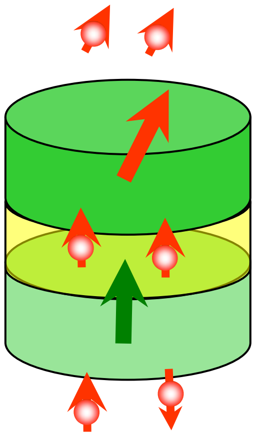
Nancy-Université

Institut Jean Lamour

Spin transfer torque in nanopillar spin valve with perpendicular magnetic anisotropy

S. Mangin

Nanomagnetism & spin-tronic team,
http://www.lpm.u-nancy.fr/nanomag/



Spintronic / Nanomagnetism

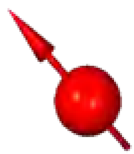
electron

magnetic nanostructure

mass

charge

spin



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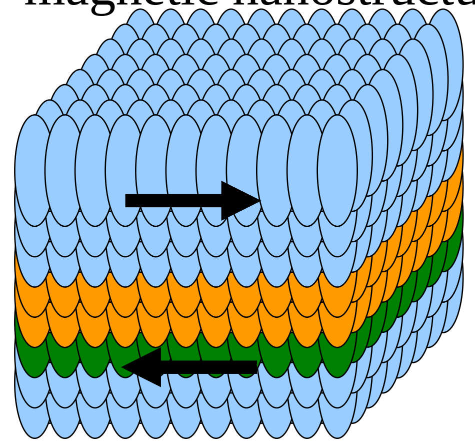


➔New phenomena

magnetization ➔ spin

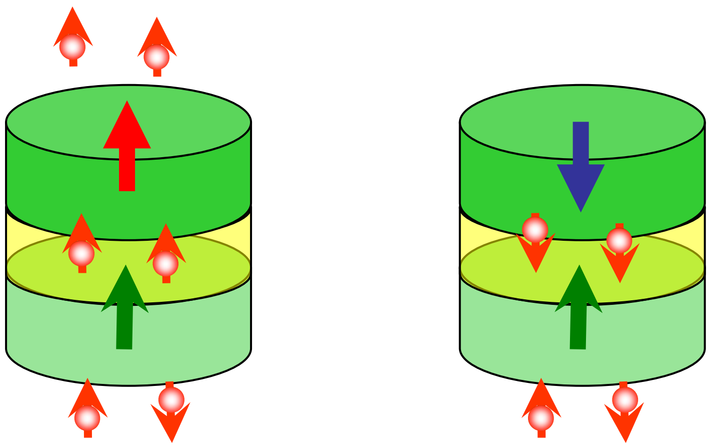
- Giant magnetoresistance (GMR)
- Tunneling magnetoresistance (TMR)
- Spin precession

$$\frac{d\vec{L}_e}{dt} = -\frac{d\vec{L}_M}{dt}$$

spin ➔ magnetization

Spin Transfer Torque (STT)

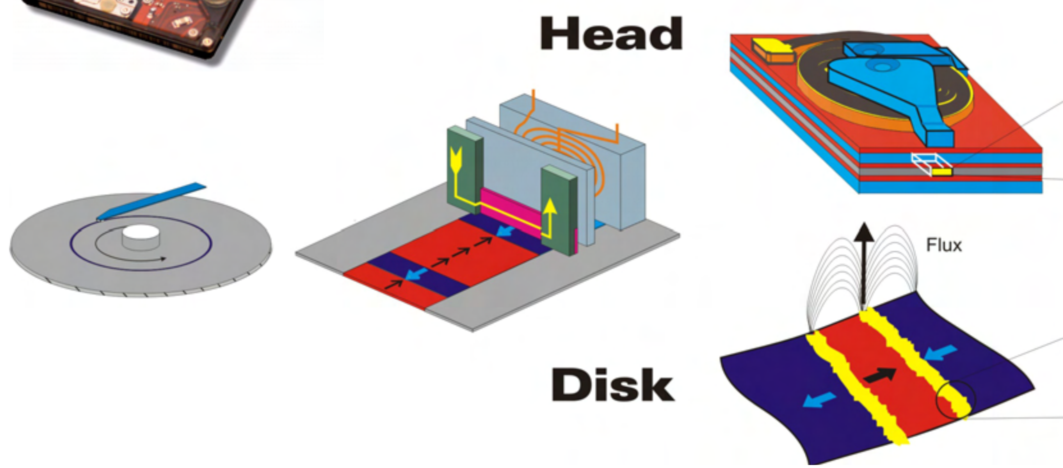
Giant MagnetoResistance



R(P) < R(AP)

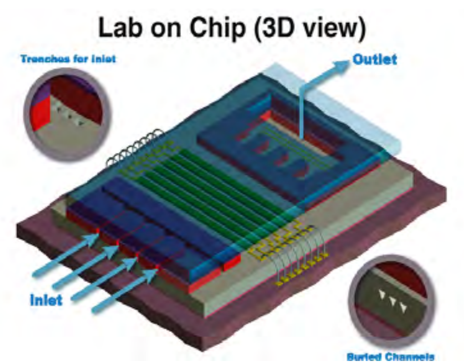
A. Fert & P. Grünberg
discovered in 1988
Nobel prize in 2007

Data Storage

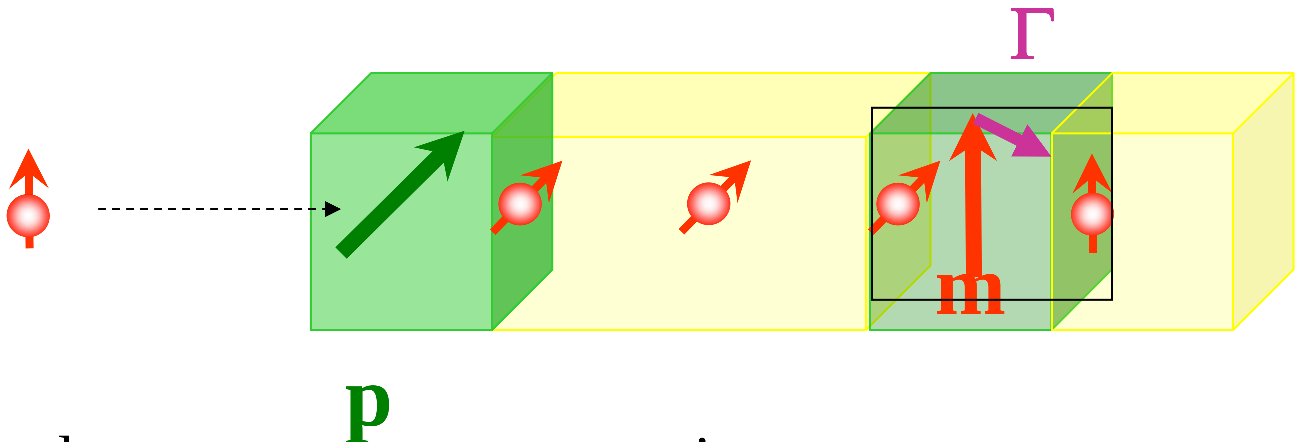


Magnetic sensors

Magnetic memories



Spin Transfer Torque



- Angular momentum conservation

$$\frac{d\mathbf{L}_e}{dt} = -\frac{d\mathbf{L}_m}{dt}$$

- Spin Transfer torque

$$\mathbf{\Gamma}_{\mathrm{m}} = \frac{\mathrm{d}\mathbf{L}_{\mathrm{e}}}{\mathrm{dt}}$$

$$\mathbf{\Gamma}_{\mathbf{m}} = \beta\, \mathbf{I}\left(\mathbf{m} \times \left(\mathbf{m} \times \mathbf{p}\right)\right)$$

J. C. Slonczewski, J. Magn. Magn. Mater. ***159****, L1 (1996).*
L. Berger, Phys. Rev. B ***54****, 9353 (1996).*

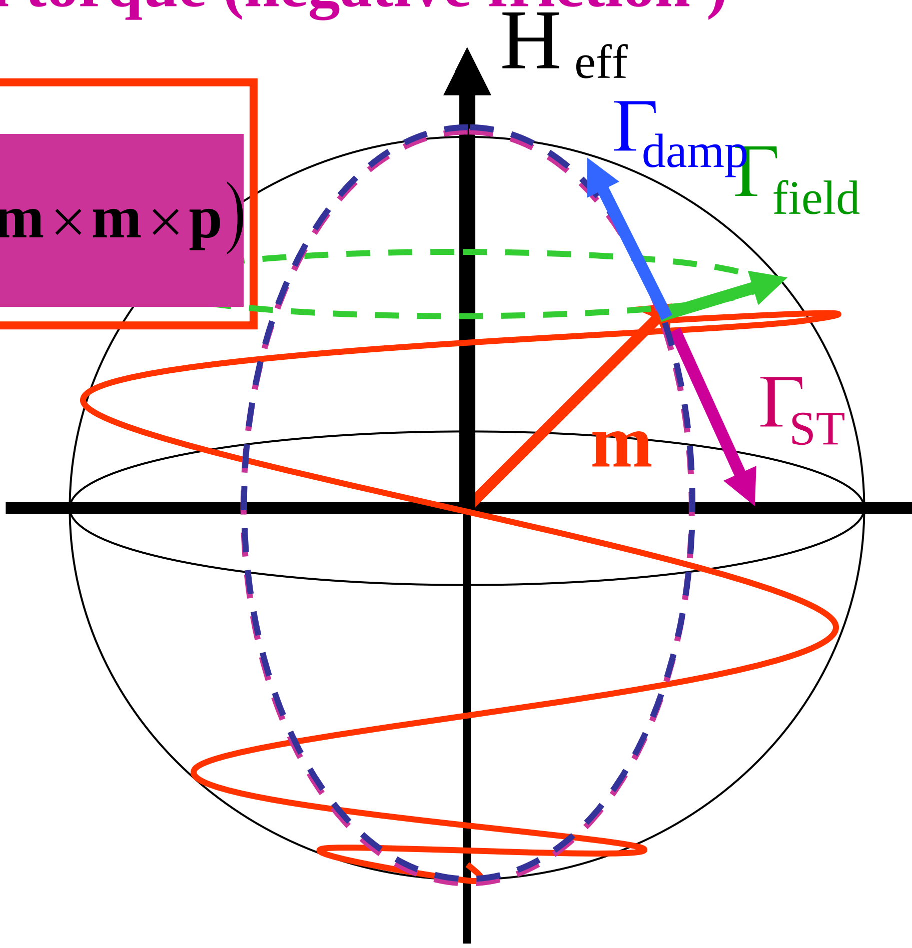
Magnetization Dynamics

Field torque (precession)

Spin torque (negative friction)

$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m}\times \mathrm{H}_{\mathrm{eff}} + \alpha\left(\mathbf{m}\times\left(\mathbf{m}\times \mathrm{H}_{\mathrm{eff}}\right)\right) + \beta\,\mathbf{I}\left(\mathbf{m}\times\mathbf{m}\times\mathbf{p}\right)$$

