X-rays have come a long way……

magnetic imaging, nanoscale, ultrafast

Science **259**, 658 (1993)

Science **304**, 430 (2004)

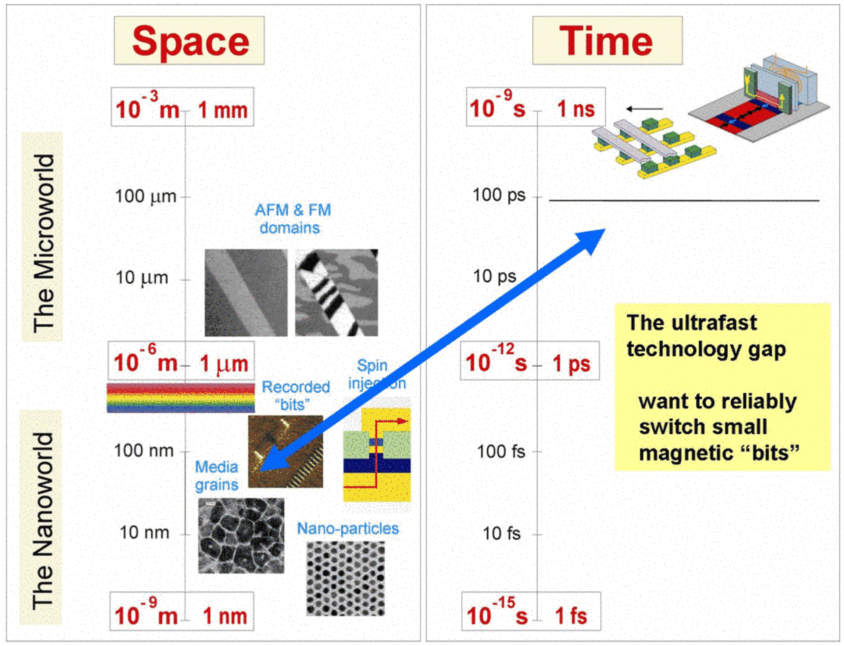
*Nature **432**, 885 (2004)*

1895

Collaborators:

Stanford:	Hitachi:
Y. Acremann	J.A. Katine
J.P. Strachan	M.J. Carey
V. Chembrolu	
S.D. Andrews	
H.C. Siegmann	

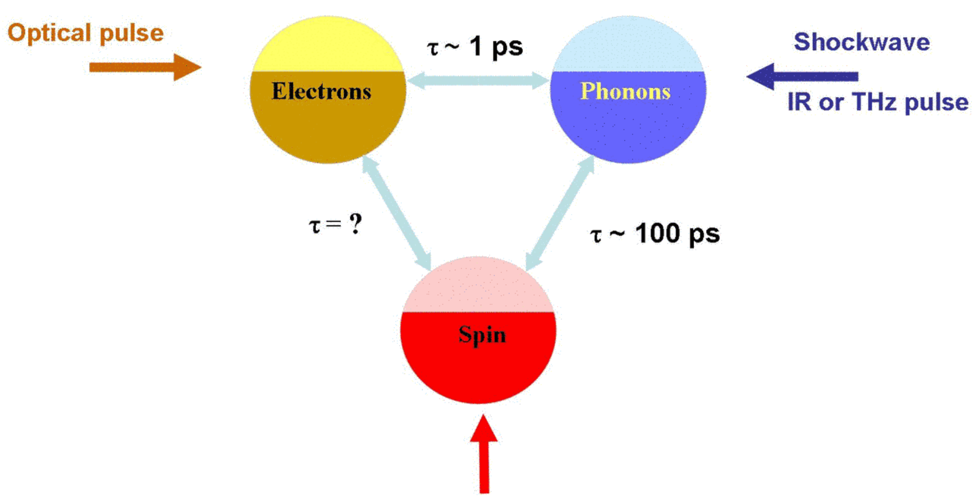
The Technology Problem: Smaller and Faster



x-rays combine nanometer spatial with picosecond time resolution

Faster than 100 ps….

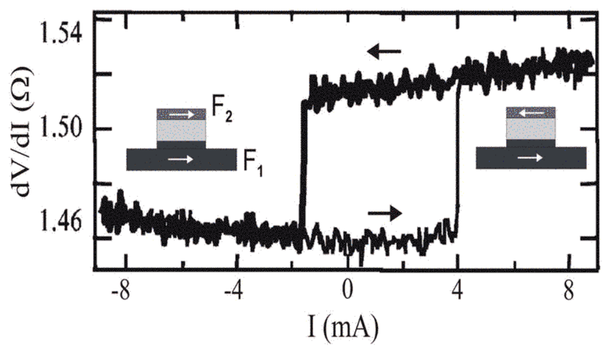
Mechanisms of ultrafast transfer of **energy** and **angular momentum**

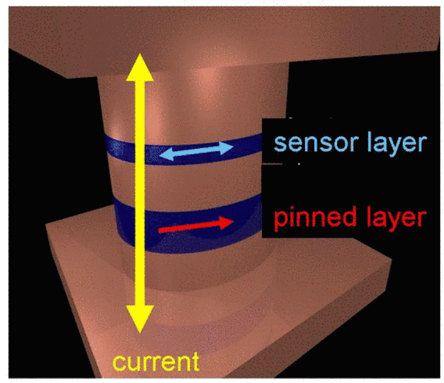


Most direct way:

- Oersted switching
- Precessional or ballistic switching
- Exchange switching (spin injection)

