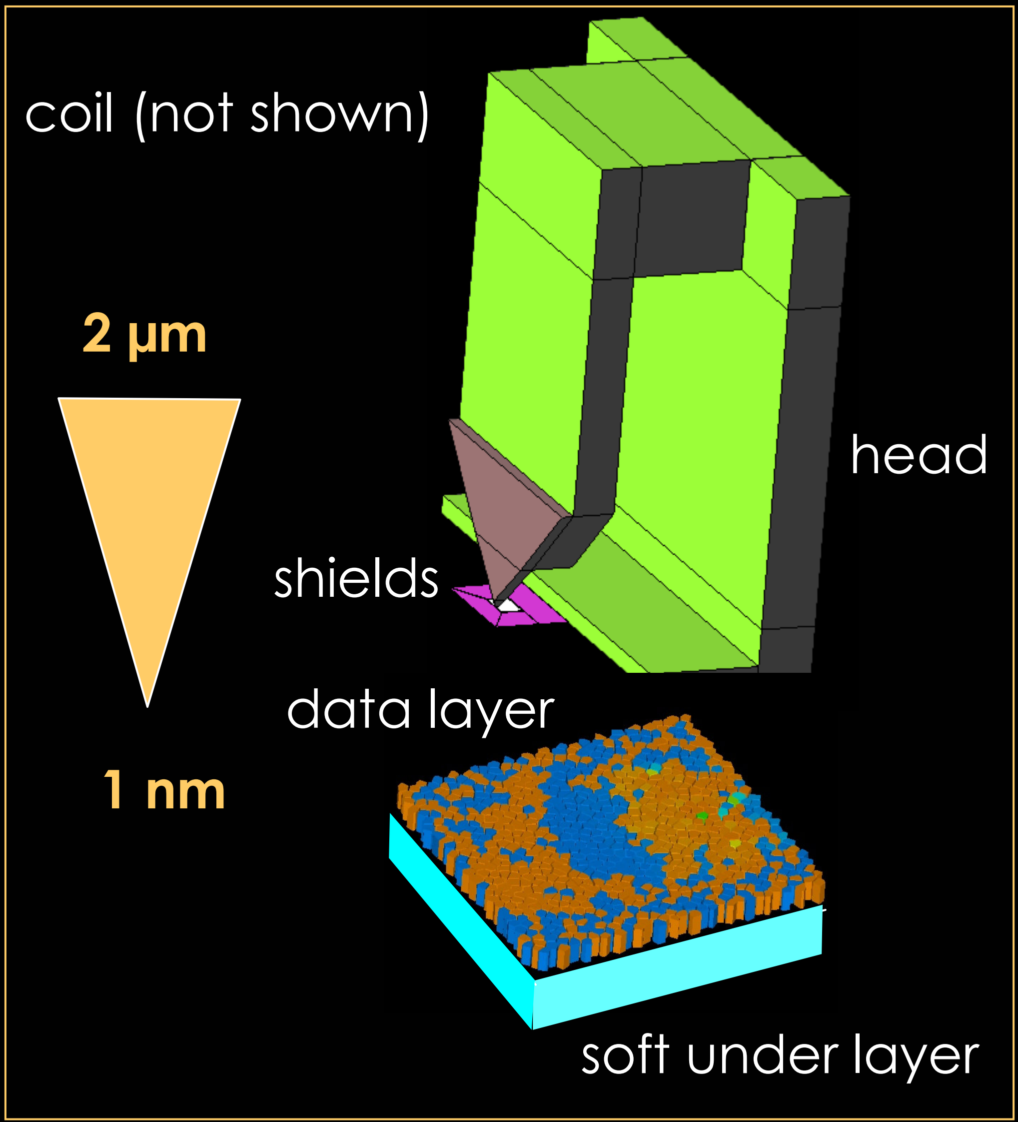




t_{switch} = 65 ps

$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\mathrm{x}\mathbf{H}_{\mathbf{eff}} - \frac{\alpha}{M_s}\mathbf{M}\mathrm{x}\mathbf{M}\mathrm{x}\mathbf{H}_{\mathbf{eff}}$$

Recording simulations

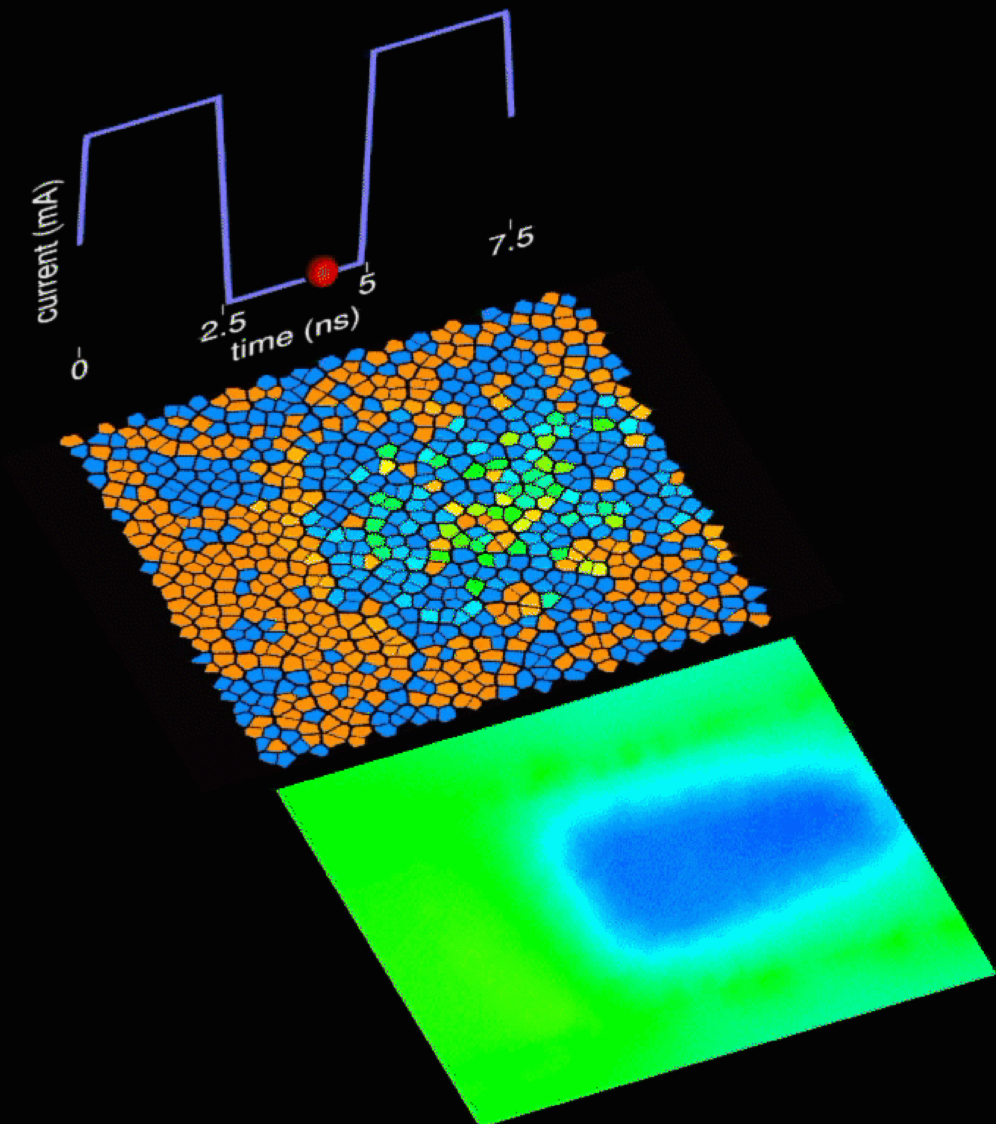


Finite elements
head and soft underlayer magnetization dynamics

Fast BEM methods
hierarchical matrices for all long range interactions

Fast Poisson solvers
interaction of moving parts

Recording of bit transitions



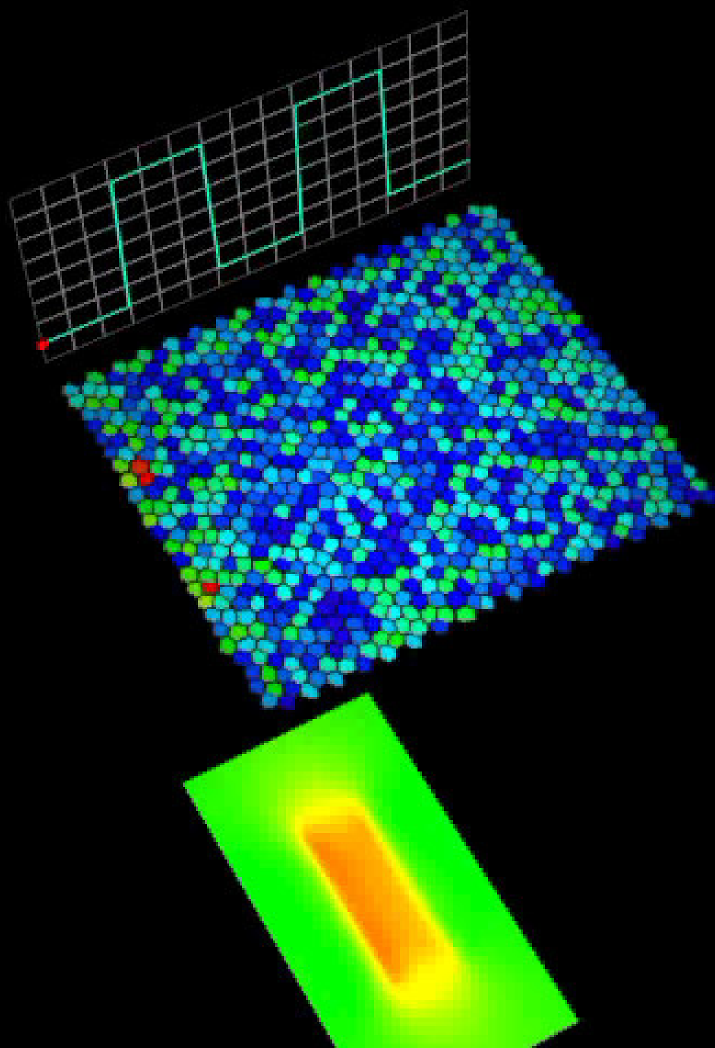
Input current
Current in the coil
as function of time

Data layer
blue **M** points down
red **M** points up

Head field
as seen by the data layer

green zero field
blue **H** points down
red **H** points up

Recording of bit transitions



Input current
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Data layer
blue **M** points down
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as seen by the data layer