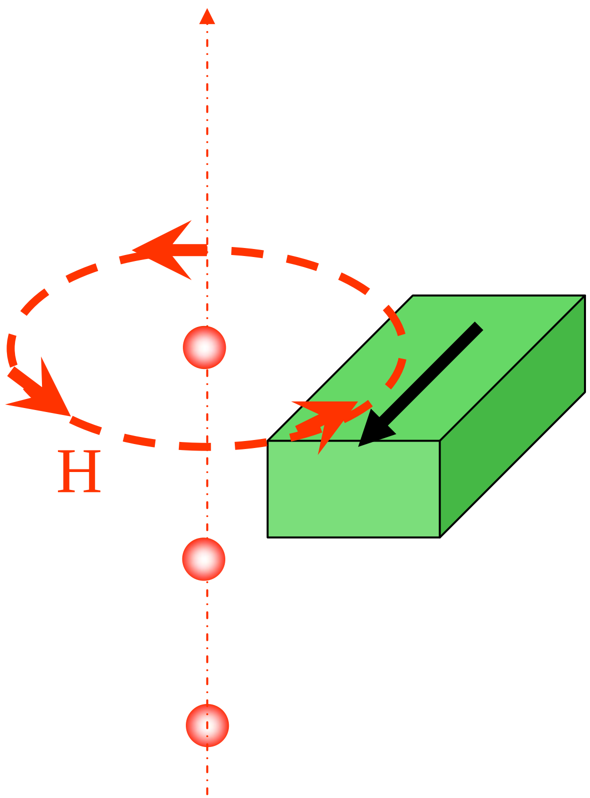
Damping torque (dissipation)



- Magnetization switching
- Steady-states precession
- Domain wall propagation

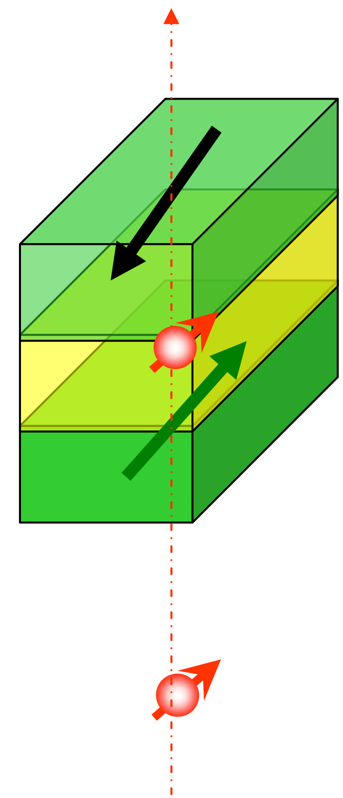
Spin transfer torque:
a new way to manipulate magnetization

Charge current



Oersted Field

Spin current



Spin transfer torque

Magnetic Random Acess Memory (MRAM)

Store information:

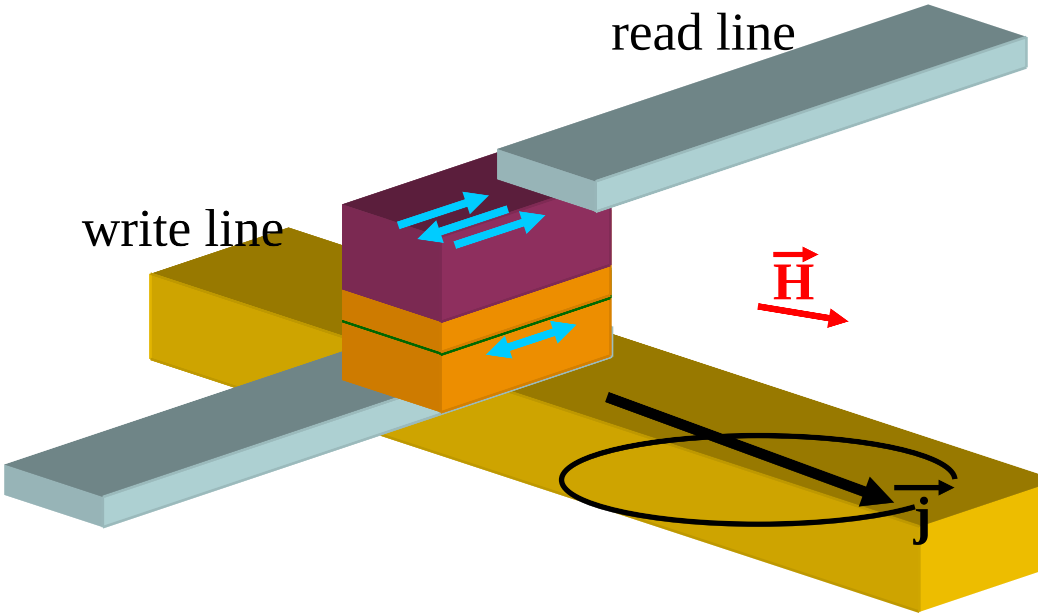
➔Orientation of a nanomagnet

Write information:

➔Oersted field (current in stripe)

Read information:

➔Measurement of GMR or TMR



STT -MRAM

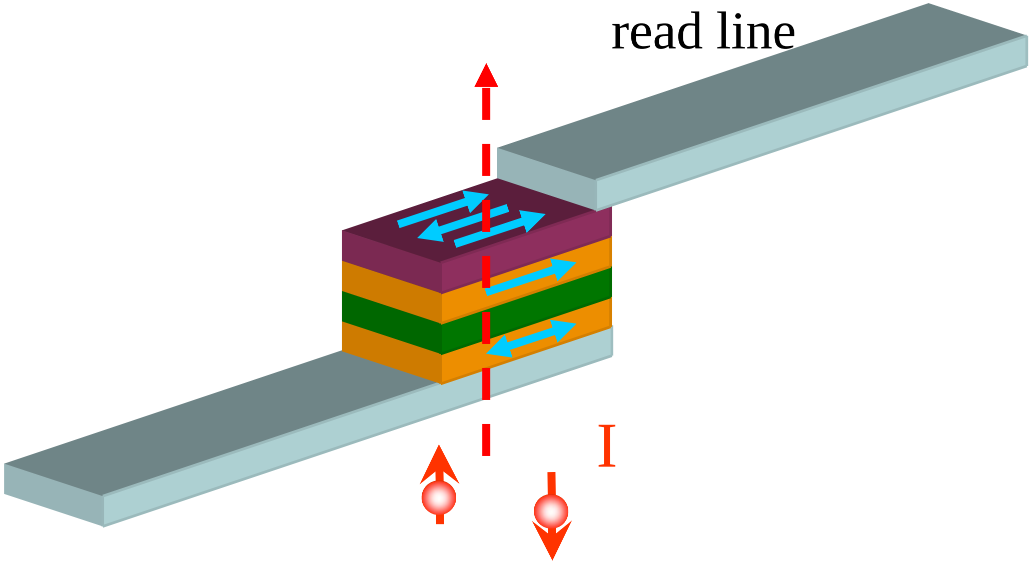
Store information:

➔Orientation of a nanomagnet

Write information:

➔~~Oersted field (current in stripe)~~

Spin Transfer Torque!



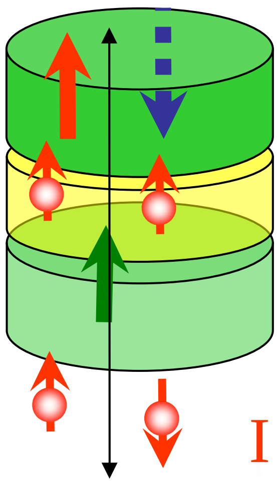
Read information:

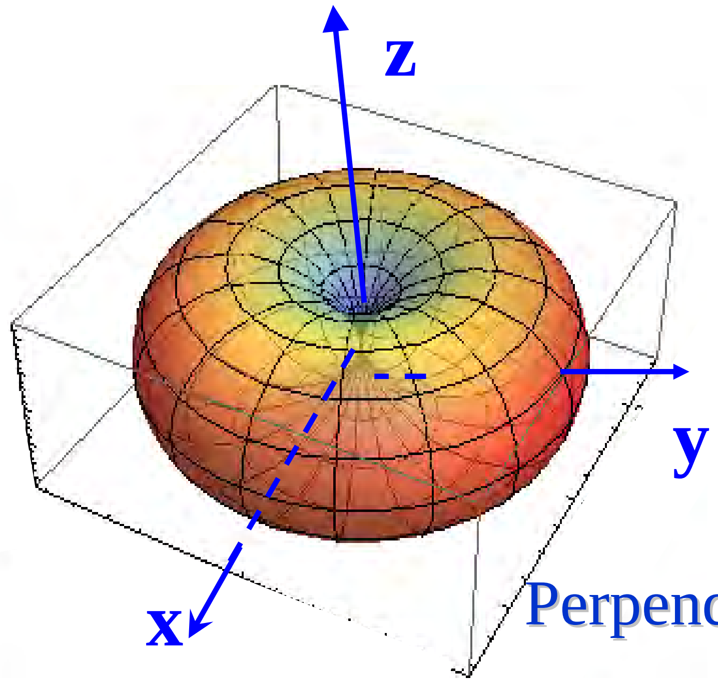
➔Measurement of magnetoresistance (GMR or TMR)

Fundamental understanding ⇨ Applications

• Magnetization switching	⇨	Low current switching
• Thermal fluctuation	⇨	Thermal Stability
• State diagram (H,I)	⇨	Low energy consumption
• Magnetization dynamics	⇨	Fast switching

Perpendicular Magnetization





Effective field along z

$$H_{eff}$$

Perpendicular → High symmetry

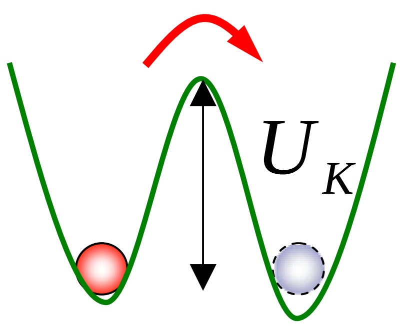
- For application

Current → Efficiency

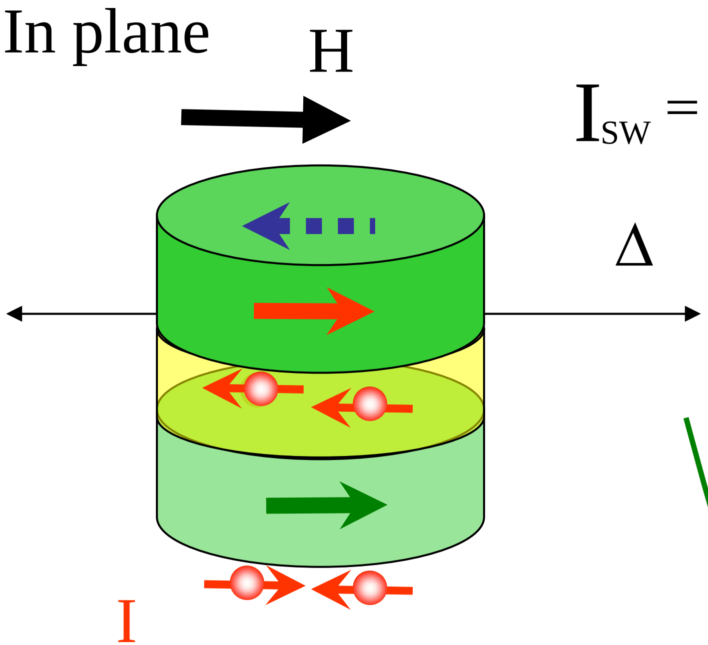
$$I_{SW} = \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(\theta)p}(H_{eff})$$