Switching using spin transfer:
concept due to Slonczewski and Berger



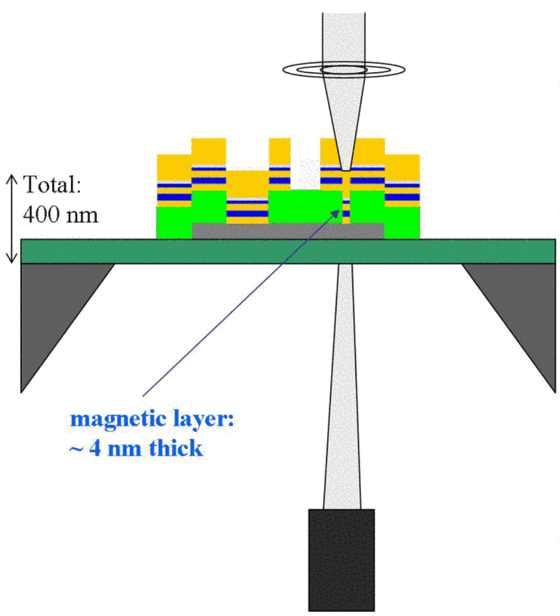


F. J. Albert *et al*, Appl. Phys. Lett. **77**, 3809 (2000)
F. J. Albert *et al*, Phys. Rev. Lett. **22**, 226802 (2002)

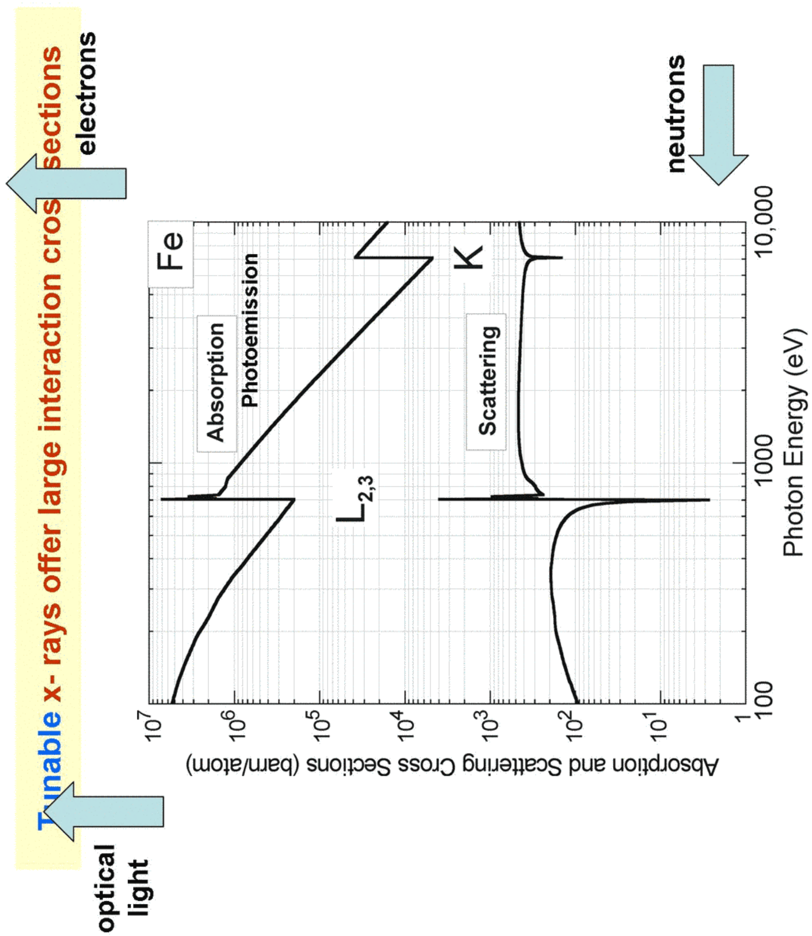
Concept proven – want to understand detailed mechanism and dynamics:

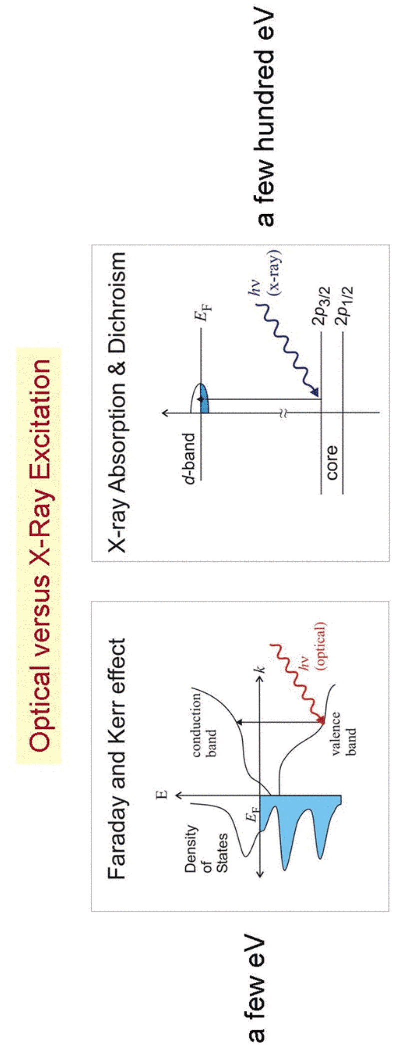
Why not take an x-ray movie?

Scanning transmission x-ray microscopy of samples

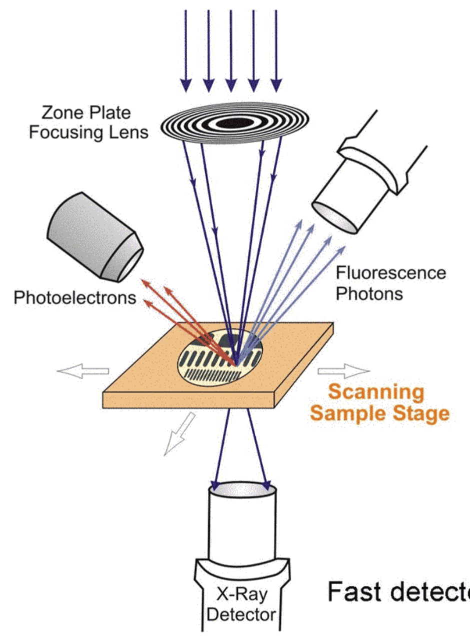


- Transmission experiment through entire pillar
- Spatial resolution ~30 nm
- X-rays can distinguish layers: elemental (Fe, Co, Ni, Cu)
- X-ray cross section large: can see signal from thin layer
- Polarized x-rays give magnetic contrast (XMCD)


Tunable x- rays offer large interaction cros sections
electrons
optical light
neutrons
Fe
Absorption
Photoemission
Scattering
L2,3
K
Photon Energy (eV)
Absorption and Scattering Cross Sections (barn/atom)

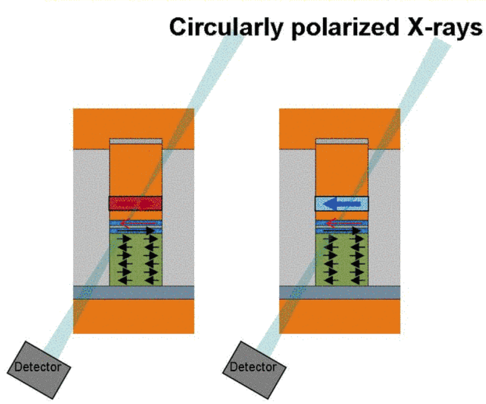

Optical versus X-Ray Excitation
Faraday and Kerr effect
X-ray Absorption & Dichroism
Density of States
conduction band
valence band
hν (optical)
d-band
core
hν (x-ray)
2p3/2
2p1/2
a few eV
a few hundred eV

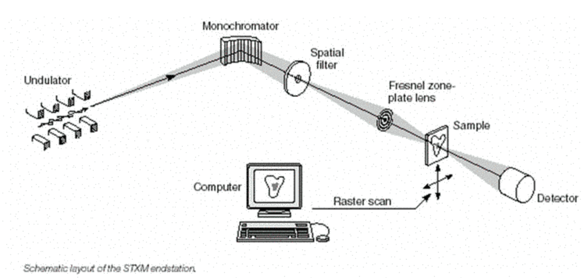
Scanning Transmission X-ray Microscopy
STXM