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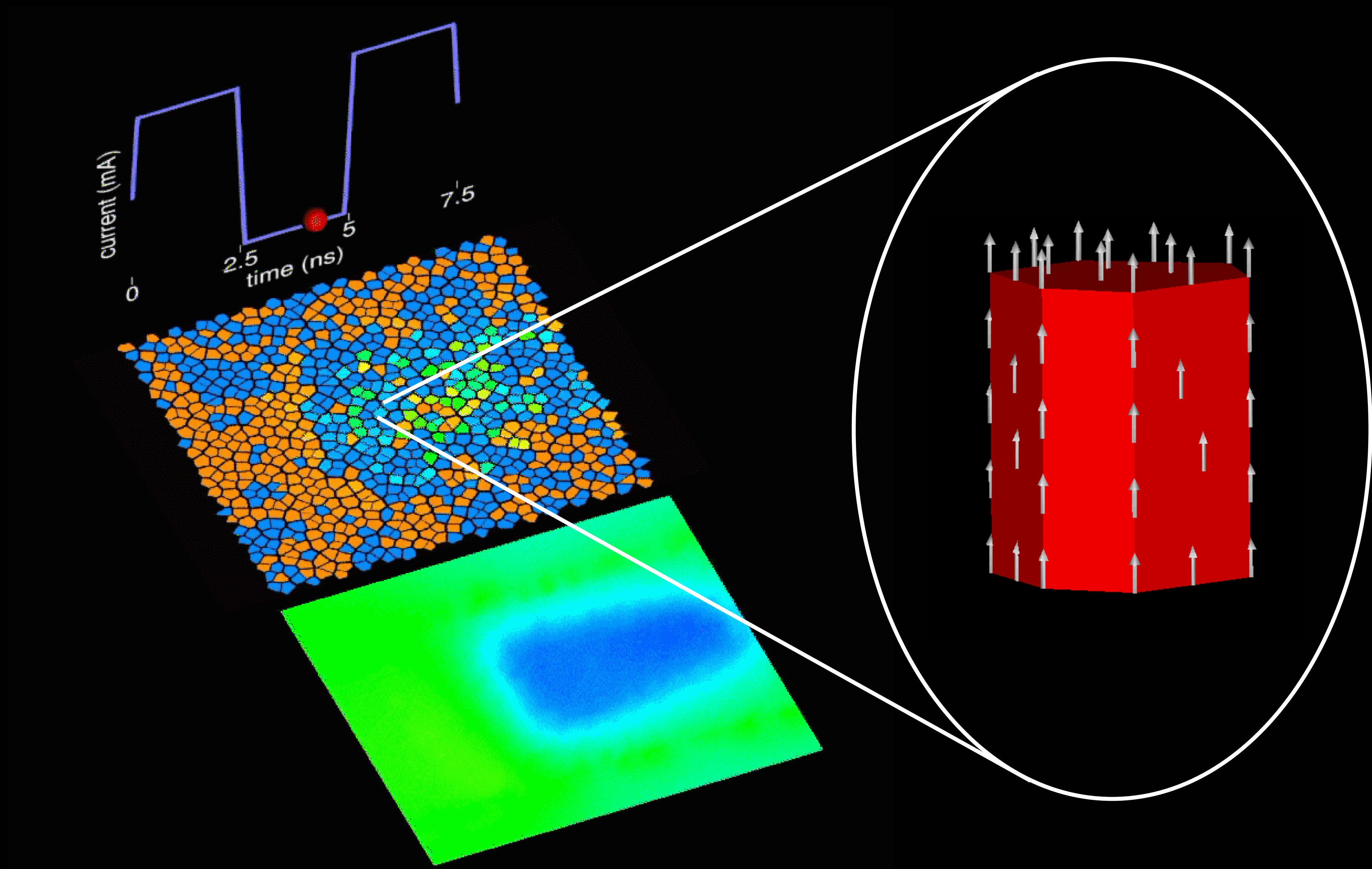
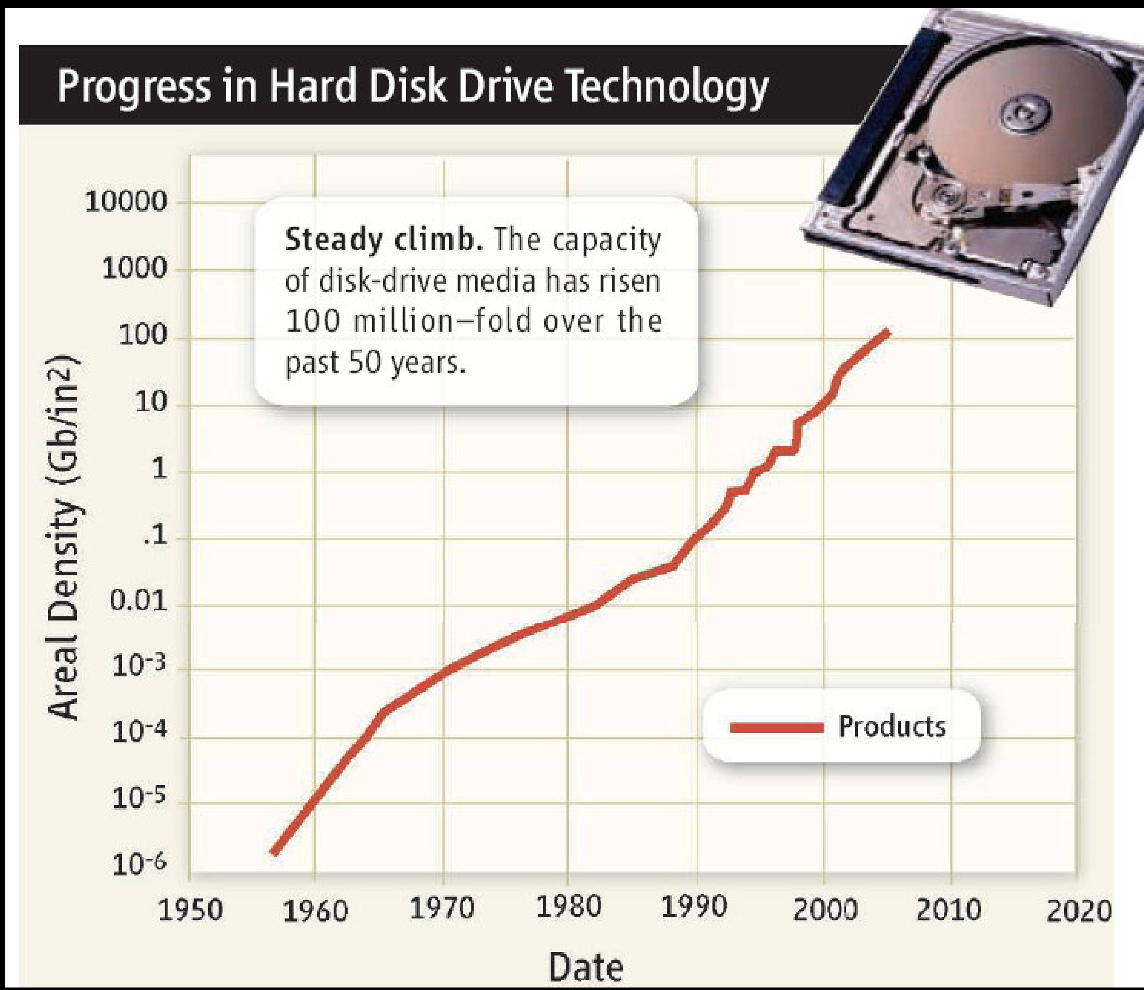


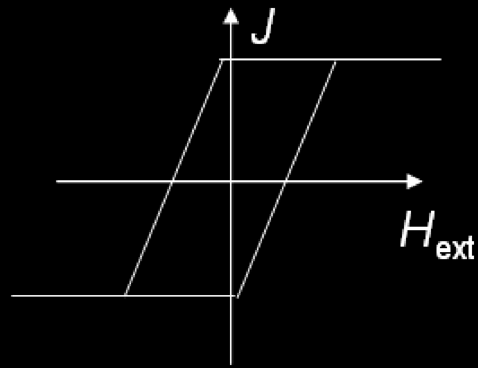
current (mA)
0
2.5
5
7.5
time (ns)

Growth of areal density in recording



- Moor's Law (Gordon E. Moore Co-founder Intel)
- Areal density doubles every 18 month

Trilemma



Writeability:

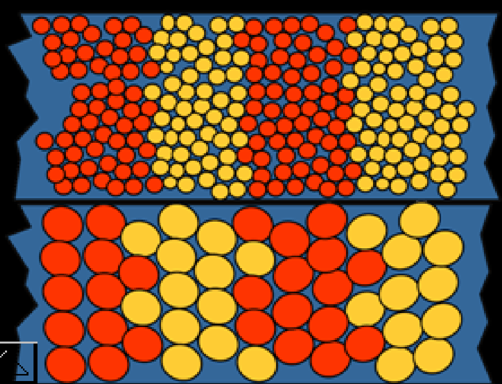
$$H_c = 2K / J_s$$

H_c < 1.3 T

Signal to Noise:

$$SNR \sim \log_{10}(N)$$

small grain V

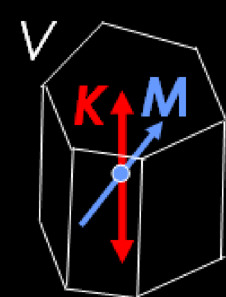


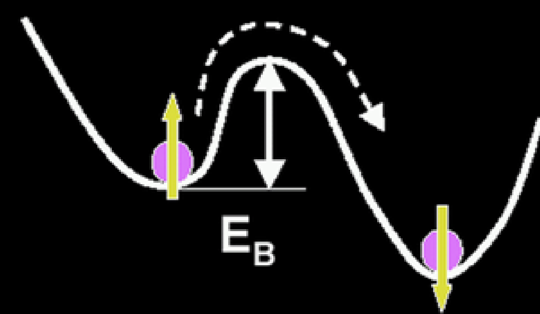
Thermal stability:

$$\Delta E_B = KV$$

high KV ~ 70 $k_b T_{300}$

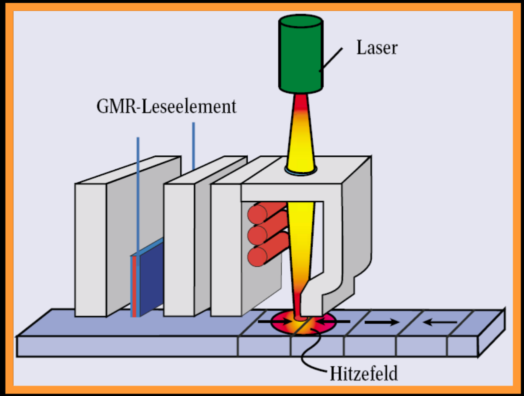
$$\tau = \tau_0 e^{\Delta E_B / k_B T}$$



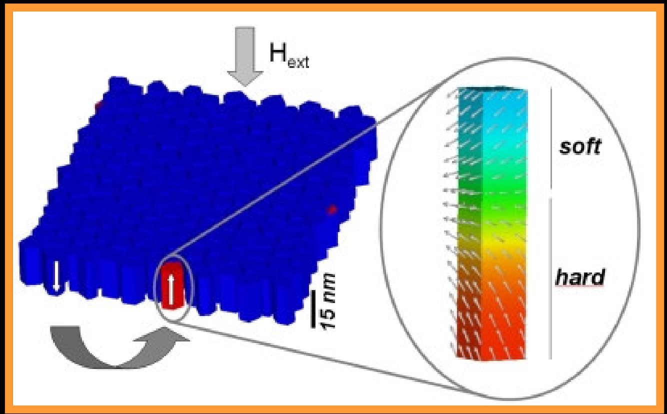


Futur Technologies

Heat assisted recording [1]