Energy Barrier height → Thermal Stability

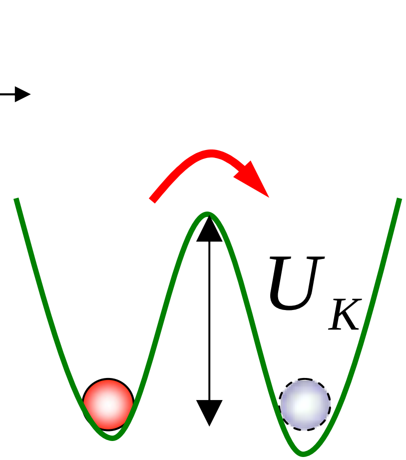
$$P(t) = \exp\left(-\frac{t}{\tau}\right) \qquad \tau = \tau_0 \exp\left(-\frac{U_K}{kT}\right)$$

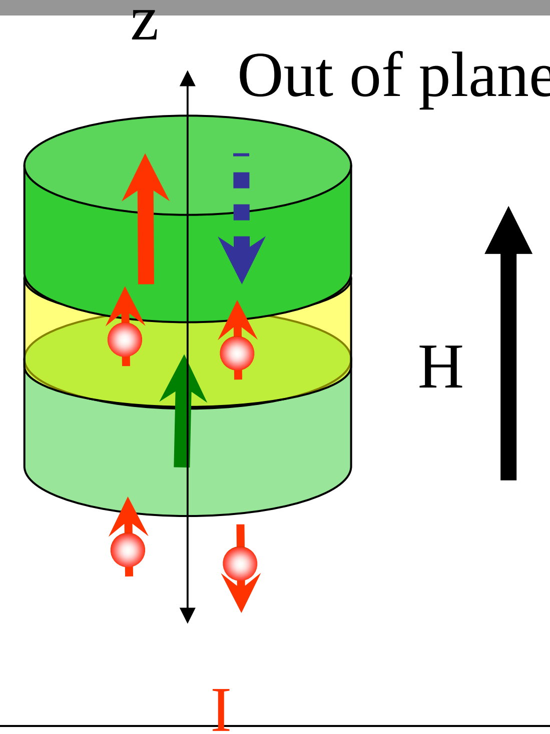


Perpendicular = Efficiency + Stability



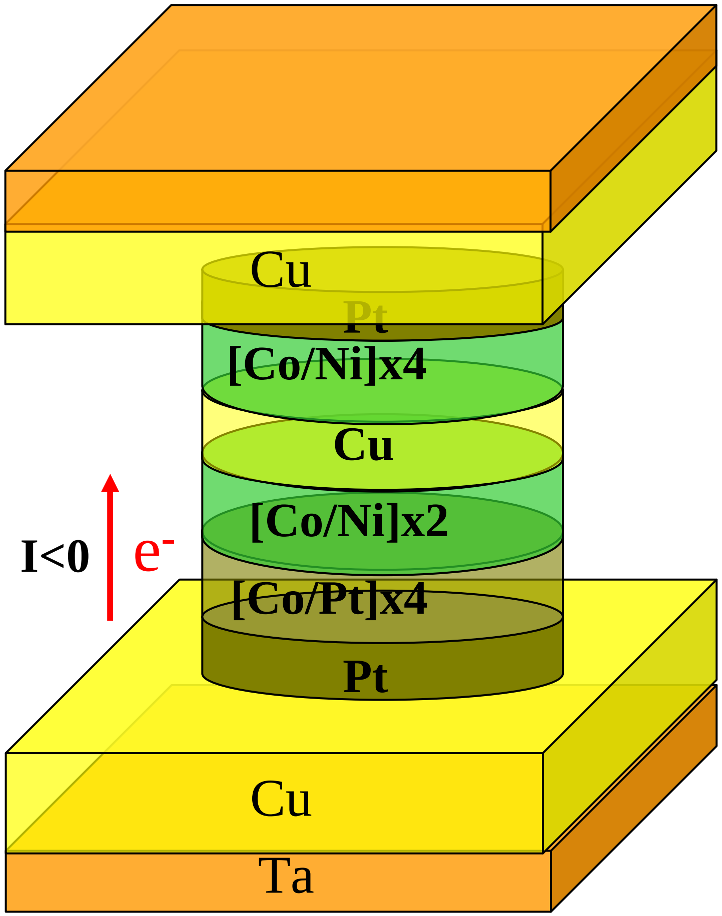
$$I_{SW} = \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(\theta)p}\left(H_{eff}\right)$$

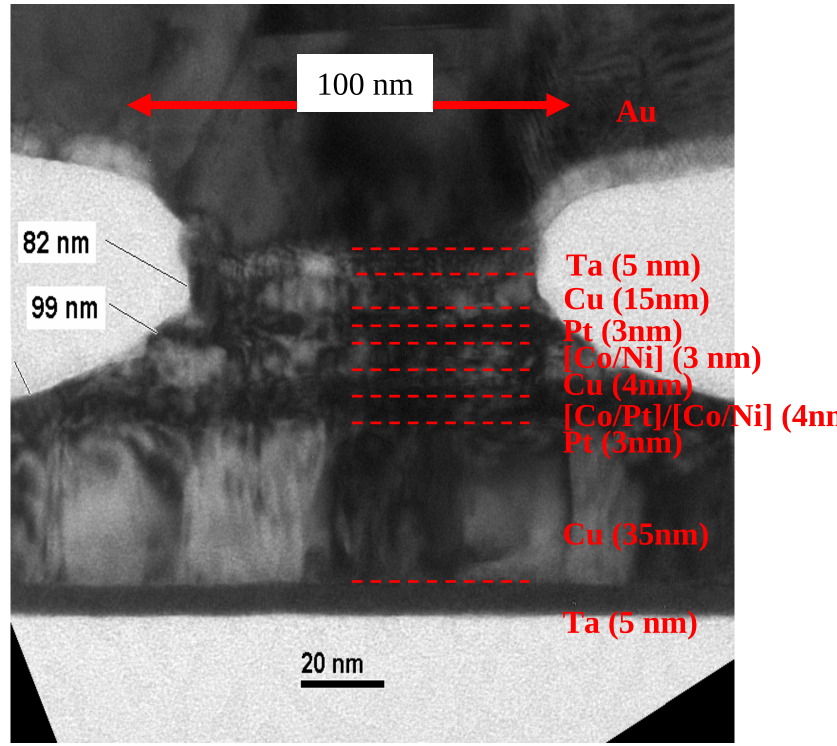




$H_{eff}^{P\to AP}$	$H + H_{K//} + 2\pi M_S$	$H + \left(H_{K\perp} - 4\pi M_S\right)$
U_K	$\left(M_s V H_{K//}\right)/2$	$\left(M_s V\left(H_{K\perp} - 4\pi M_S\right)\right)/2$
$\lvert I_{SW}\rvert$	$\left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}\left(U_K + \pi M_S{}^2 V\right)$	$\left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}\left(U_K\right)$