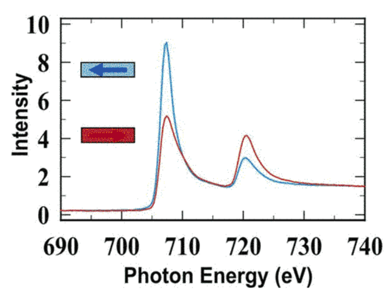


Fast detector for dynamics

Sanning X-ray Microscopy – ALS Berkeley



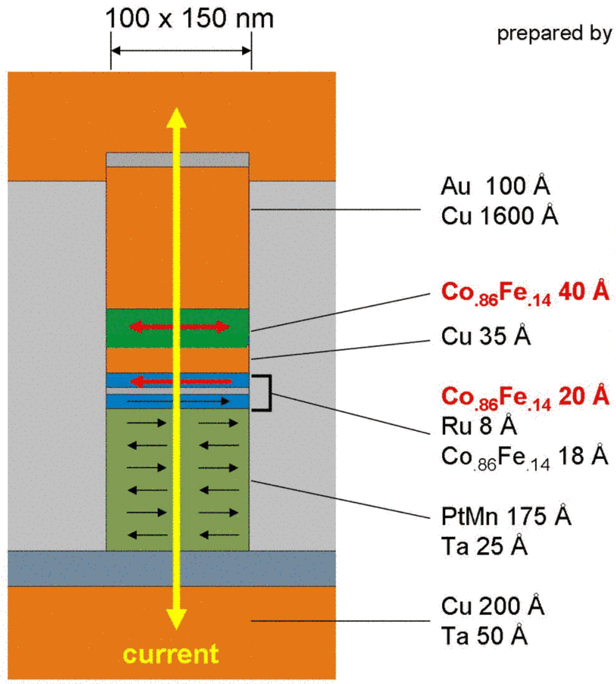




- Measure in-plane components of magnetization
- Spatial resolution 30 nm (x-ray spot size)
- Time resolution 70ps (x-ray bunch length)
- Need lock-in type sampling to extract small magnetic signal

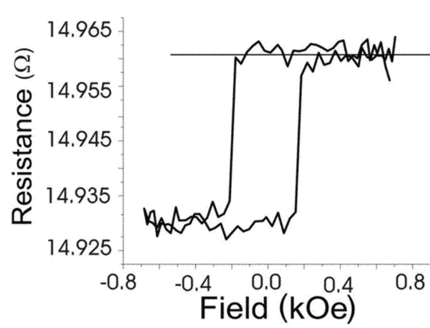
Pillar samples for spin-injection studies

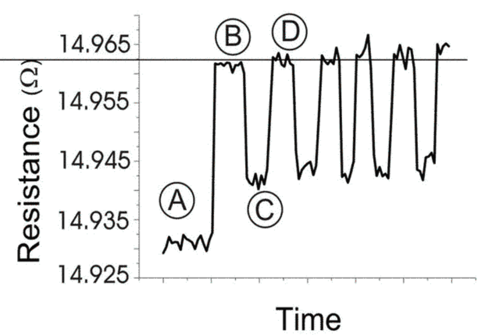
prepared by Jordan Katine, *Hitachi Global Storage*



Challenge – measuring thin 4 nm magnetic layer buried in 400 nm of metals!

Switching Behavior of 100nm x 150nm Pillar





Applying a magnetic field:

Full switching

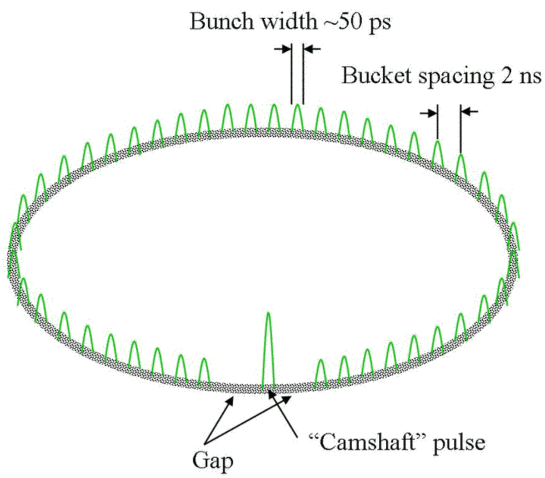
Applying current pulses:

Intermediate state C

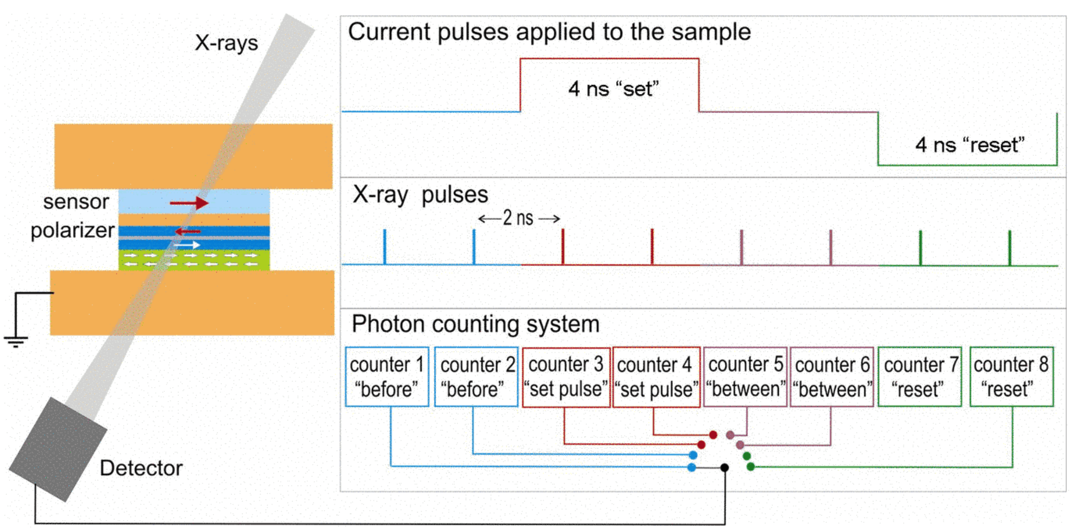
Spatially resolved measurements needed to determine state C !