Exchange spring media [2]
ECC media [3]

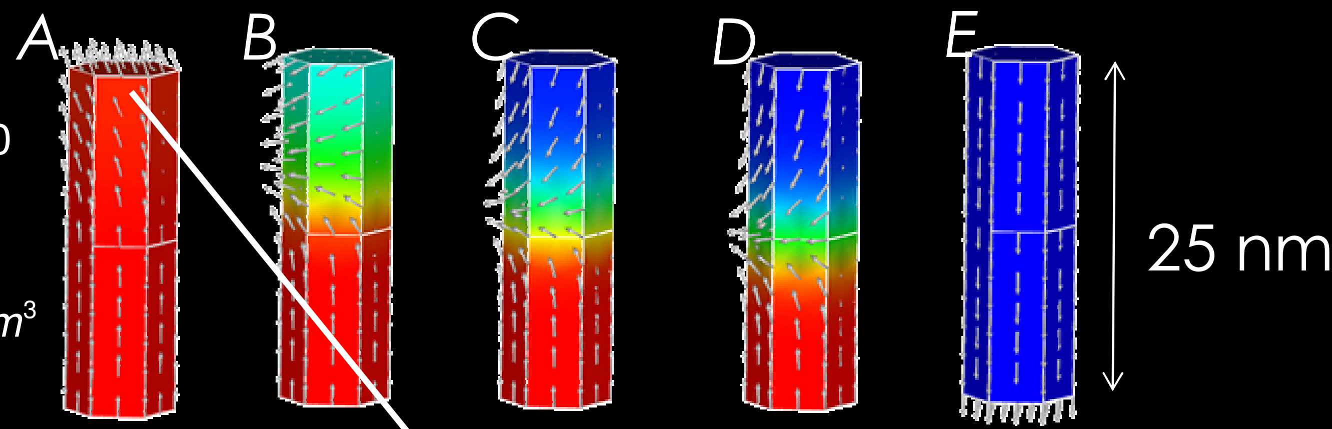


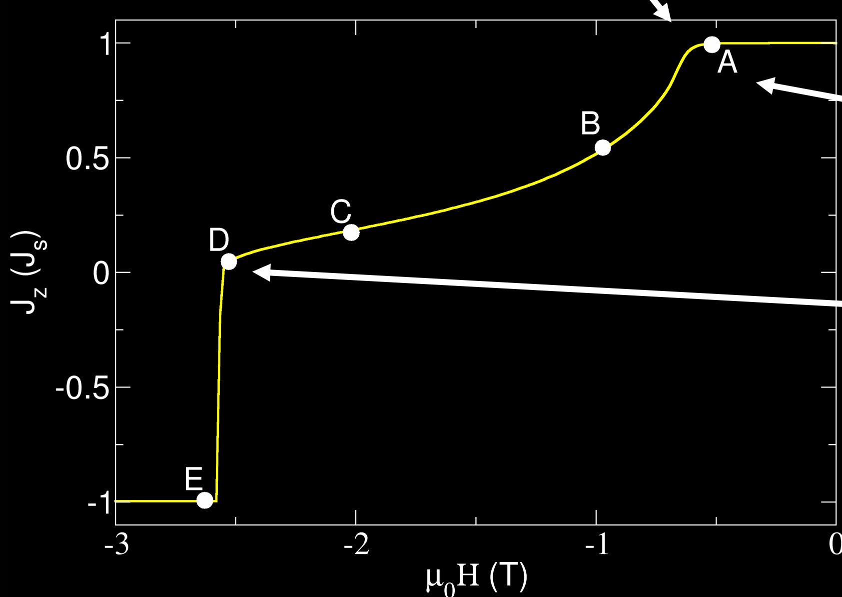
[1] RUIGROK, J. J. M., et al J. Appl. Phys., 87, 5398-5403, 2000.
[2] D Suess et al. Appl. Phys. Lett., vol. 87, Art. No. 012504, 2005.
D. Suess, US- Patent, 424,859, pending.
[3] R Victora, IEEE Trans Magn 41 (2005) 573

Exchange Spring Media

$K_1 = 0$

$K_1 = 2\times10^6\, J/m^3$





$$H_n = \frac{2K_{soft}}{J_s} + \frac{2A\pi^2}{4t_s^{\,2}J_s} \quad [1]$$

$$H_p = \frac{1}{4}\times\frac{2(K_{hard} - K_{soft})}{J_{hard}} \quad [2]$$

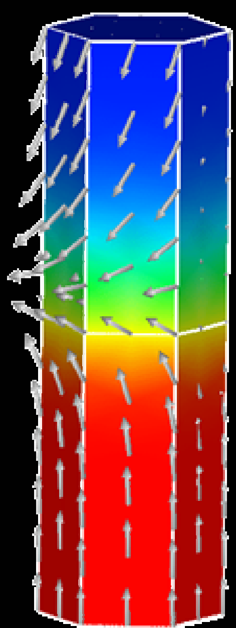
$$H_{switching} = \max(H_p, H_n)$$

[1] H. Kronmüller and H. R. Hilzinger, J. Magn. Magn. Mater. 154, 3 (1976).

[2] H. Kronmuller and D. Goll, Physica B, vol. 319, pp. 122-126 (2002).

Exchange Spring Media

K_S
J_S
A_S



K_H
J_H
A_H

$J_s = J_H$

$A_s = A_H$

$$H_n = \frac{2K_{soft}}{J_s} + \frac{2A\pi^2}{4t_s^{\,2}J_s}$$

$$H_p = \frac{1}{4} \times \frac{2(K_{hard} - K_{soft})}{J_{hard}}$$

$$\boxed{H_{switching} = \max(H_p, H_n)}$$

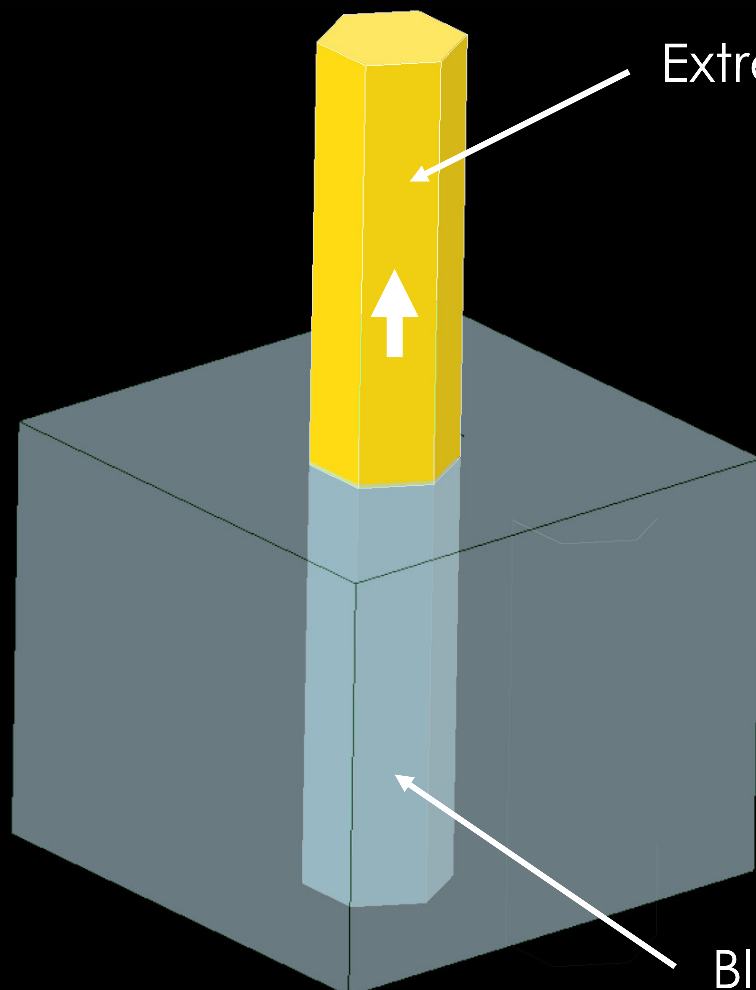
$$H_c = \frac{1}{4} \times \frac{2K_{hard}}{J_{hard}} \qquad K_s = 0 \quad [1]$$

$$H_c = \frac{1}{5} \times \frac{2K_{hard}}{J_{hard}} \qquad K_s = K_H / 5 \quad [2]$$

[1] A. Aharoni, Phys. Rev. 119, 127 (1960).

[2] F. B. Hagedorn, J. Appl. Phys. 41, 2491 (1970).

Ultimate Limit



$H_a = H_s = 8$ T

Which field do I need to switch it ?

Ultimate Limit

$$H_{switching} \to 0$$

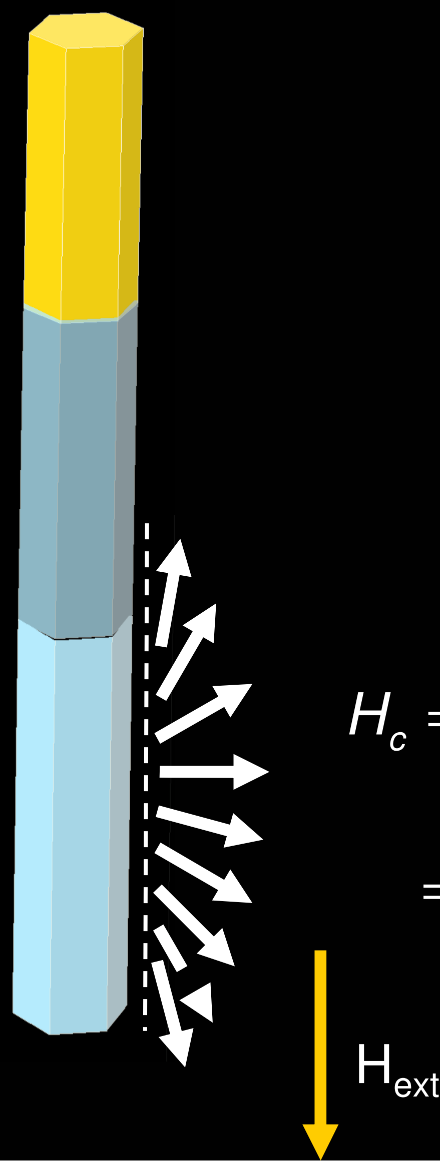
The FePt grain can be switched with aribitary small fields !!!