Nanopillars spin valve

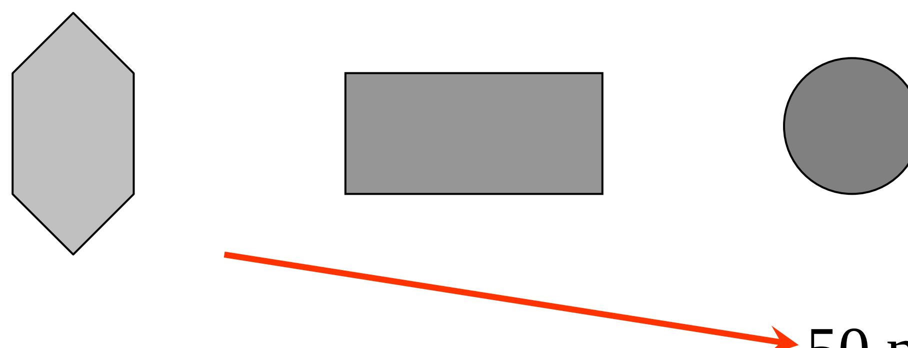




HITACHI
Inspire the Next

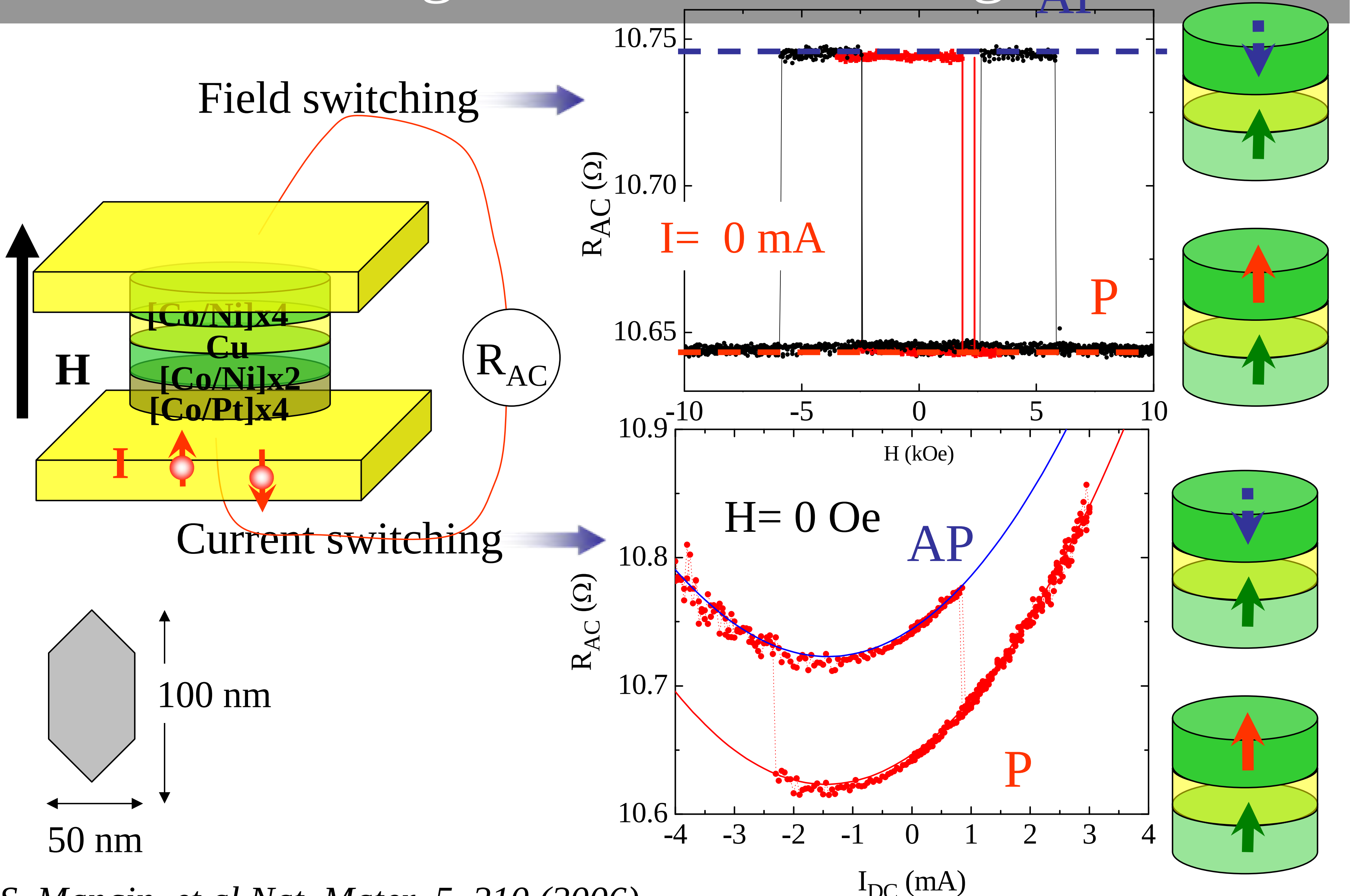
Jordan Katine

5 µm



50 nm

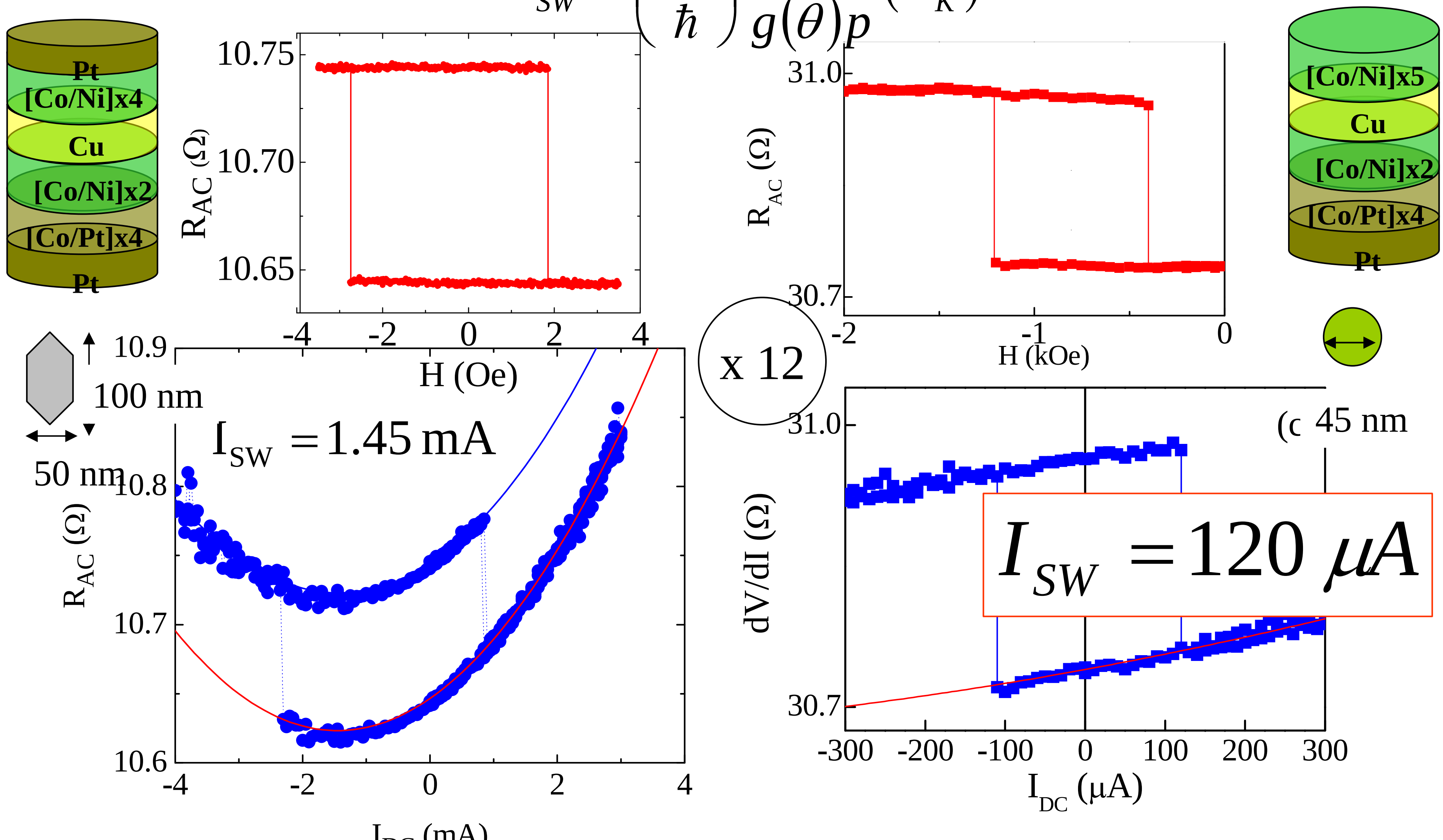
Magnetization switching



S. Mangin, et al Nat. Mater. 5, 210 (2006)

Perpendicular = Efficiency + Stability

$$I_{SW} = \left(\frac{2e}{\hbar}\right)\frac{2\alpha}{g(\theta)p}\left(U_K\right)$$



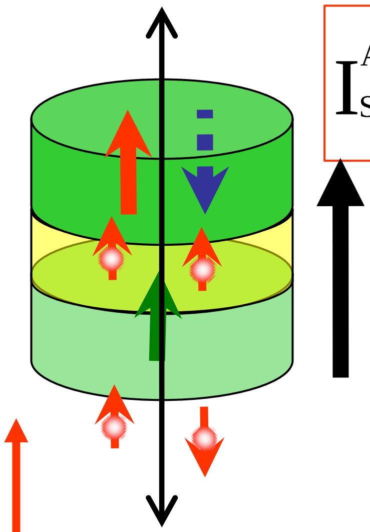
S. Mangin et al Appl. Phys. Lett ***94*** *012502 (2009)*

State diagram (H,I)

$$I_{SW}^{AP\to P} = \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(\pi)p}\left(H_{eff}^{AP\to P}\right)$$

$$I_{SW}^{P\to AP} = \left(\frac{2e}{\hbar}\right)\frac{\alpha M_S V}{g(0)p}\left(H_{eff}^{P\to AP}\right)$$