Synchrotron Radiation Pulses from Storage Ring

"multi-bunch" mode: 500 MHz
328 RF buckets total
276 +1 filled with electrons ~1.4mA each bucket
Normal mode of operation

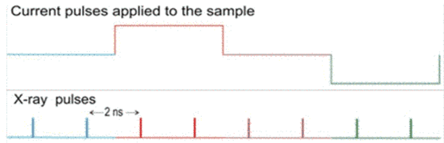


Current Pump Pulse – X-Ray Probe Pulse Synchronization



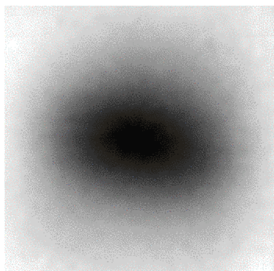
Rotation of sample about pillar axis gives orthogonal in-plane (x,y) components of **M**

Attempt to get a Magnetic Image of Sensor Layer

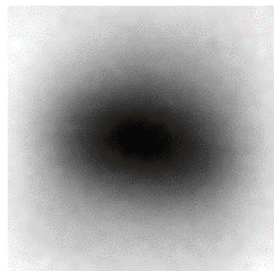


Pick delay time – take image with one polarization then with opposite polarization

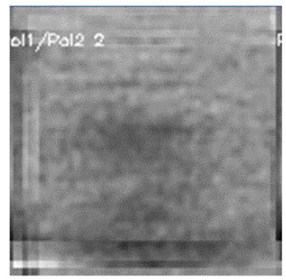
Left polarization



Right polarization



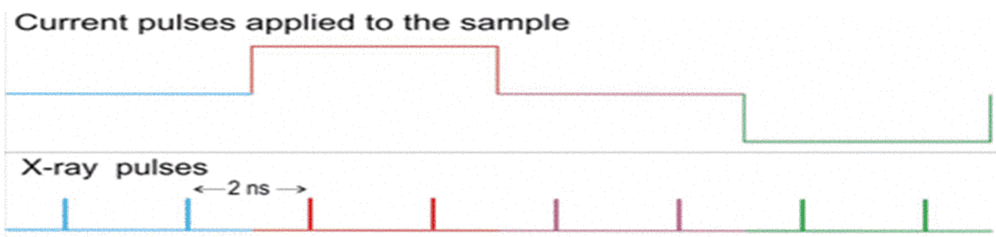
difference



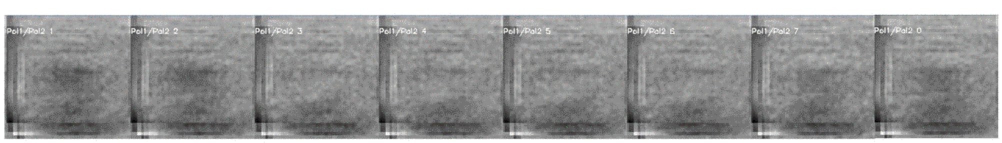
Cannot reliably see magnetic contrast

sample drift causes problem on timescales of a complete image (tens of minutes)

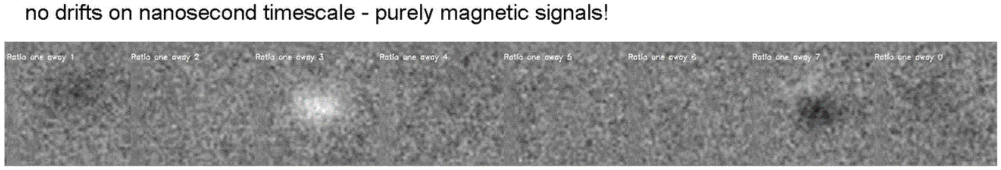
Method of Magnetic Contrast



Subtract whole images: (Left polarization) – (Right polarization) for each counter:
cannot see magnetic contrast due to drifts

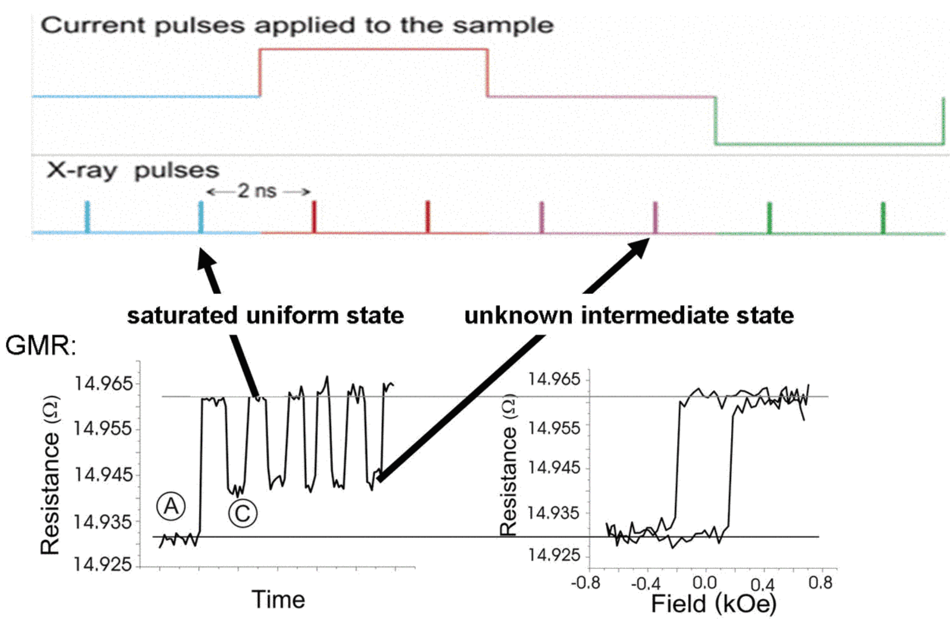


Fix polarization: Take differences (pixel by pixel) between neighboring counters
no drifts on nanosecond timescale - purely magnetic signals!