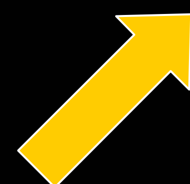
Trilayer

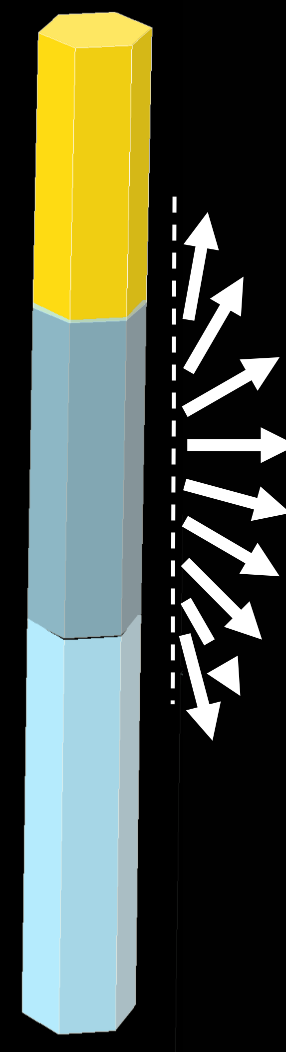
$K_1 = K_H$

$K_2 = K_H / 2$

$K_3 = 0$







$$H_c = \frac{1}{4} \times \frac{2(K_2 - K_3)}{J_{hard}}$$

$$= \frac{1}{8} \times \frac{2K_H}{J_{hard}}$$

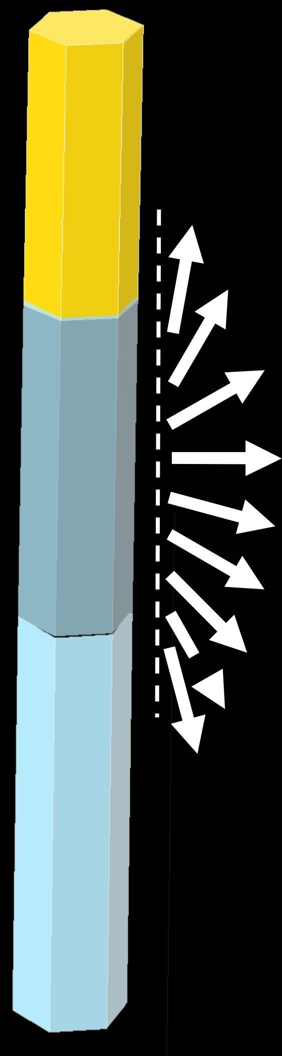
D. Suess, Appl. Phys. Lett ***89****, 113105 (2006)*

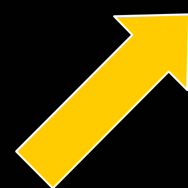
Trilayer

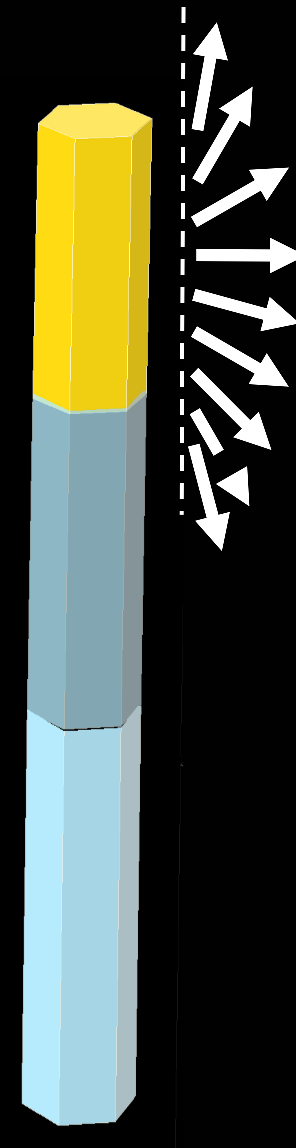
$K_1 = K_H$

$K_2 = K_H / 2$

$K_3 = 0$







$$H_c = \frac{1}{4} \times \frac{2(K_1 - K_2)}{J_{hard}}$$

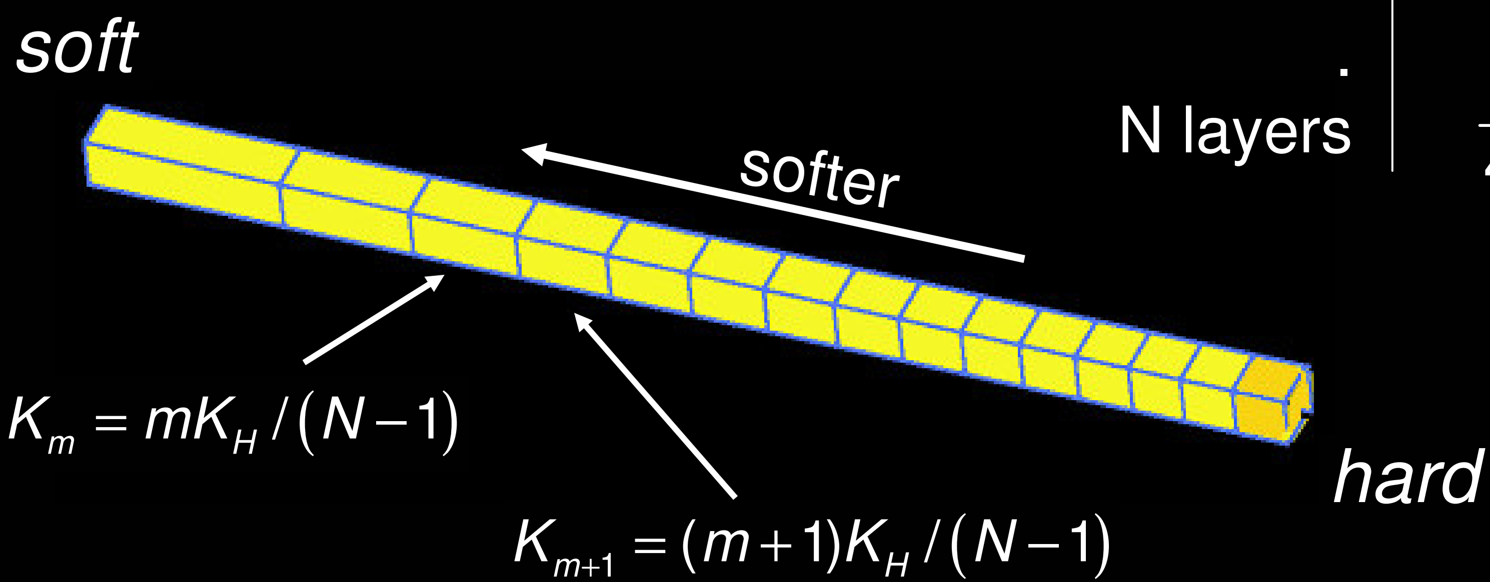
$$= \frac{1}{8} \times \frac{2K_H}{J_{hard}}$$

Ultimate Limit

$$H_c = \frac{1}{4} \times \frac{2(K_2 - K_3)}{J_{hard}}$$

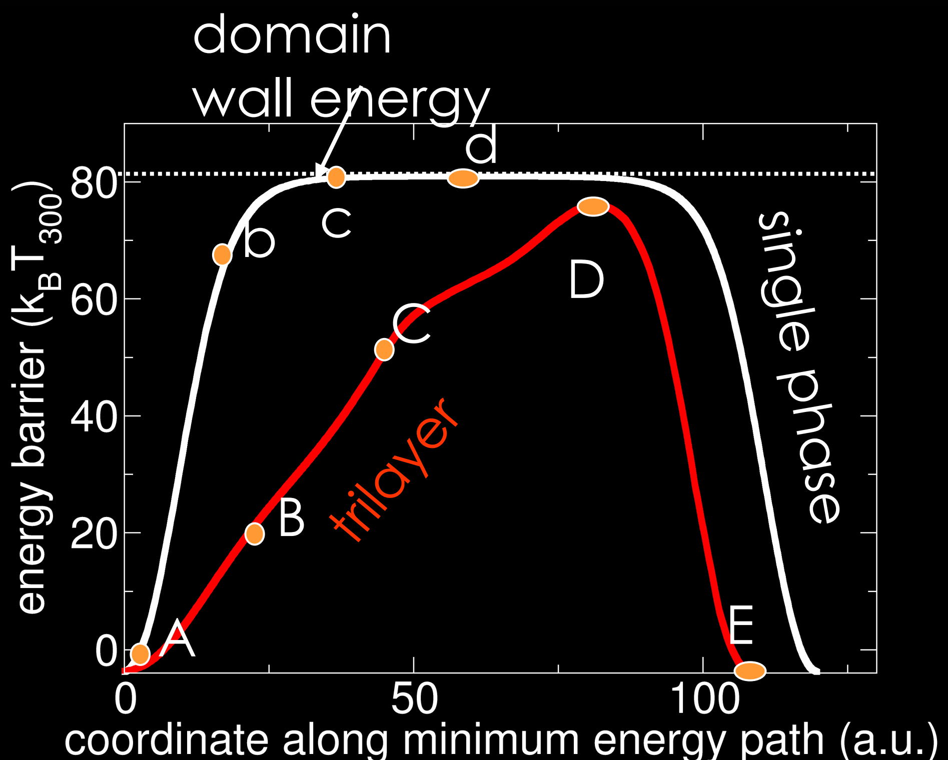
$$= \frac{1}{4(N-1)} \times \frac{2K_H}{J_{hard}}$$

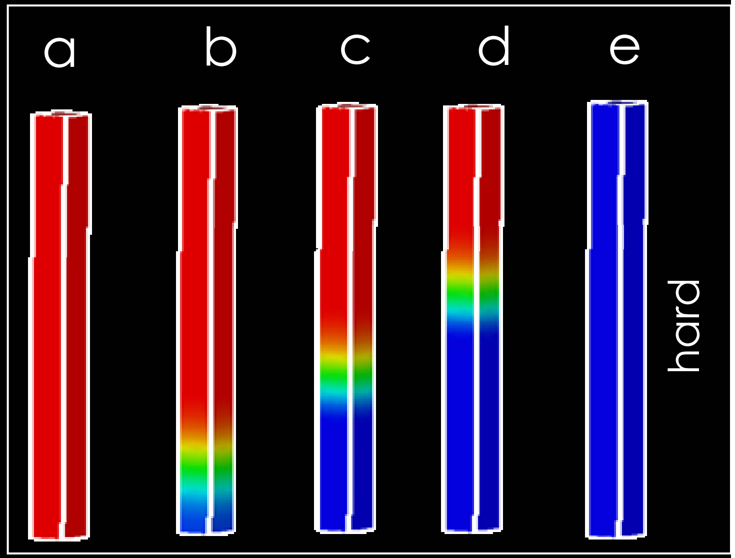
Struktur	Reduktion H_c	
single	1	1
bilayer	1/4	(1/5)
trilayer	1/8	(1/9)
4 layers	1/12	
.		
.		
N layers	$\frac{1}{4(N-1)}$	