H>0



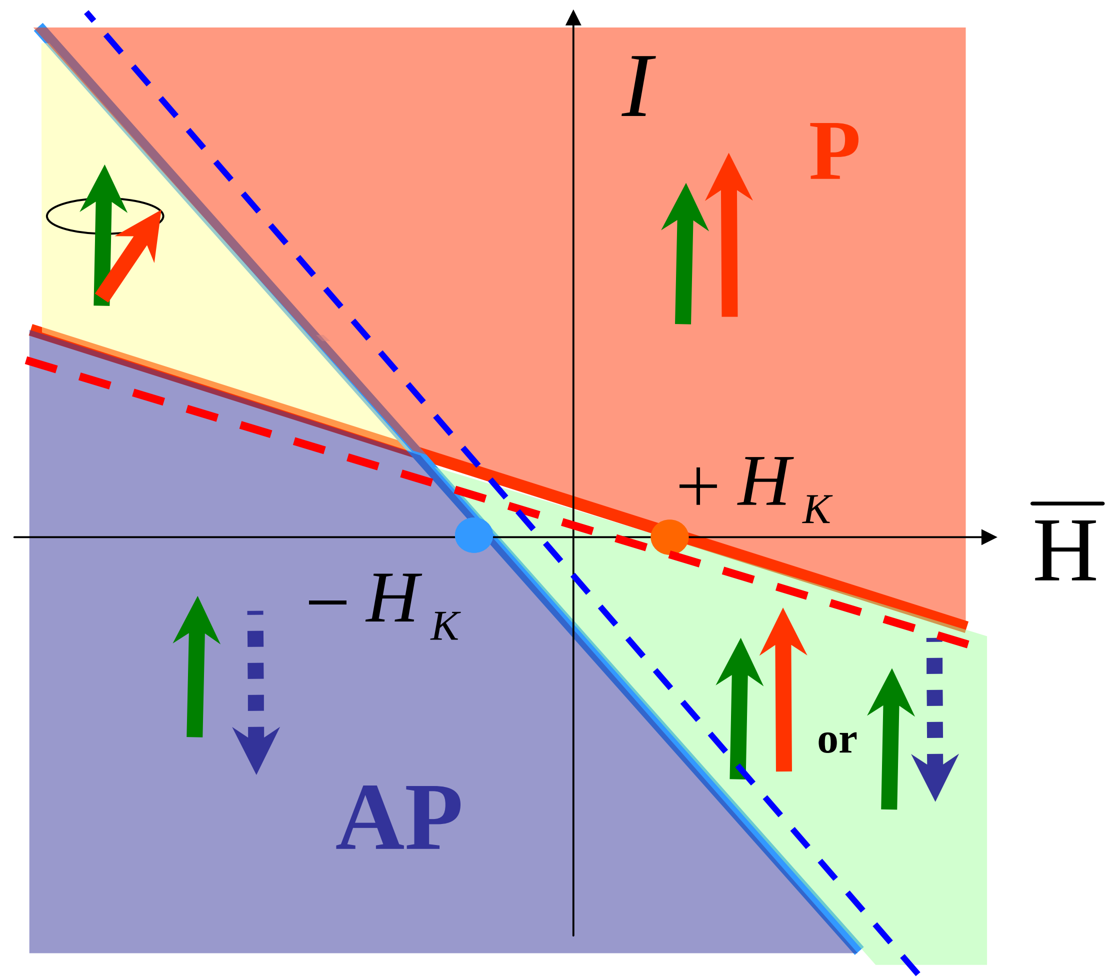
I>0

$$H // H_{eff} // u_z$$

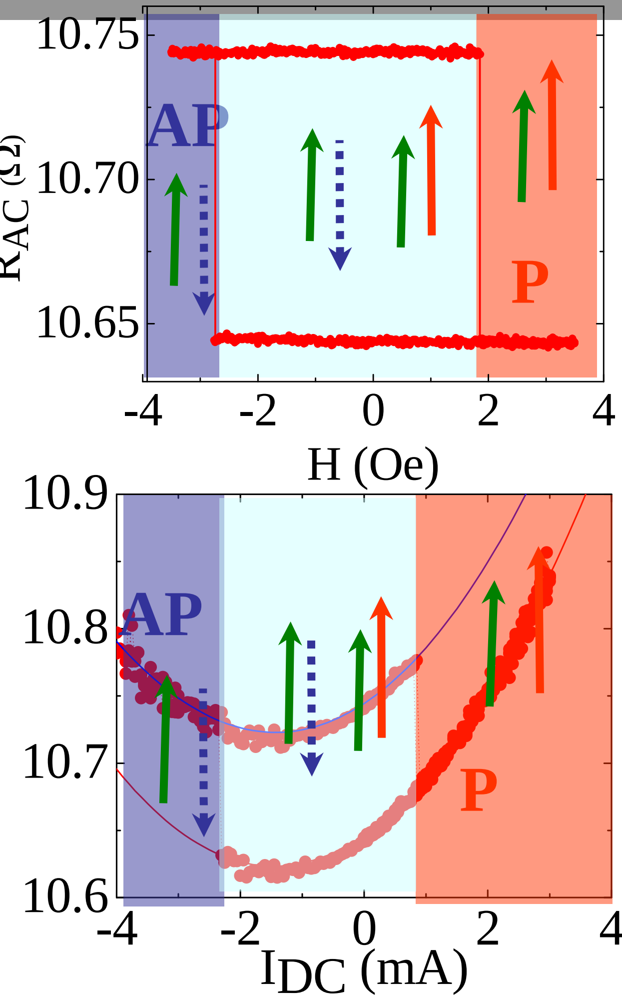
$$H_K = H_{K\perp} - 4\pi M_S$$

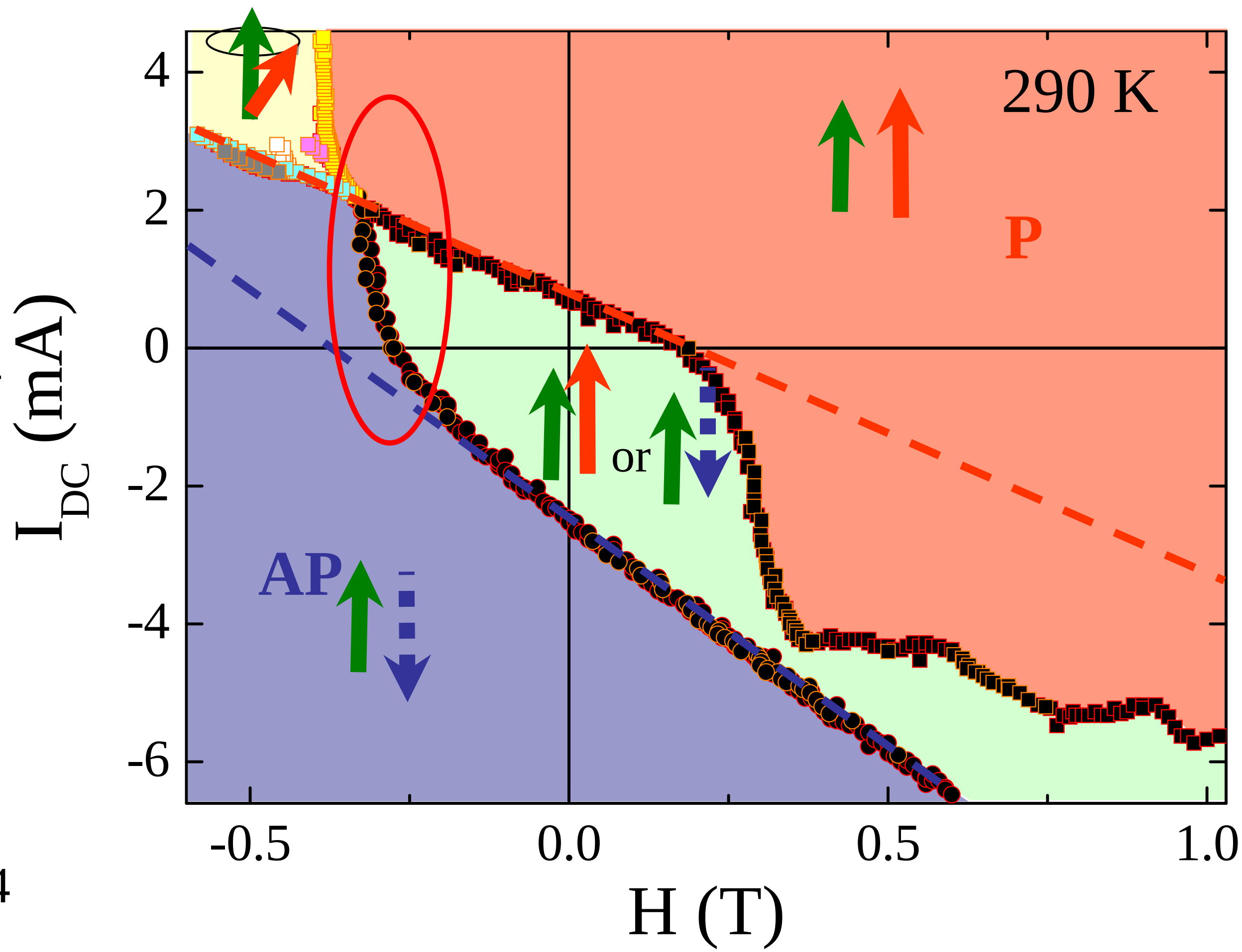
$$H_{eff}^{P\to AP} = H - H_K$$

$$H_{eff}^{AP\to P} = H + H_K$$



Experimental state diagram (H,I)





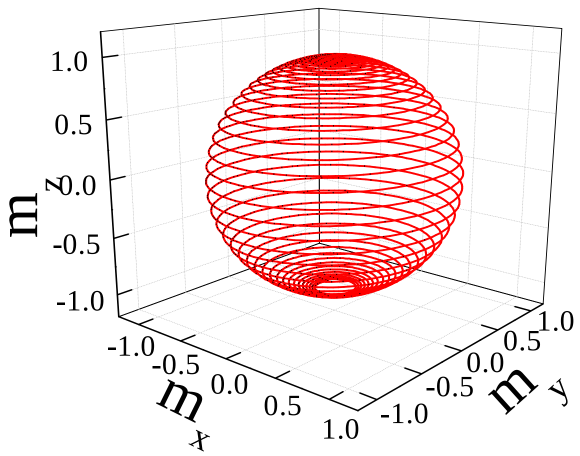
- Qualitative agreement: 4 different areas, some linear dependence
- Quantitative disagreement: reversal independent of current ??

J. Cucchiara et al Phys Rev B 84, 100405 (2011)

Dynamics : fast & slow

Short time → Precession

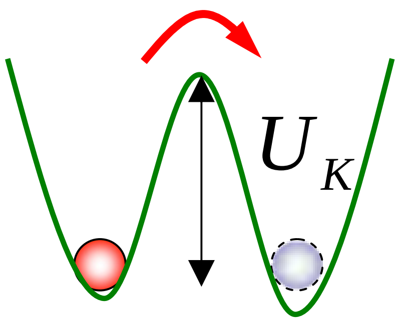
$$\frac{1}{\tau} = A\cdot(I - I_{c0})$$



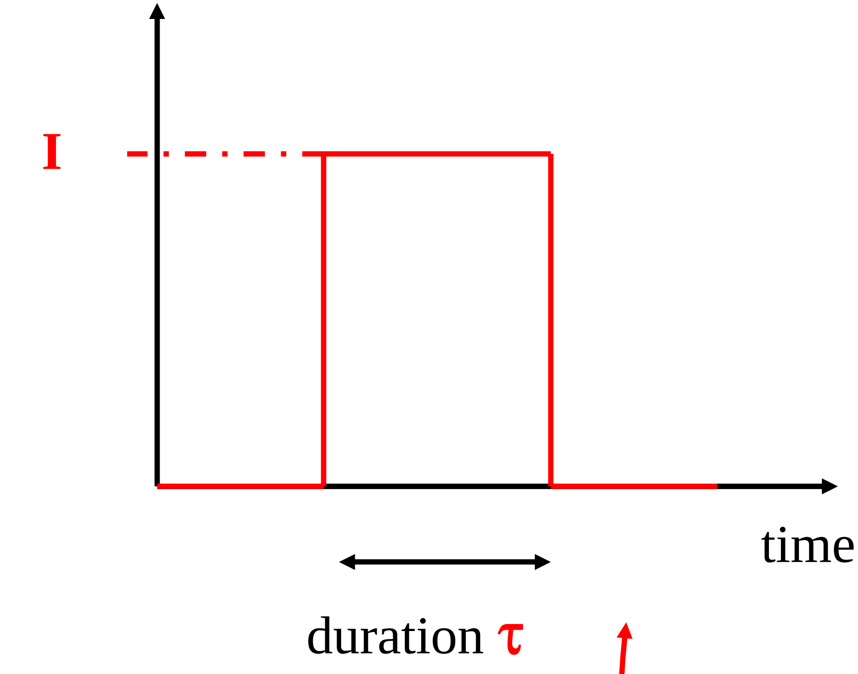
Long time → Thermally activated

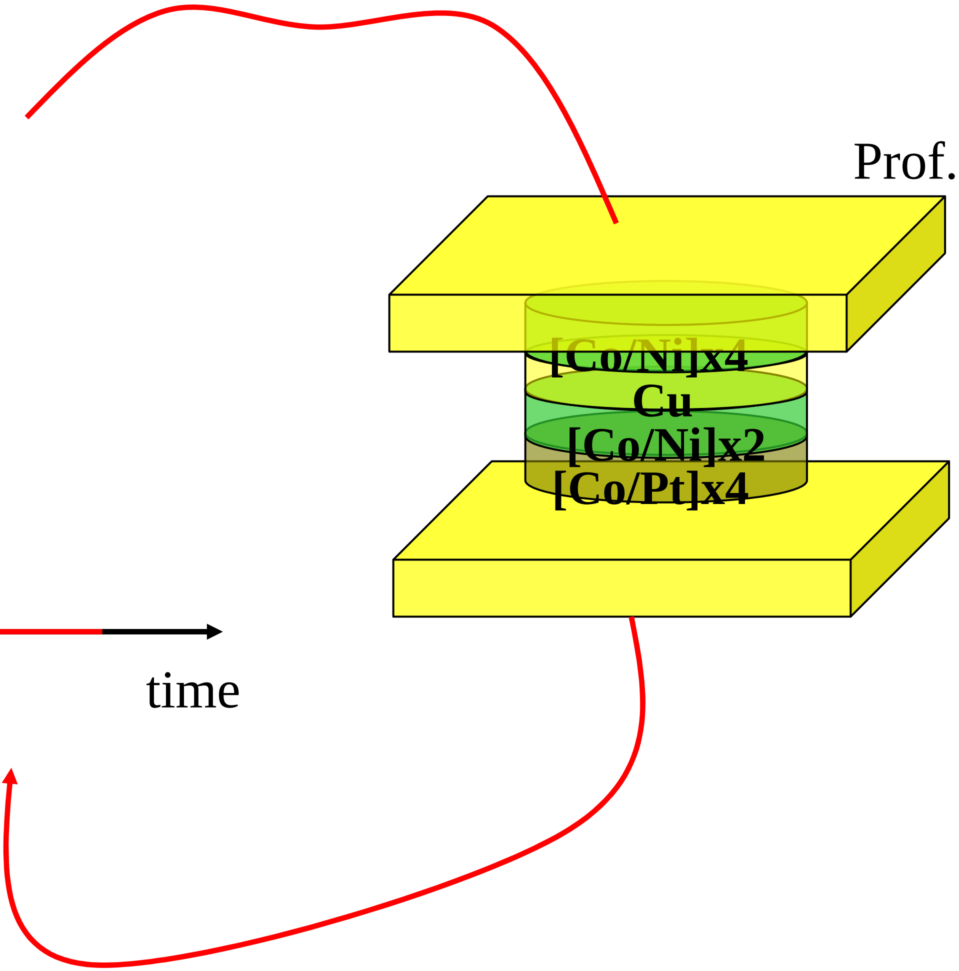
$$P(t) = \exp\left(-\frac{t}{\tau}\right)$$