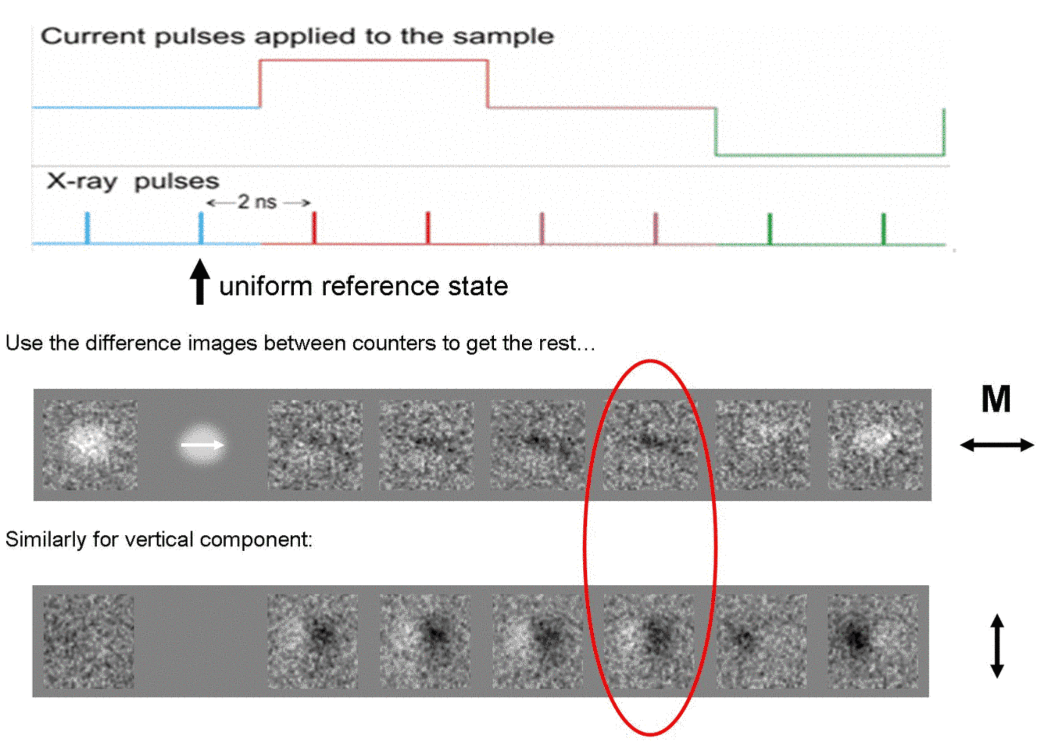


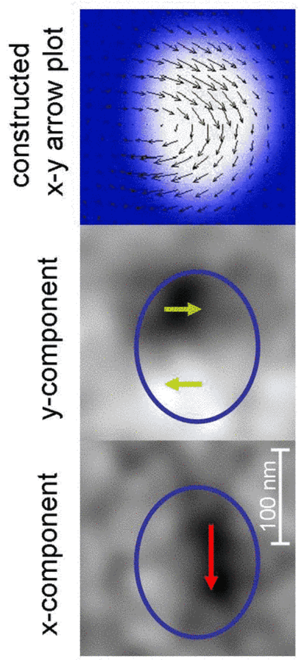
Can only obtain difference images: change of magnetization – not absolute magnetization

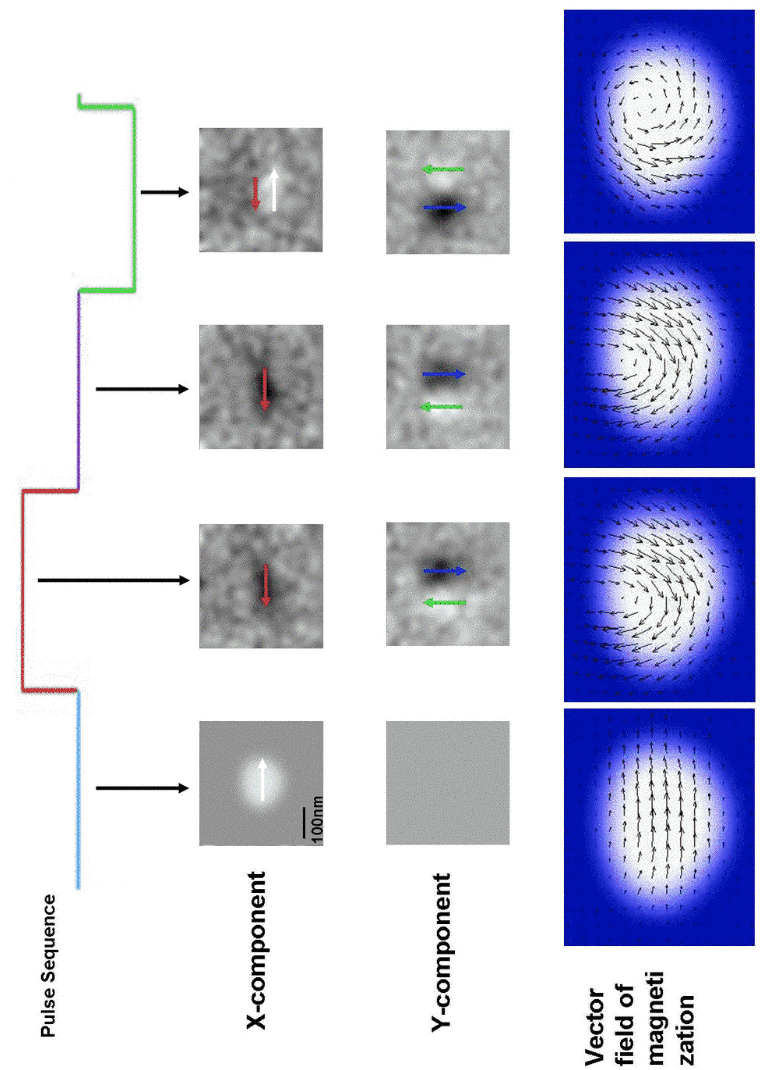
Use "reference state" to reconstruct absolute Magnetization:

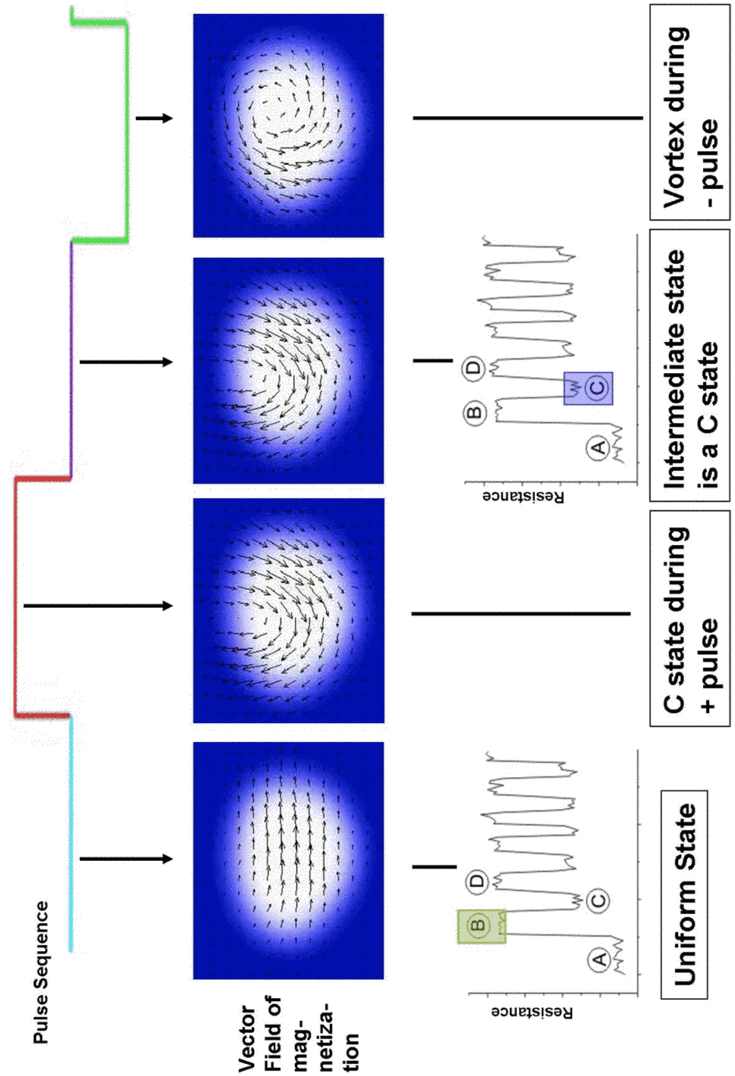


Reconstruction of Magnetization:

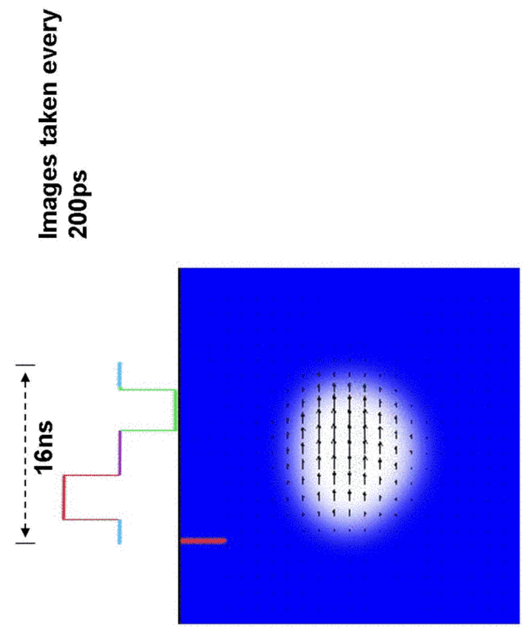


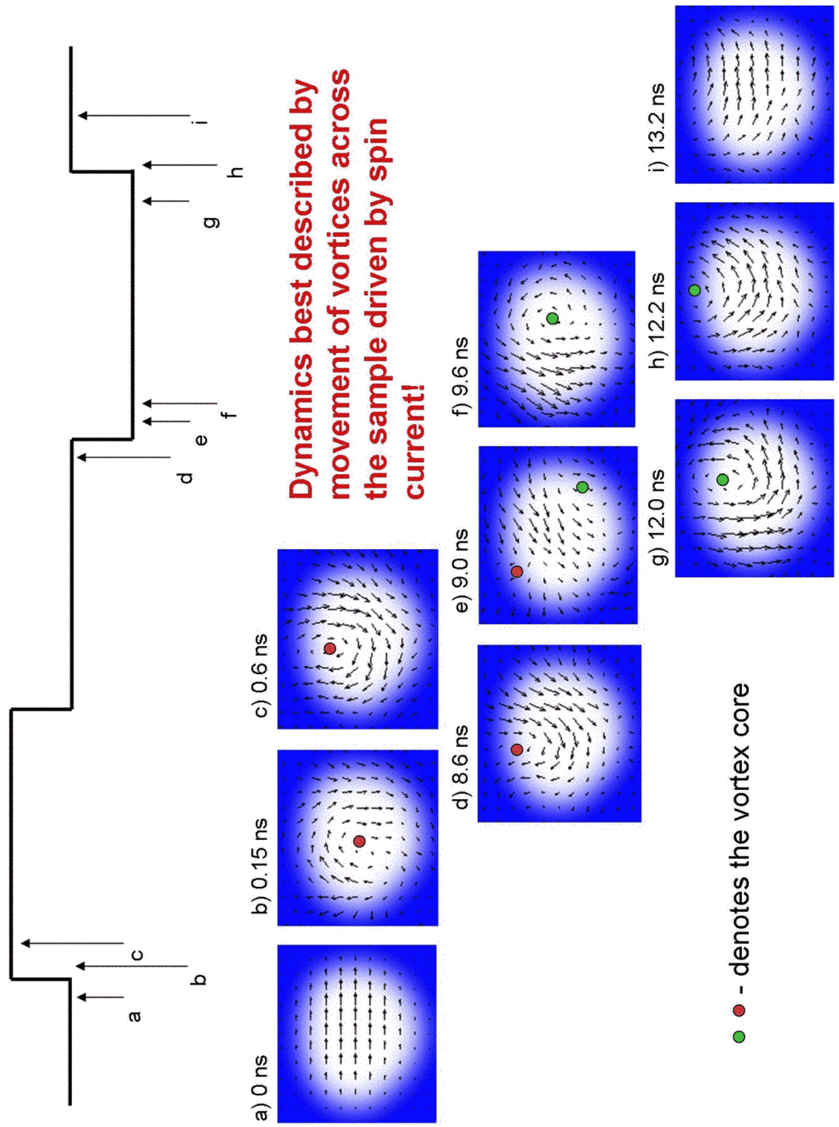

constructed
x-y arrow plot
y-component
x-component
100 nm

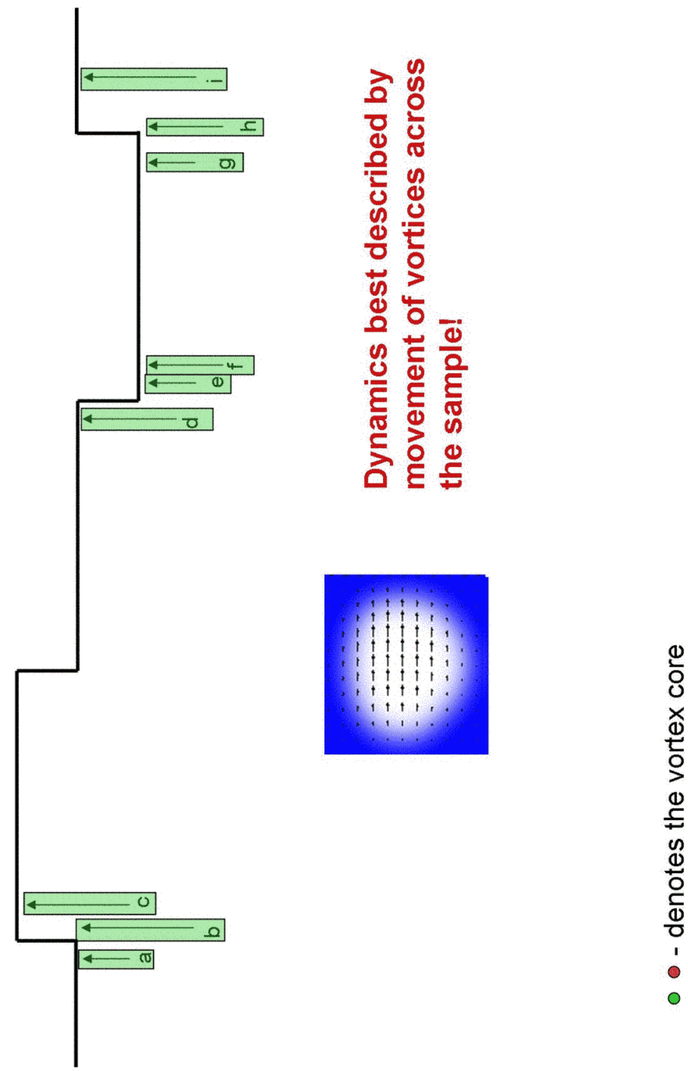

Pulse Sequence
X-component
Y-component
100nm
Vector
field of
magneti
zation



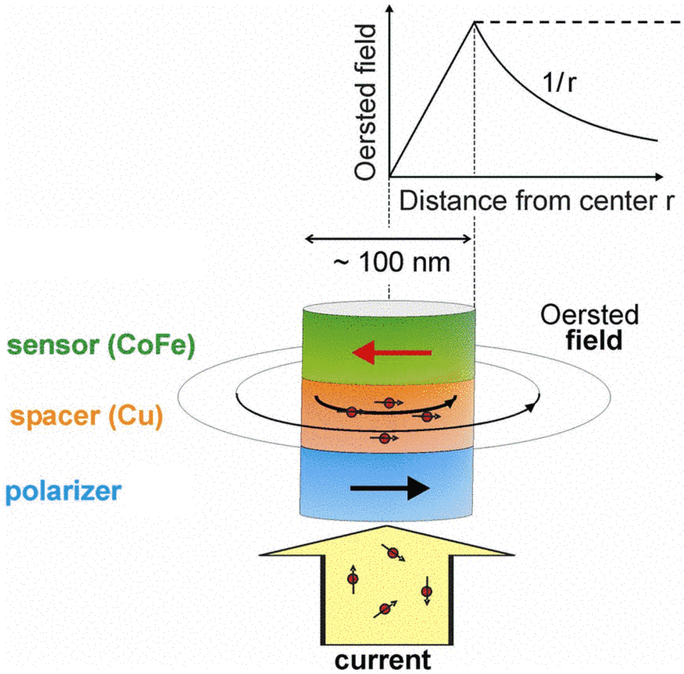
Movie of Magnetization



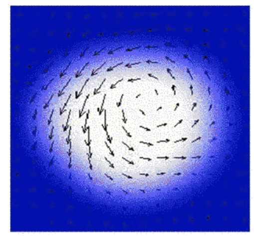

a
b
c
d
e
f
g
h
i
a) 0 ns
b) 0.15 ns
c) 0.6 ns
d) 8.6 ns
e) 9.0 ns
f) 9.6 ns
g) 12.0 ns
h) 12.2 ns
i) 13.2 ns
Dynamics best described by movement of vortices across the sample driven by spin current!
- denotes the vortex core


a
b
c
d
e
f
g
h
i
Dynamics best described by movement of vortices across the sample!