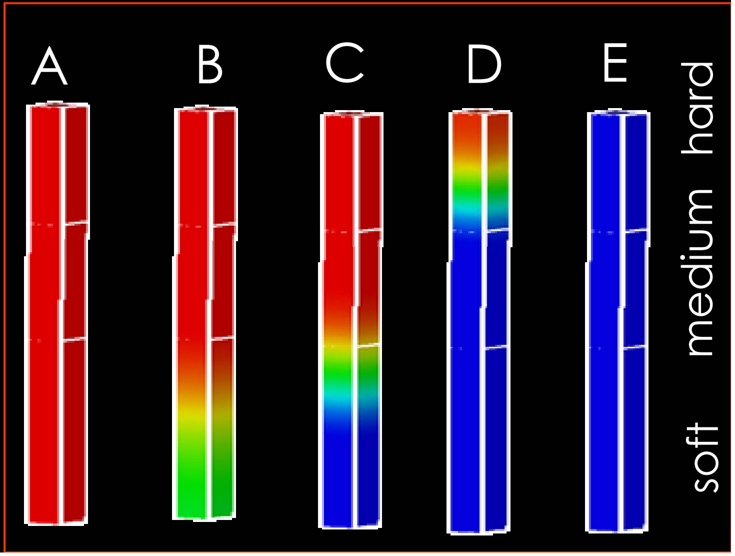


D. Suess, APL ***89****, 113105 (2006)*

Energy Barrier Comparission



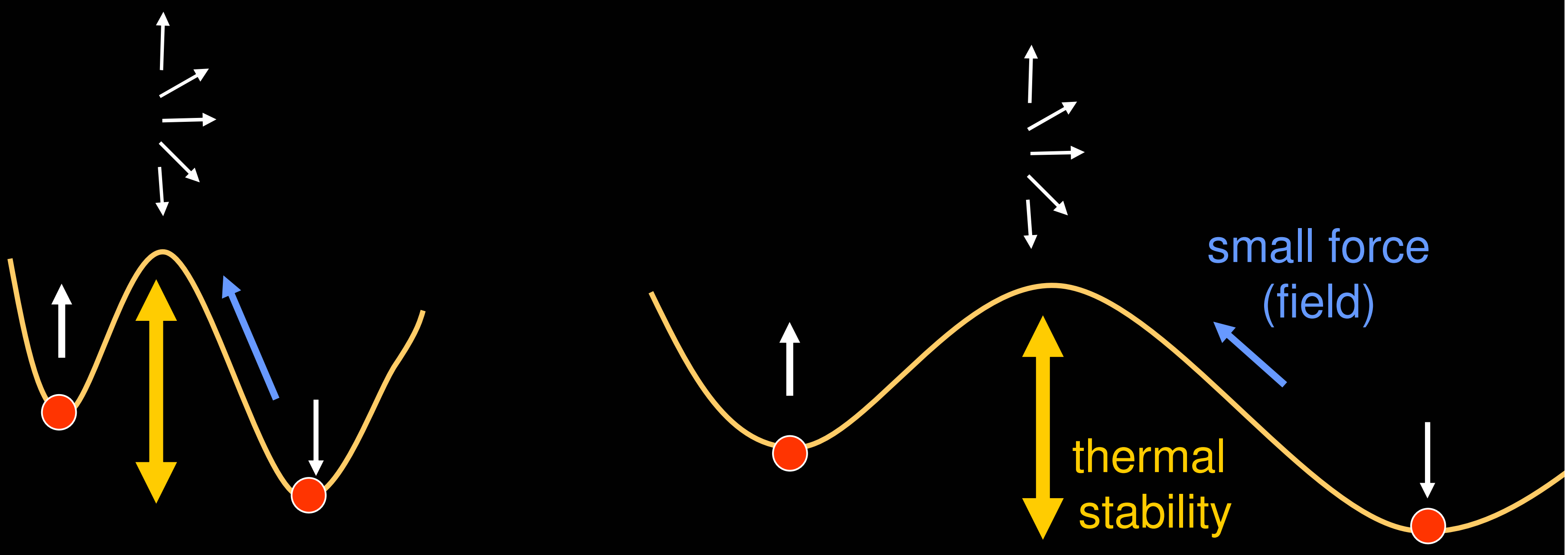




Trilayer has same energy barrier as single phase media

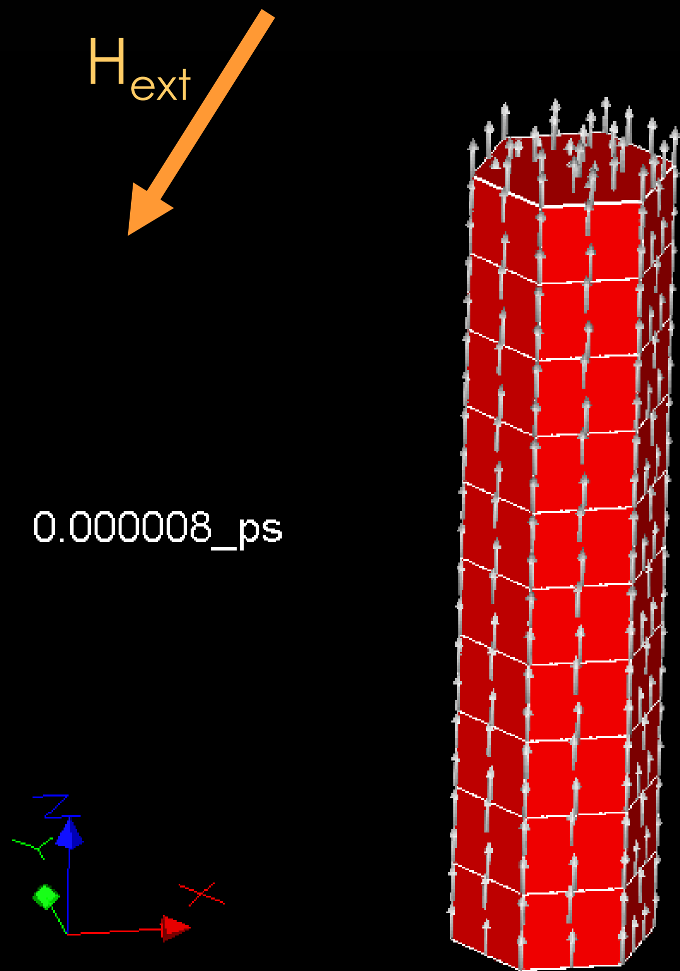
$$\Delta E_{max} = 4r^2\pi\sqrt{AK_{hardest}}$$

Conceptional Picture – Particle in potential well



- The particle needs the **same thermal activation** to overcome the energy well
- **The force** to push the particle from one minimum to the other depends on the slope of the energy landscape
- The microstructure allows to change the energy landscape

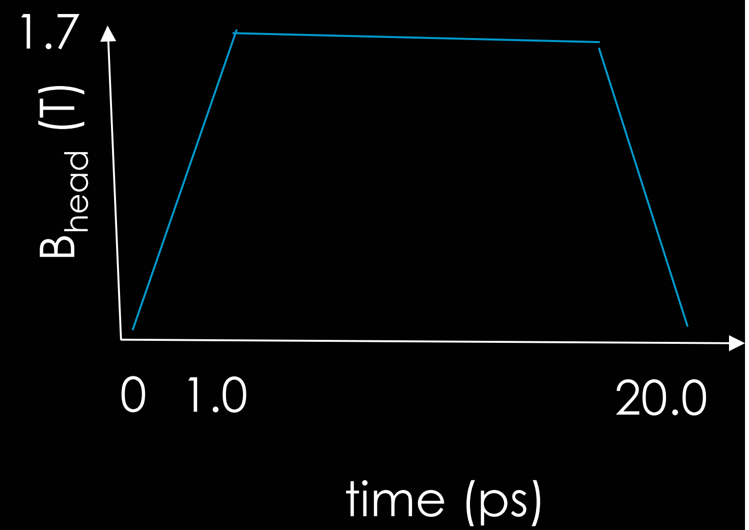
Reversal



K_1 = 0.12

K_1 =1.0

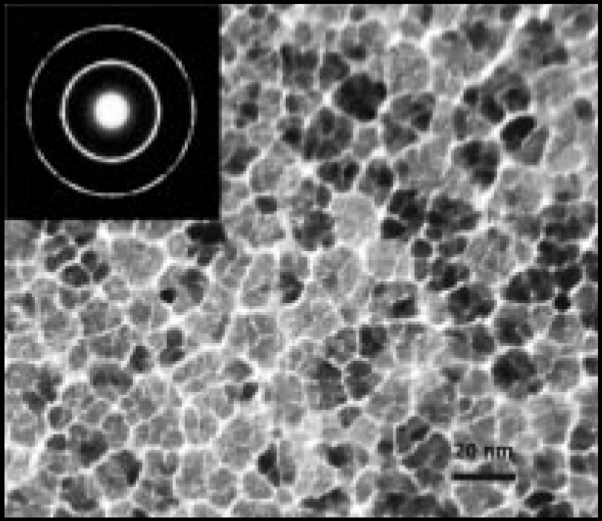
K_1 =2.0

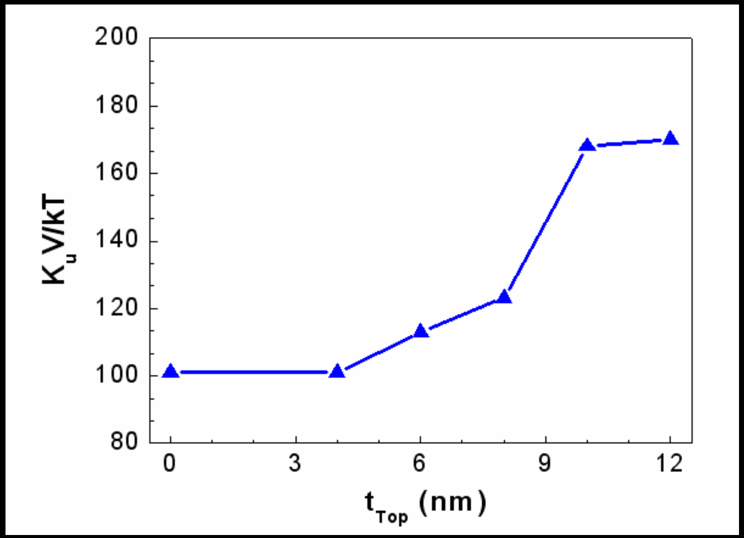


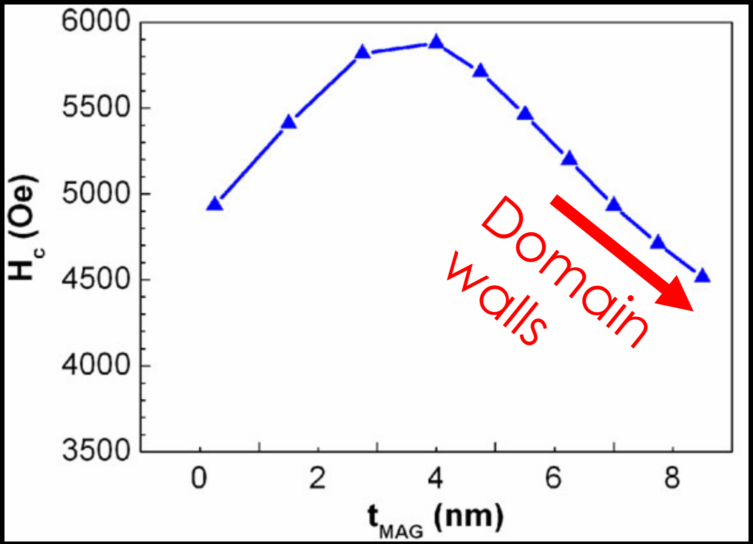
Units of K_1 are MJ/m^3
damping = 0.02
J_s=0.5 T
A = 10^{-11} J/m