$$\tau = \tau_0 \exp\left(-\frac{\Delta E}{kT}\right)$$



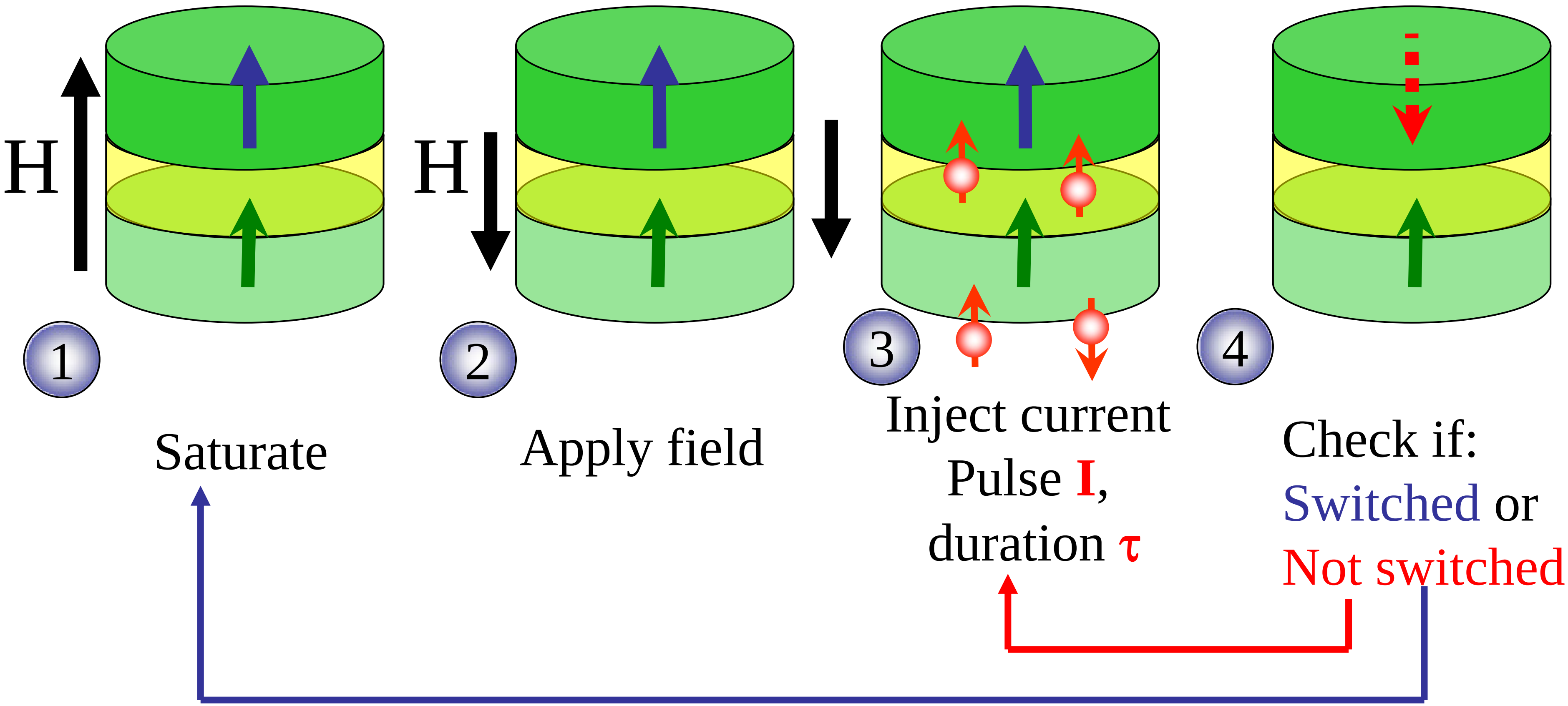
Current pulse





Prof. A. Kent NYU

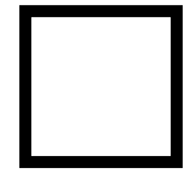
Current Pulse Procedure



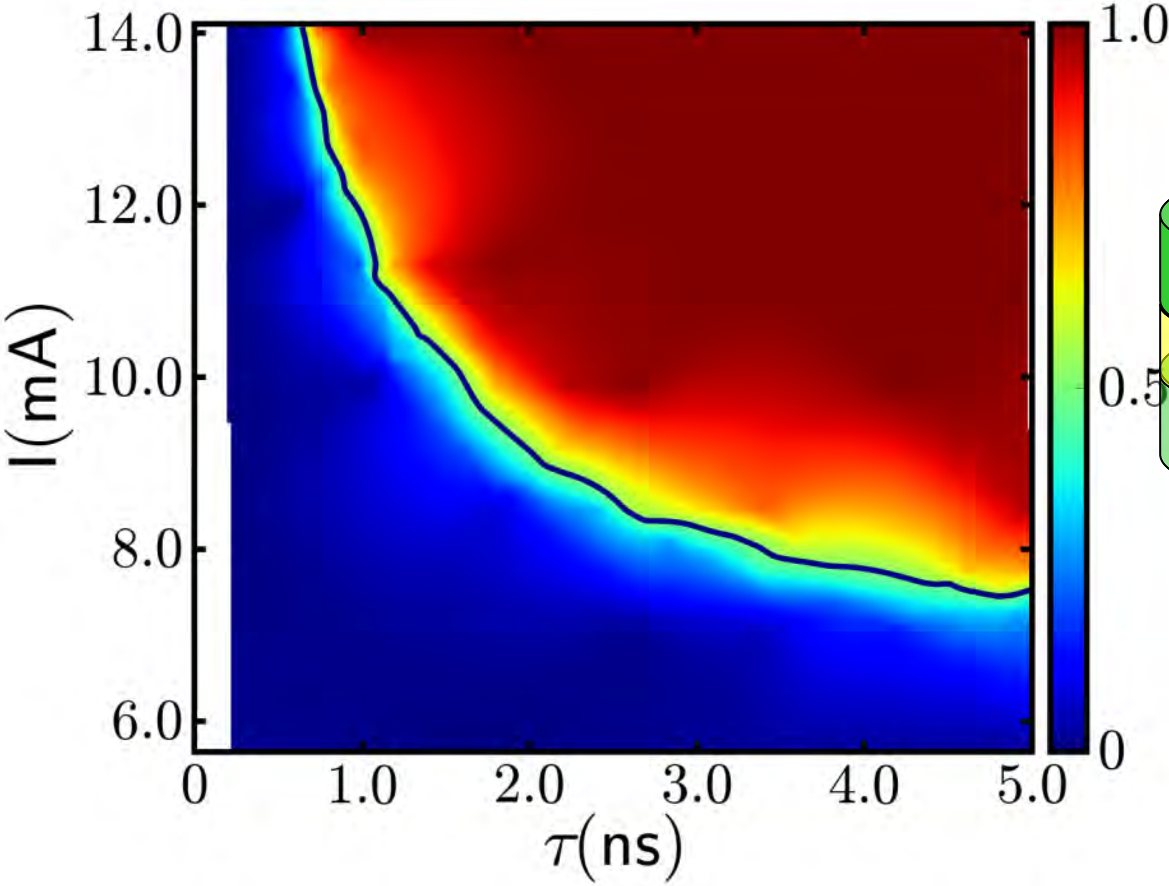
Apply the same pulse 100 – 10,000 times

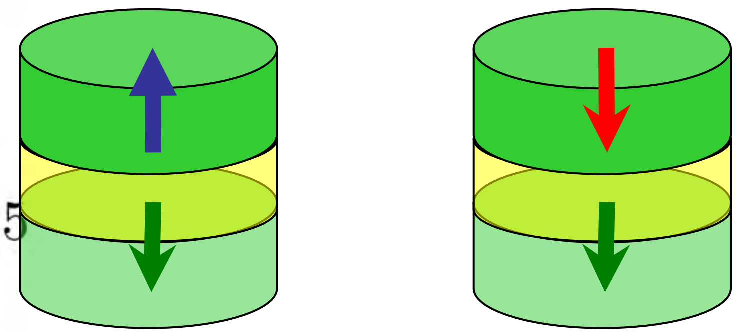
$$P(\tau) switching \quad probability = \frac{\# \quad of \quad switched}{\# \quad of \quad pulse \quad applied}$$