- denotes the vortex core

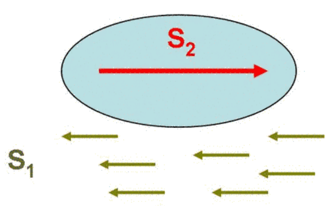
Charge current – creates vortex state
Spin current – drives vortex across sample



= 950 Oersted
for 150x100nm
j = 2×10^8 A/cm^2

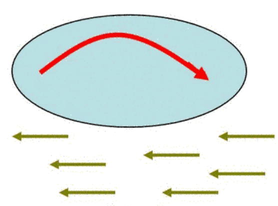


Consequences for the switching speed



Perfect uniform magnetization, anti-parallel to the spin direction: thermal fluctuation needed to generate

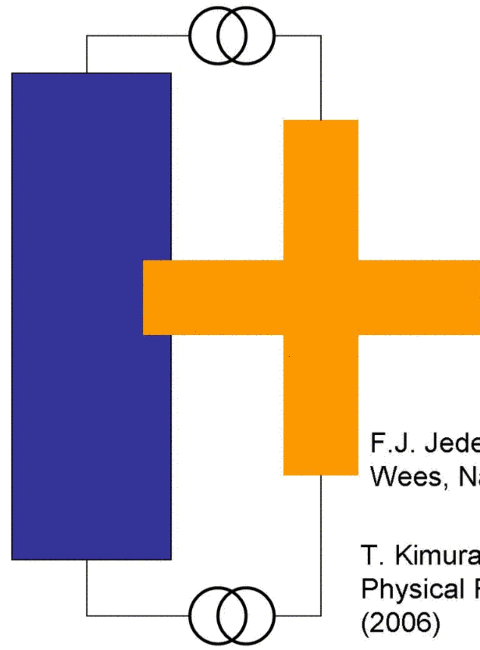
spin torque term $S_1 \times S_2$



Vortex brakes the symmetry: no thermal fluctuations needed to start

speeds up switching

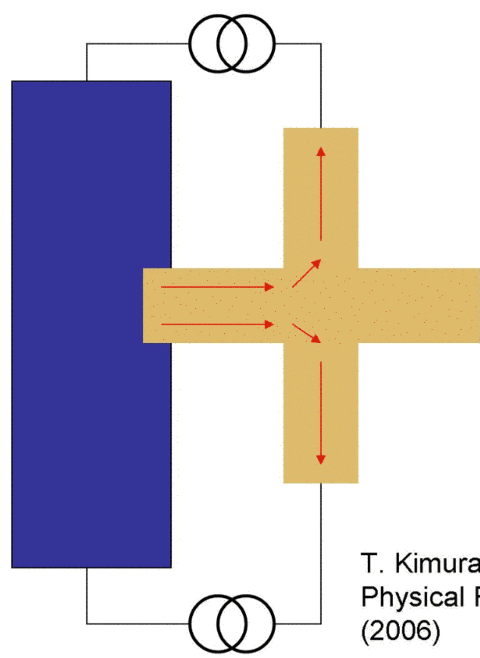
Test of hypothesis: non-local spin switching



F.J. Jedema, A.T. Filip, B.J. van Wees, Nature 410, p.345 (2001)