Experimental Data

- CoCrPtO bilayers
- 11 nm thick hard layer
- soft layer with different thickness





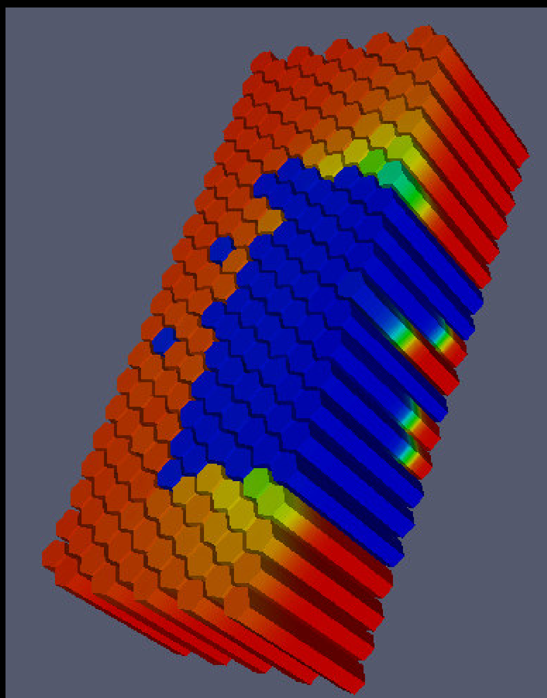


[1] H. S. Jung, E. M. T. Velu, S. S. Malhotra, U. Kwon, D. Suess, G. Bertero, IEEE Trans. Mag. 43 (2007) 2088.
[2]D. Suess, S. Eder, J. Lee, et al. Phys. Rev. B 75, (2007) 174430.

Limit of Graded media

5 – 10 Tbit/inch² Design
(media today: 512 Gbit/inch²)

Tapered head / Planer head
perpendicular field (maximum) 1.8 T
(minimum) 1.0T

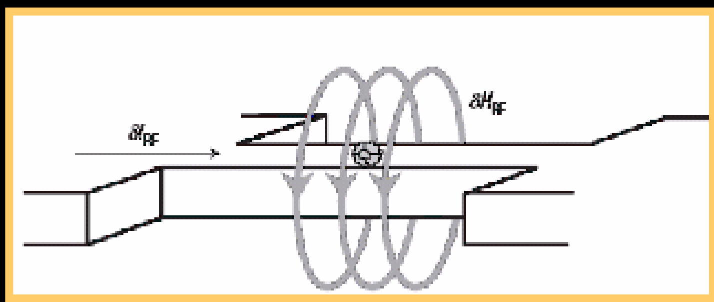


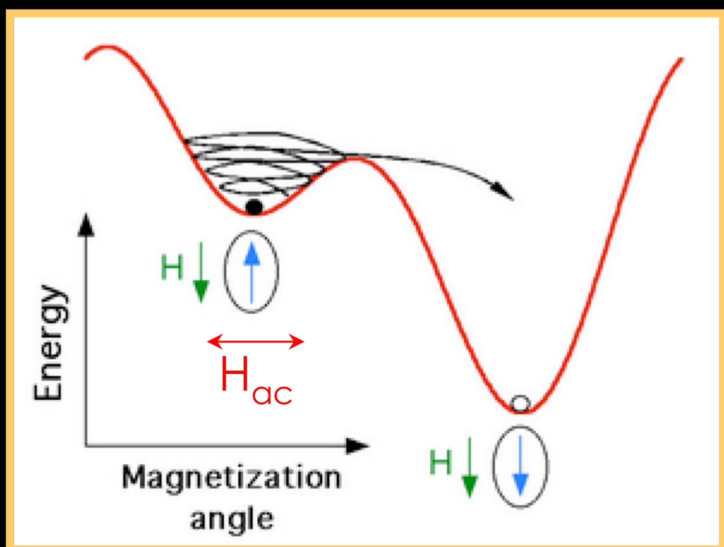
Multilayer media

grain size	**3.2 nm**
thickness	20 nm
J_s	0.8 T
K(z)	$\alpha\ z^{1.5}$
anisotropy	$0.1 MJ/m^3$ to $6.6 MJ/m^3$
Energy barrier	$60\ k_B T$

Hope that the area density can be increased up to a factor 10 !

Microwave assisted switching





C Thirion, W Wernsdorfer D Mailly,
Nature Materials 2, 524 (2003)

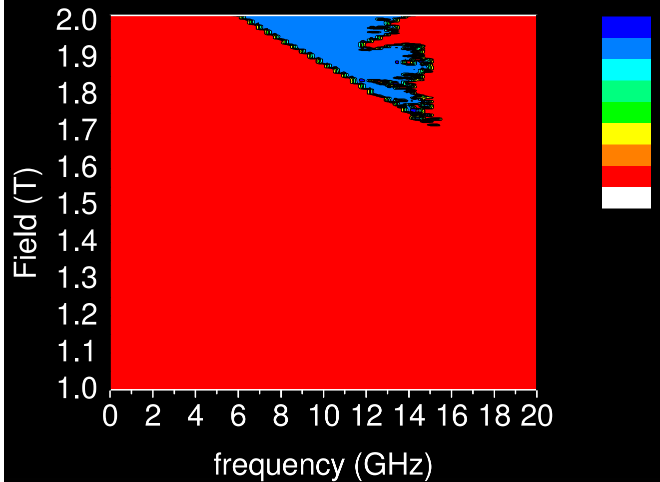
External field
Raises the energy level of one magnetic state

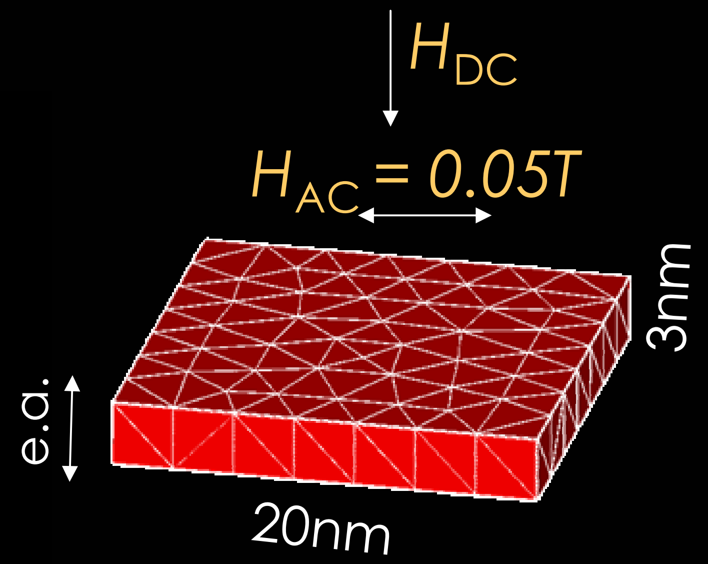
Rotating field
creates large angle precession if in resonance

Switching
If energy gain is high enough to overcome the barrier

Microwave Assisted Recording

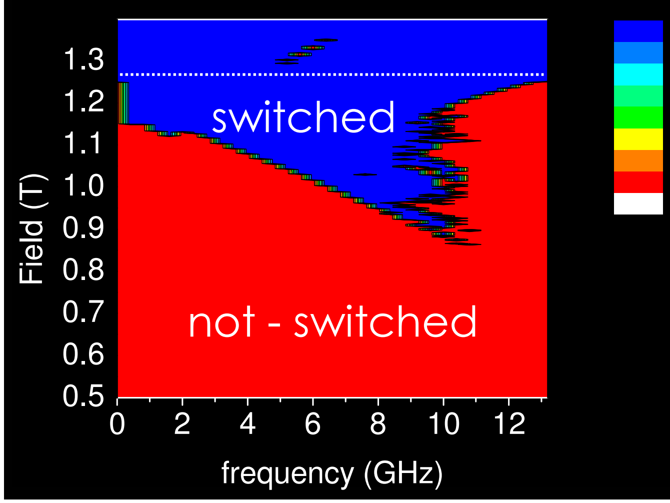
K_1=0.67 MJ/m³:



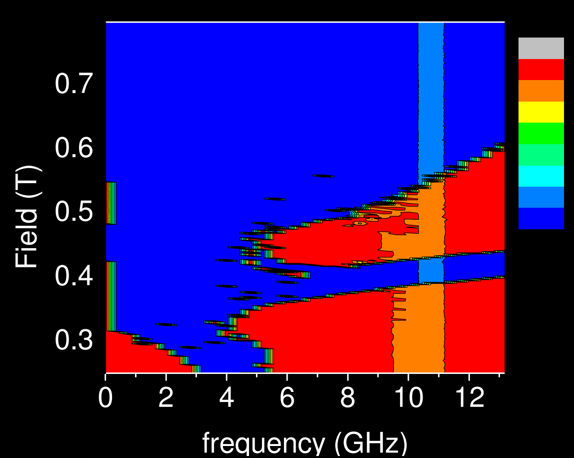


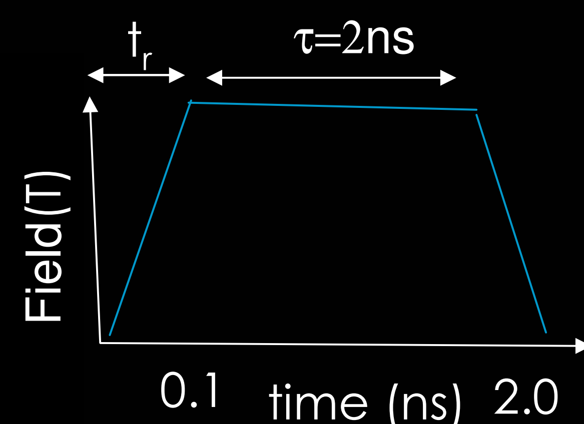
alpha = 0.05
Js = 0.6T
A = 1e-11 J/m

K_1=0.42 MJ/m³:



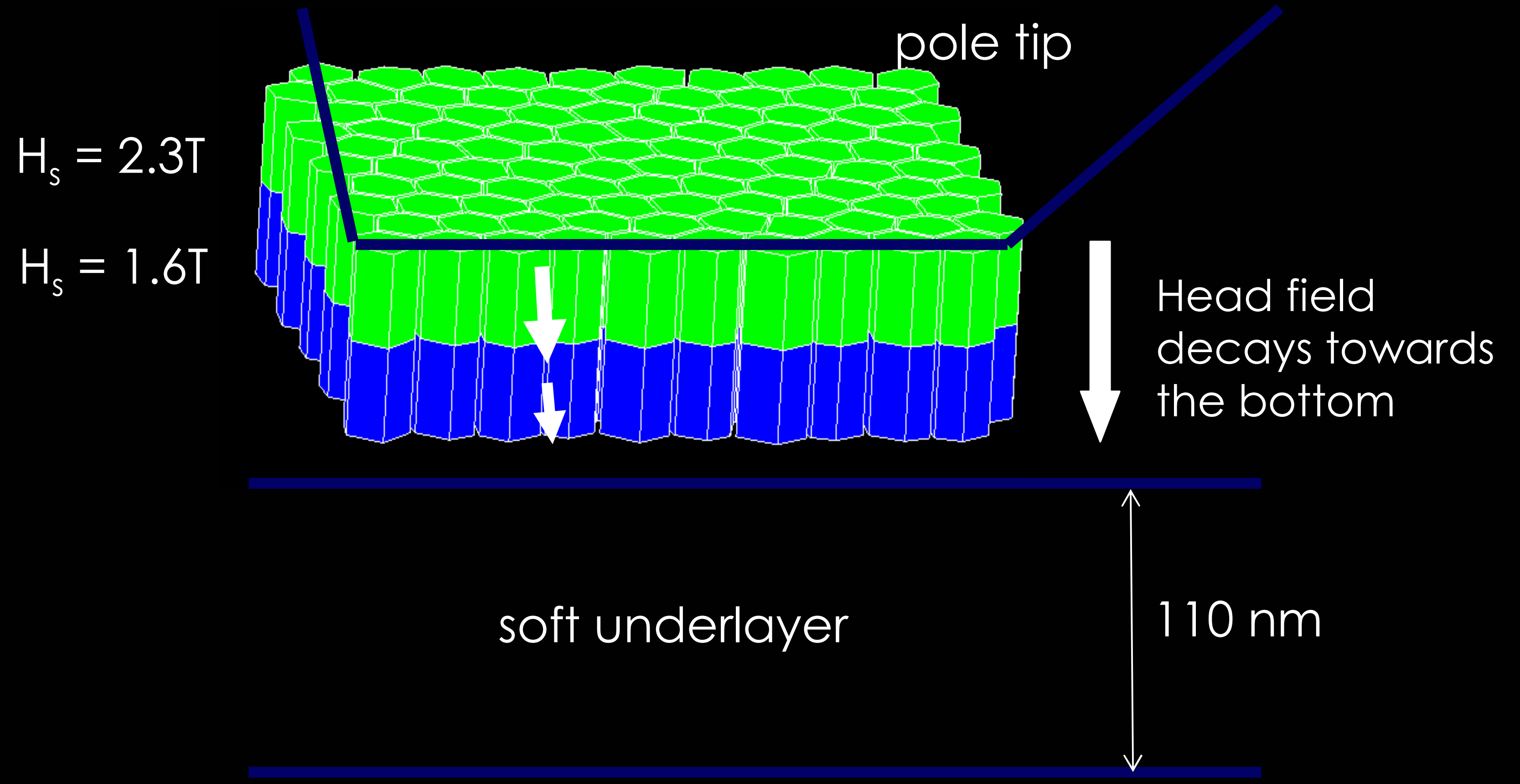
K_1=0.2 MJ/m³:





3D Storage

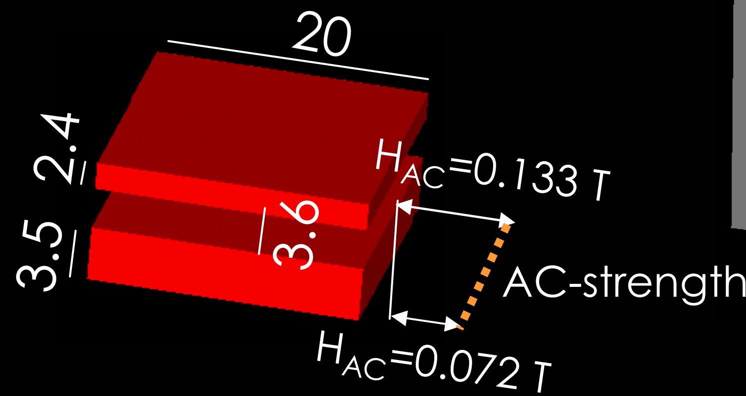
- Anisotropy in each layer adjusted to match head field
- Due to different anisotropy each layer has different resonance frequency

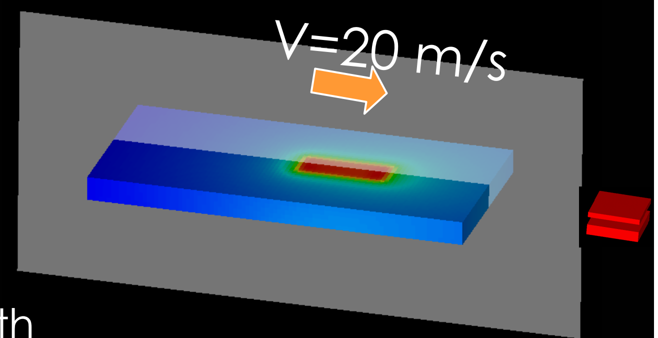


D Suess, TU Vienna
T Schrefl, Univ Sheffield

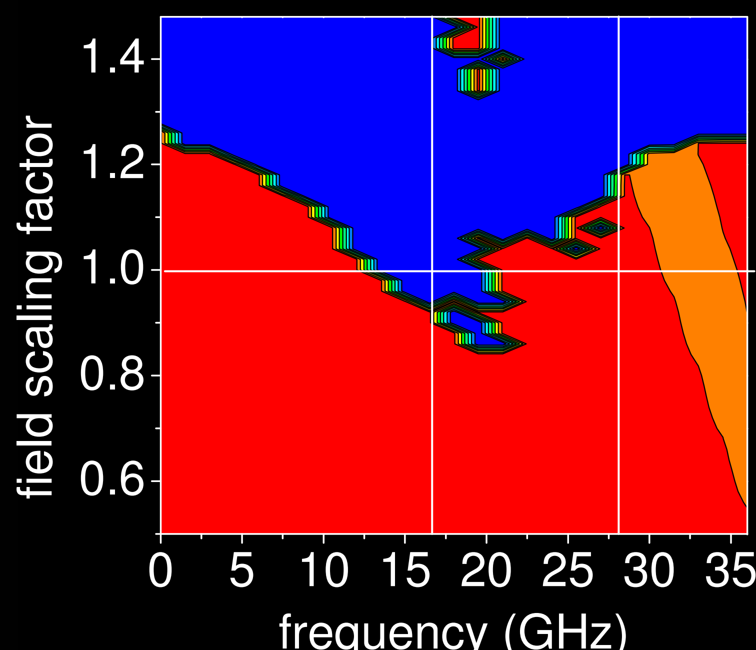
Phase Diagrams

J_s = 0.2 T
A = 10^{-11} J/m
$K_{1,top}$ = 0.210 MJ/m³
$K_{1,bottom}$ = 0.142 MJ/m³
α = 0.05
(ΔE_{top} = 46 $k_b T_{300}$)
(ΔE_{bottom} = 48 $k_b T_{300}$)

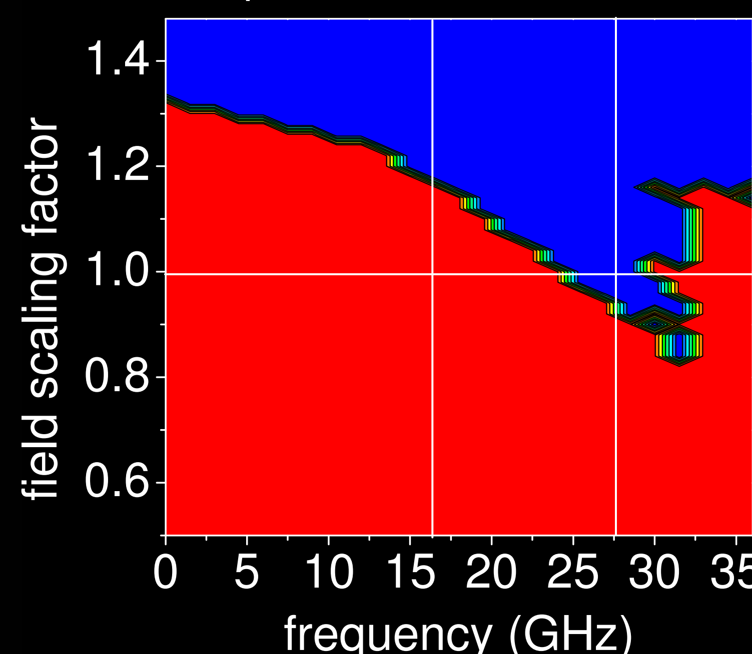




Bottom:

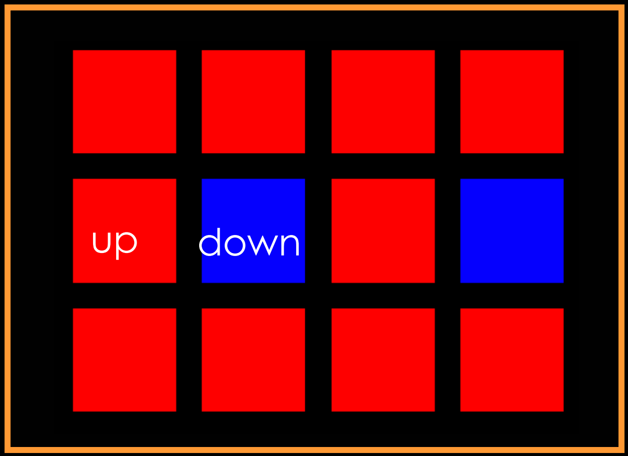


Top:

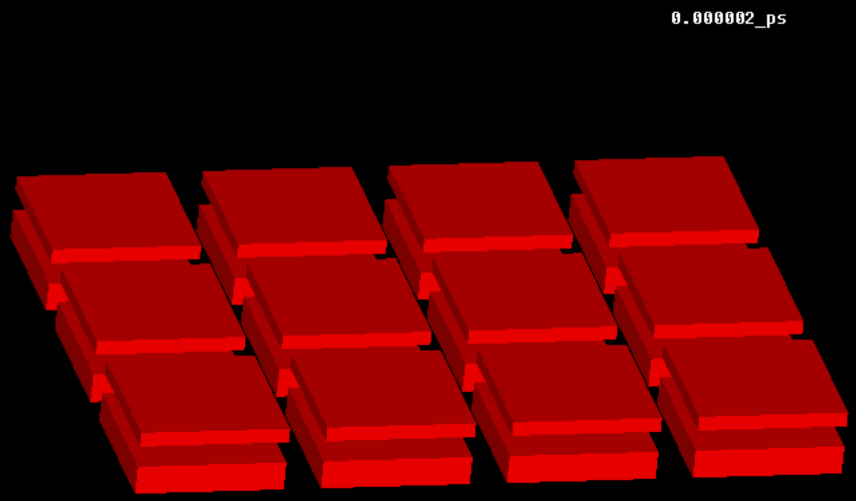


Recording: all up

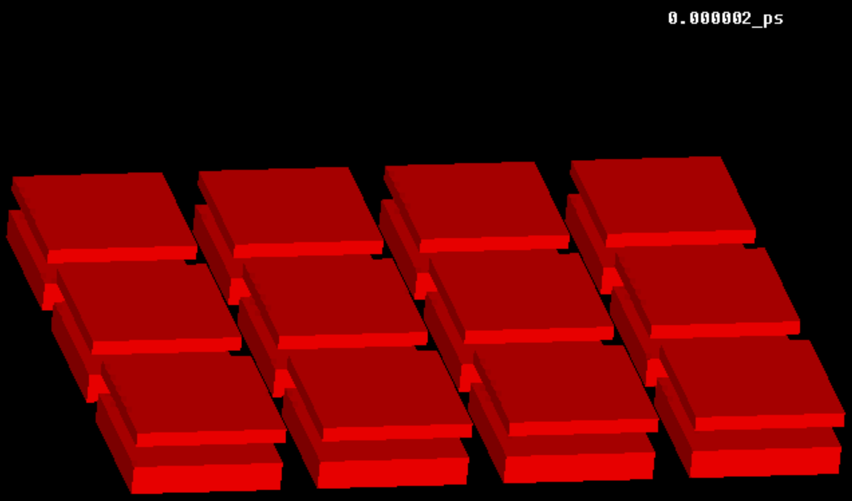
Want to write
Up-down-up-down
(red-blue-red-blue)