Switching probability



100nm x 100nm

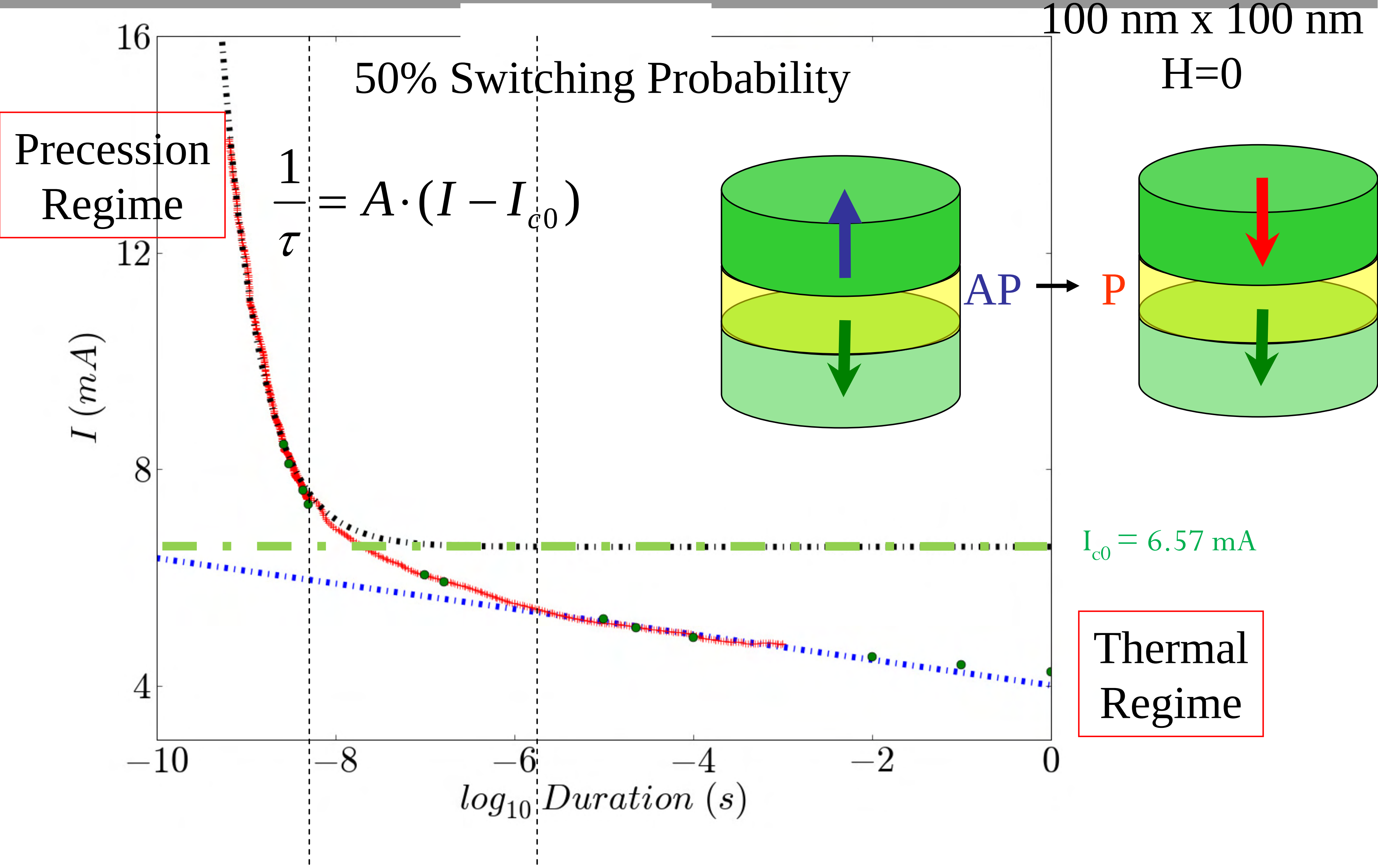




AP to P

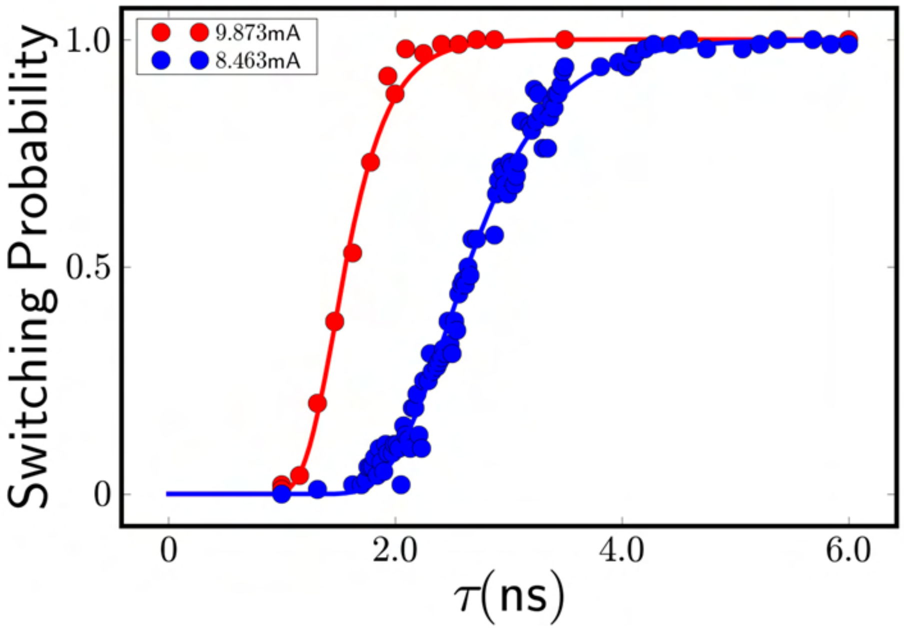
D. Bedau et al, Appl. Phys. Lett **96** 022514 (2010)

Switching for different time domains



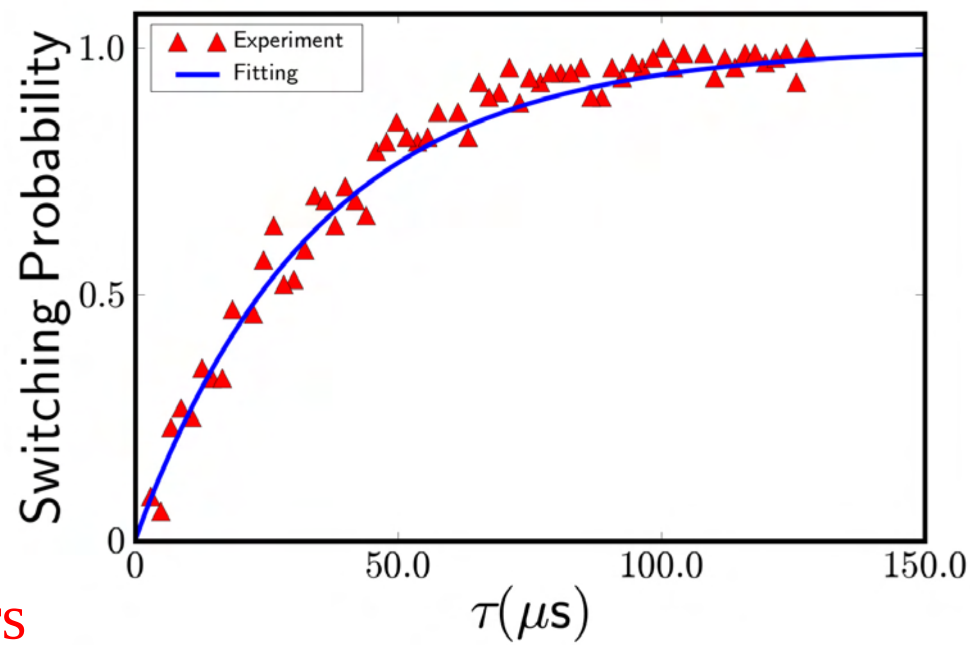
D. Bedau, et al Appl. Phys. Lett ***97*** *262502 (2010)*

Switching probability ~ time



Short time

Long time



- The probability distribution differs significantly for short and long times.

D. Bedau, et al Appl. Phys. Lett ***97*** *262502 (2010)*

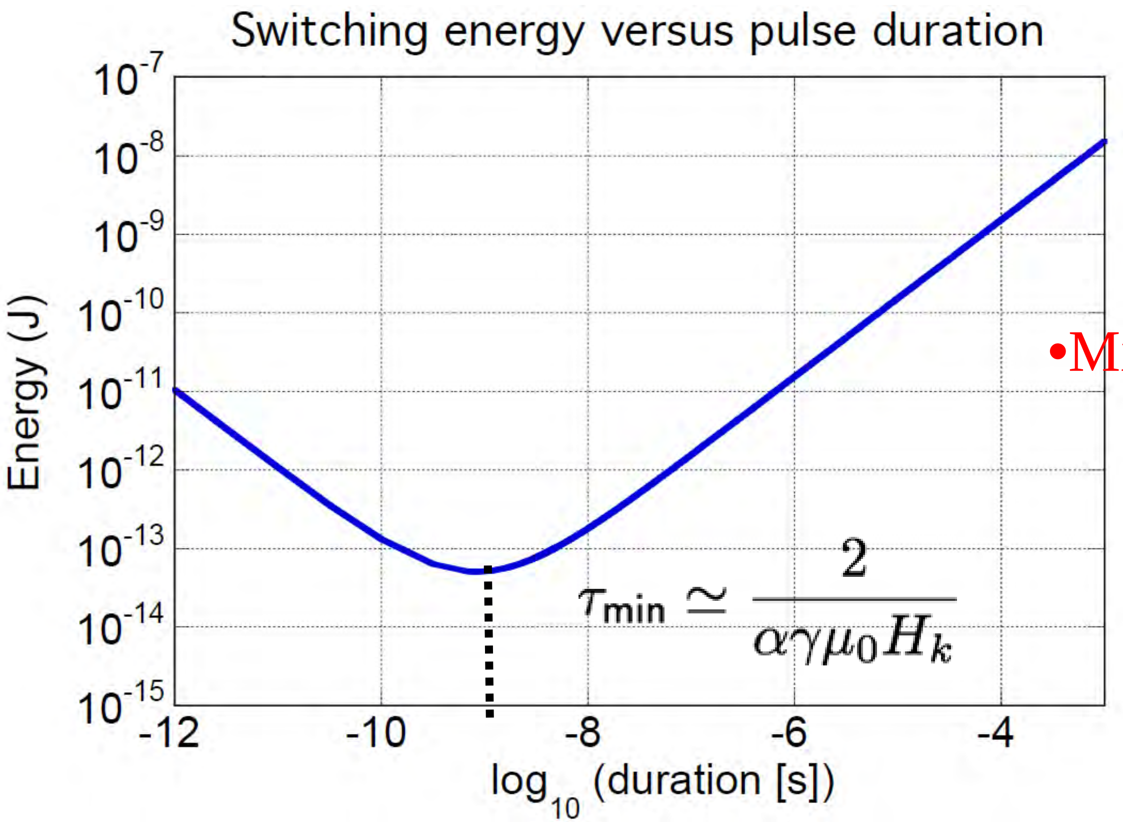
Optimal Pulse Duration

$$E = I^2 R\tau$$

-Short times $I \sim 1/\tau$

-Long times $I \sim \text{constant}$

$$\frac{1}{\tau} = A\cdot(I - I_{c0})$$



50 nm x 50 nm

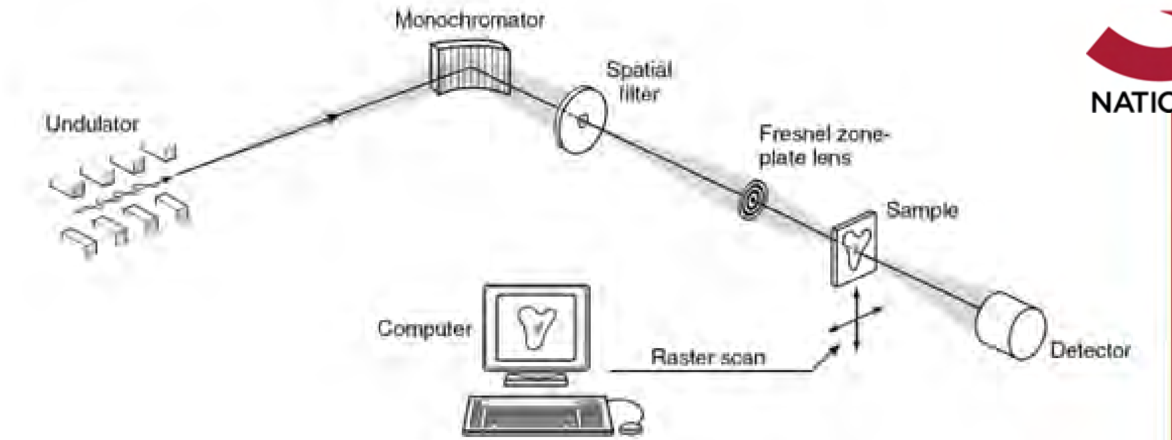
•Minimum Energy switching at:
E<0.1 pJ, τ=800 ps
•U_k =30-40 kT

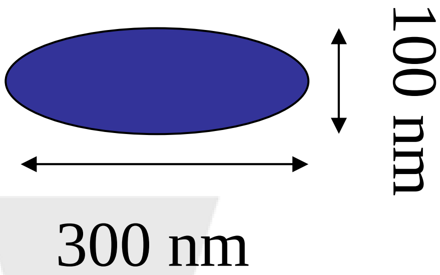
- There is a minimum energy pulse required to switch the magnet
- Minimum occurs for pulses ~0.8 ns with an energy of ~100 fJ