T. Kimura, Y. Otani, J. Hamrle, Physical Review Letters 96 p.037201 (2006)

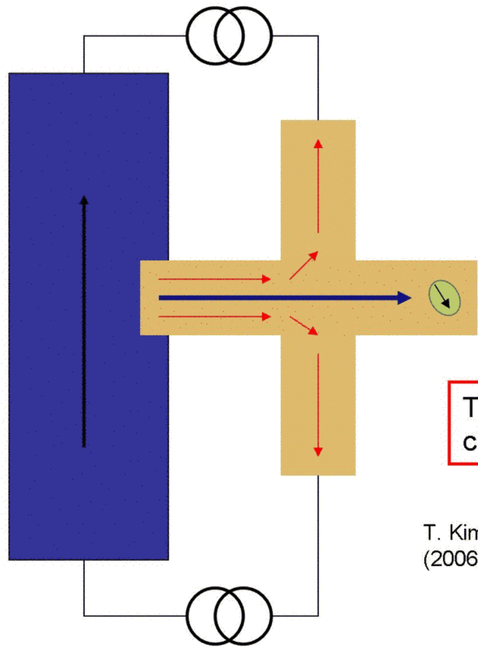
Non-local spin switching



Cu gets polarized, formation of a spin voltage

T. Kimura, Y. Otani, J. Hamrle, Physical Review Letters 96 p.037201 (2006)

Non-local spin switching



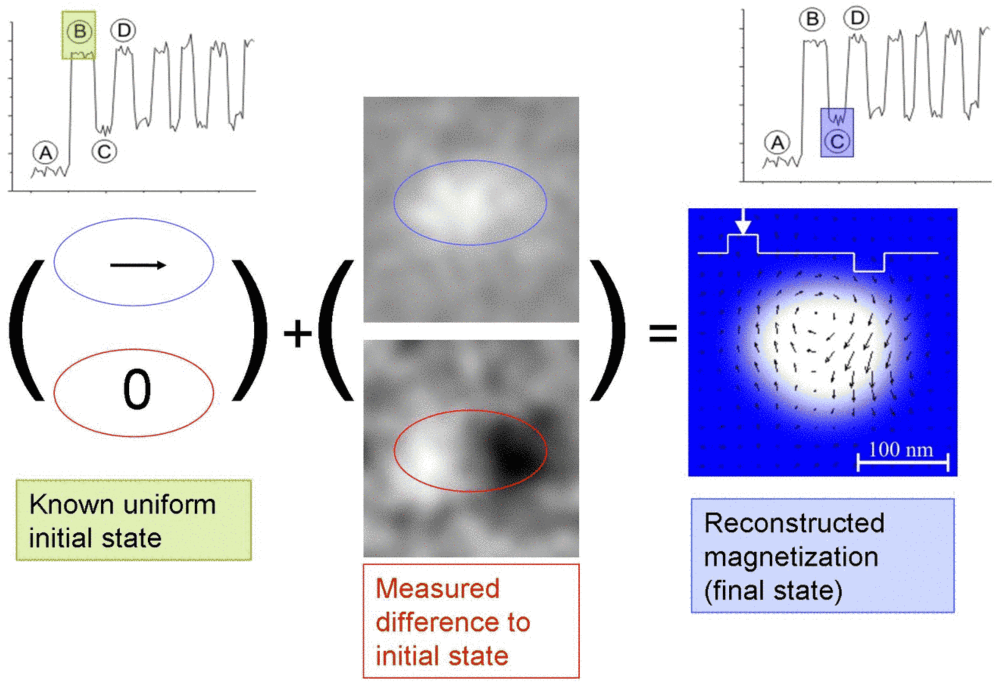
There is a spin current without a charge current!

T. Kimura, Y. Otani, J. Hamrle, PRL **96**, 037201 (2006)

Results

- X-ray imaging of the dynamics of buried magnetic layers is possible!
- Shows fast transitions (< 600ps) between states
- Dynamics best described by vortex motion rather than uniform coherent rotation
- Spin transfer can not necessarily be explained by the macrospin model
  - Need to include influence of non-uniform Oersted field in calculations
- C states are bi-stable with uniform states in our structures
  - Non-uniform intermediate states might accelerate dynamics

Reconstruction of the magnetization



Conclusion

- The vortex in a ferromagnet can influence the dynamics on a large length scale.
- Spin transfer can not necessarily be explained by the macrospin model.
- The vortex can be used to switch the magnetization by spin injection.

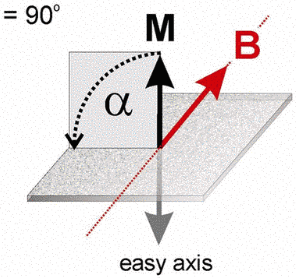
The simplest case: perpendicular magnetic medium

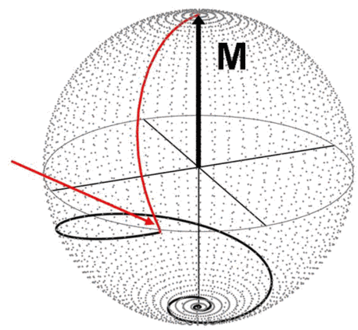
"precessional switching" - max. torque on **M**

initiate switch: $\alpha = 90^\circ$

$B\,\tau = \alpha$

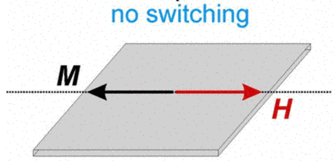
B = 1 Tesla
τ = 9 ps





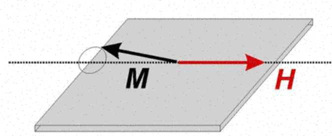
186 years of "Oersted switching"….

No torque on ***M***
no switching



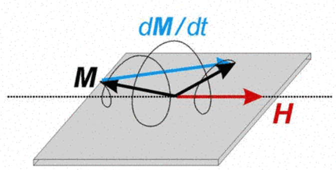
easy axis

Thermal excitation → torque ***T*** = ***H*** x ***M***
starts precession: ***T***=- *d**M**/dt* transferred to field ***H***



1 Tesla - 180° precession in 36 ps

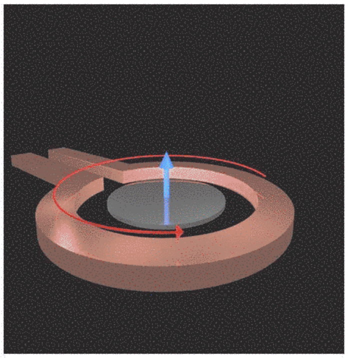
During reversal, change in angular momentum *d**M**/dt*
transferred to lattice



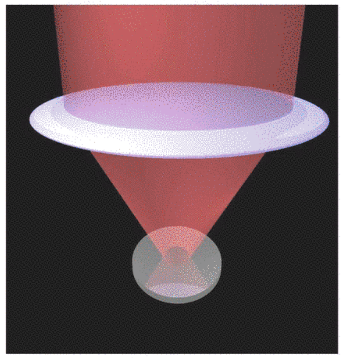
angular momentum transfer limited by
spin-lattice relaxation time ~ 100 ps

How can we switch faster ?

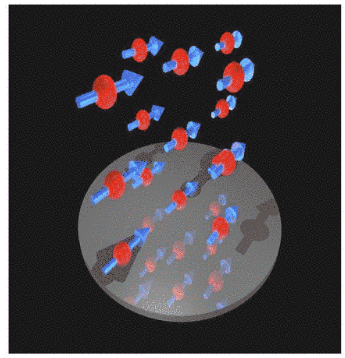
How can we Manipulate the Magnetization of a Ferromagnet?



By applying a magnetic field



By heating (using a laser pulse)



By spin polarized electrons!