f = 18 GHz

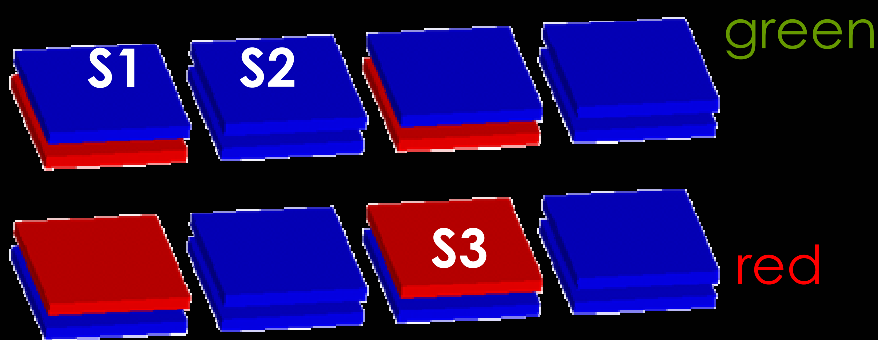


f = 28 GHz

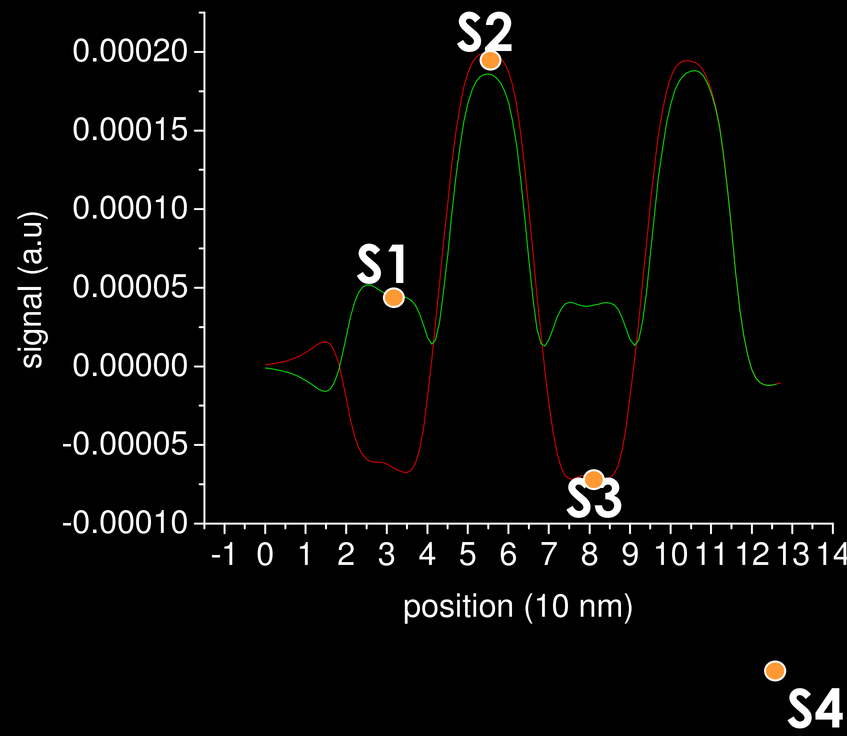


Readback

All 4 states give a clear different signal
(distance between signal almost same)

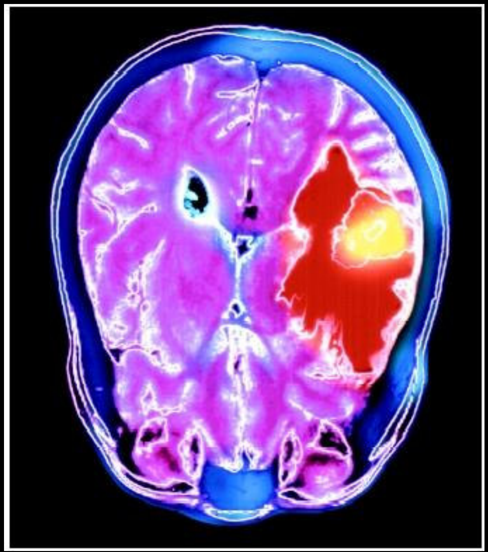


(S4 symmetric to S2)



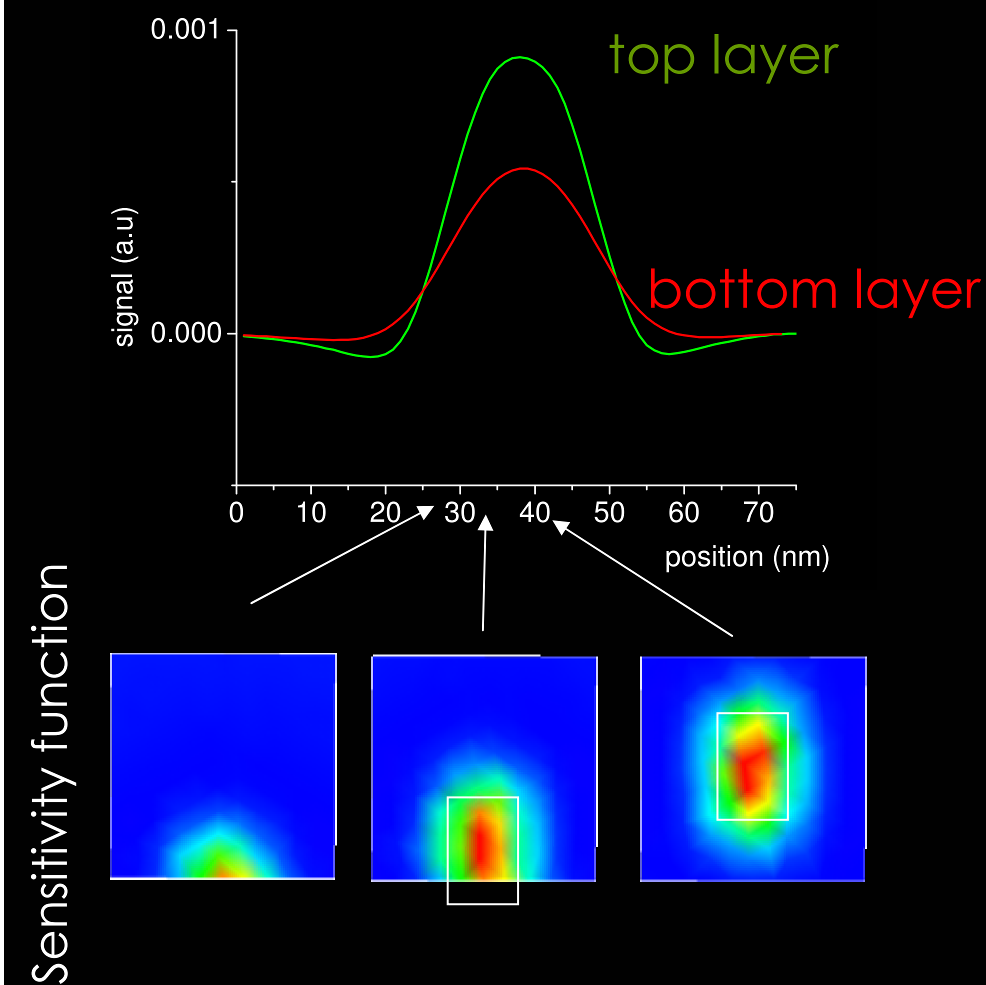
MRI (Magnetic Resonance Image)

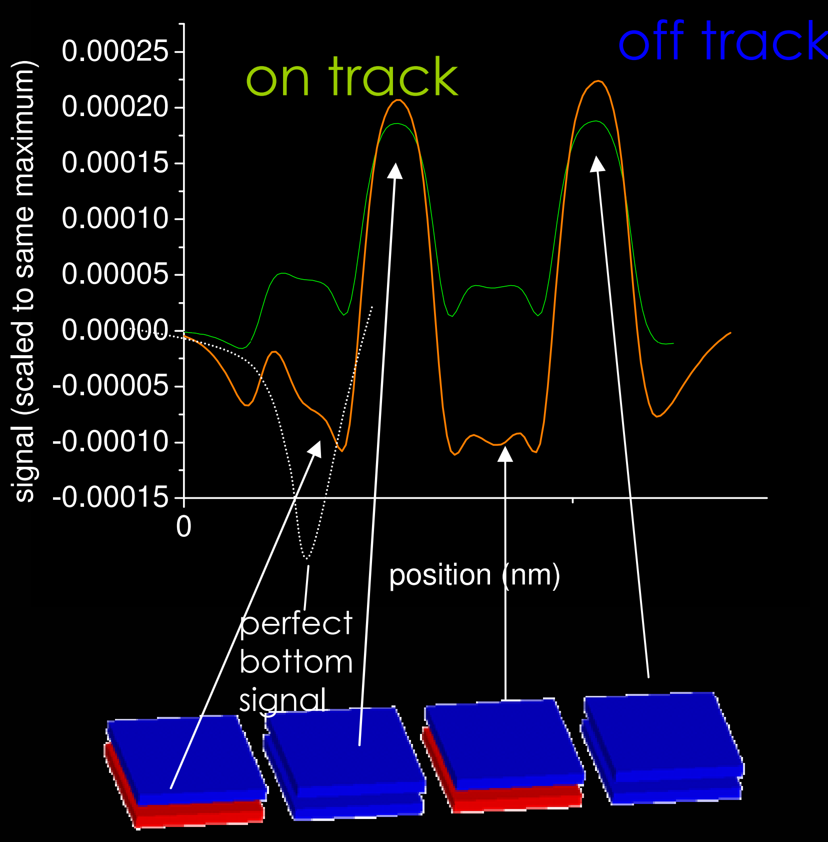
- Object is sensed from different direction



- Using 2 heads with different sensitivity in the top and bottom layer
- Moving the head in the cross – track direction

Readback – off track





Reading off track

more sensitivity to the bottom layer !

Summary

Multilayer Media - Exchange Spring Media

- Superparamagnetic limit can again be extended
- Reproducible switching has fast as 5 ps
- Thermal stability and writeability can be decoupled

Multilayer recording

- 3D concepts of recording on the basis of microwave assisted recording
- Different resonance condition in different layer