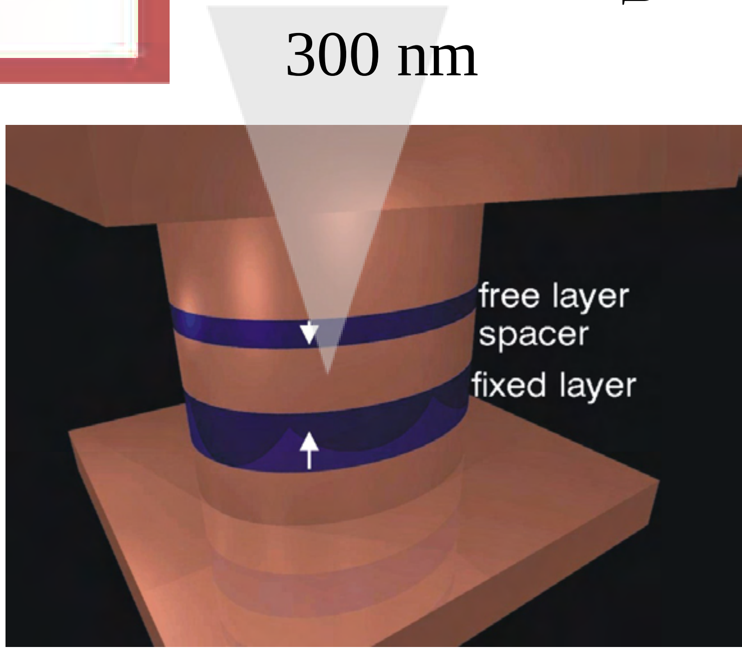
*Bedau et al. APL **96**, 022514 (2010)*

Scanning Transmission X-ray Microscopy

SLAC
NATIONAL ACCELERATOR LABORATORY







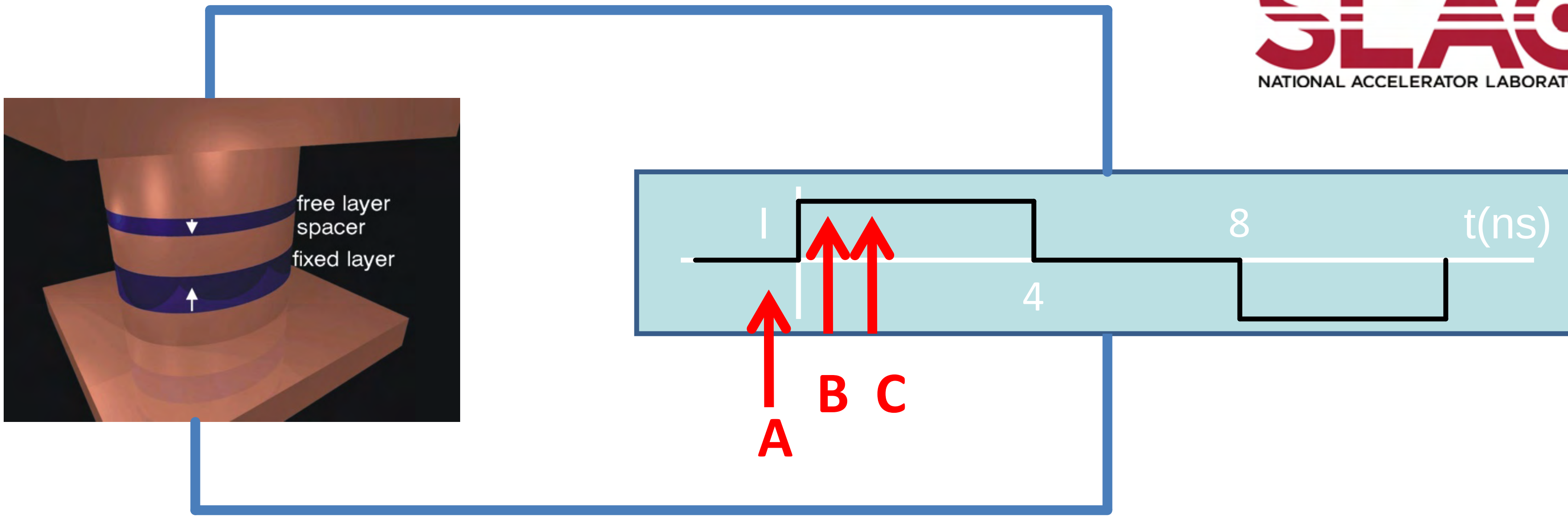
Element specific

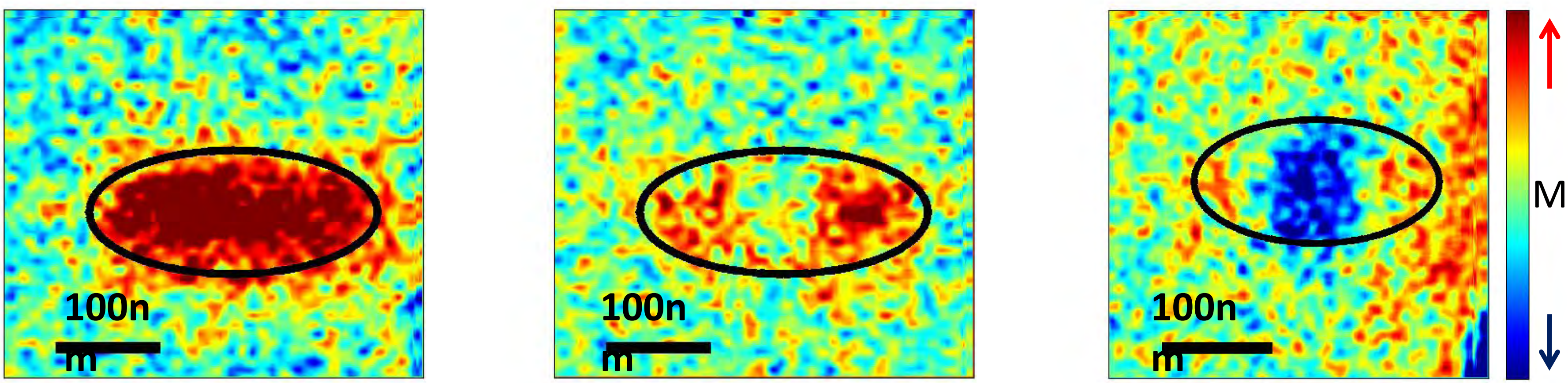
Magnetic contrast

Time resolution (10 ps)

Spatial resolution (10 nm)

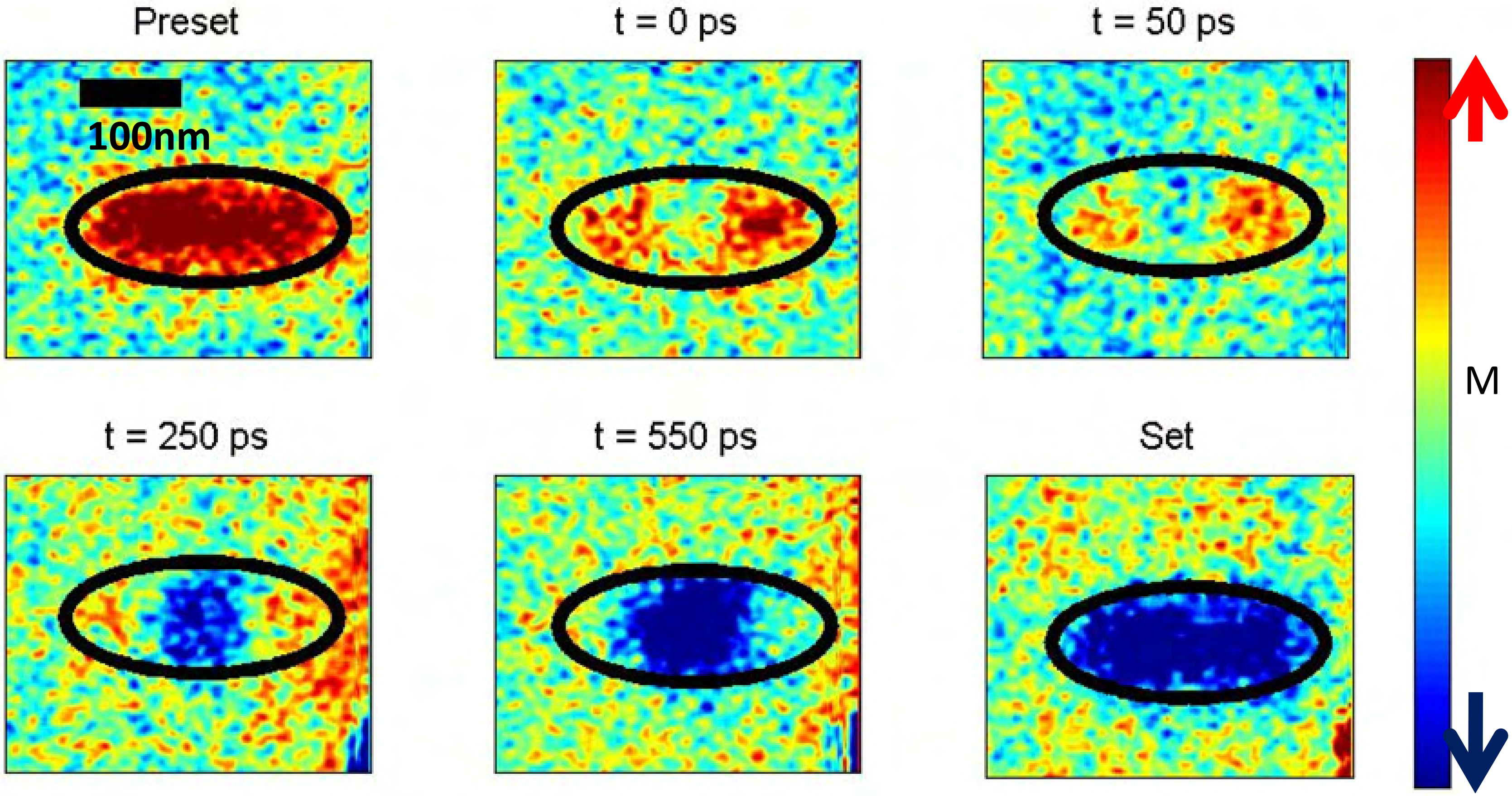
Time Resolved Magnetic Microscopy





A B C

Looking at a Time Series



Macro-spin approximation is no longer valid

D. P. Bernstein, et al Phys rev B 83, 180410® (2011)

Conclusion

Nanopillar spin valve with perpendicular magnetization

- Model system to study spin transfer torque effect
- Large efficiency: Spin Torque application
- Slow Dynamic: Thermal fluctuations
- Fast Dynamic: Angular momentum conservation
- Non uniform magnetization

Acknowledgments

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Advanced Light Source, Lawrence Berkeley National Lab, USA

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