X-rays have come a long way……

magnetic imaging, nanoscale, ultrafast

1895

Collaborators:

SSRL – Stanford

H. C. Siegmann
H. Ohldag
Y. Acremann
J. Lüning

W. Schlotter
S. Andrews
J. P. Strachan
V. Chembrolu

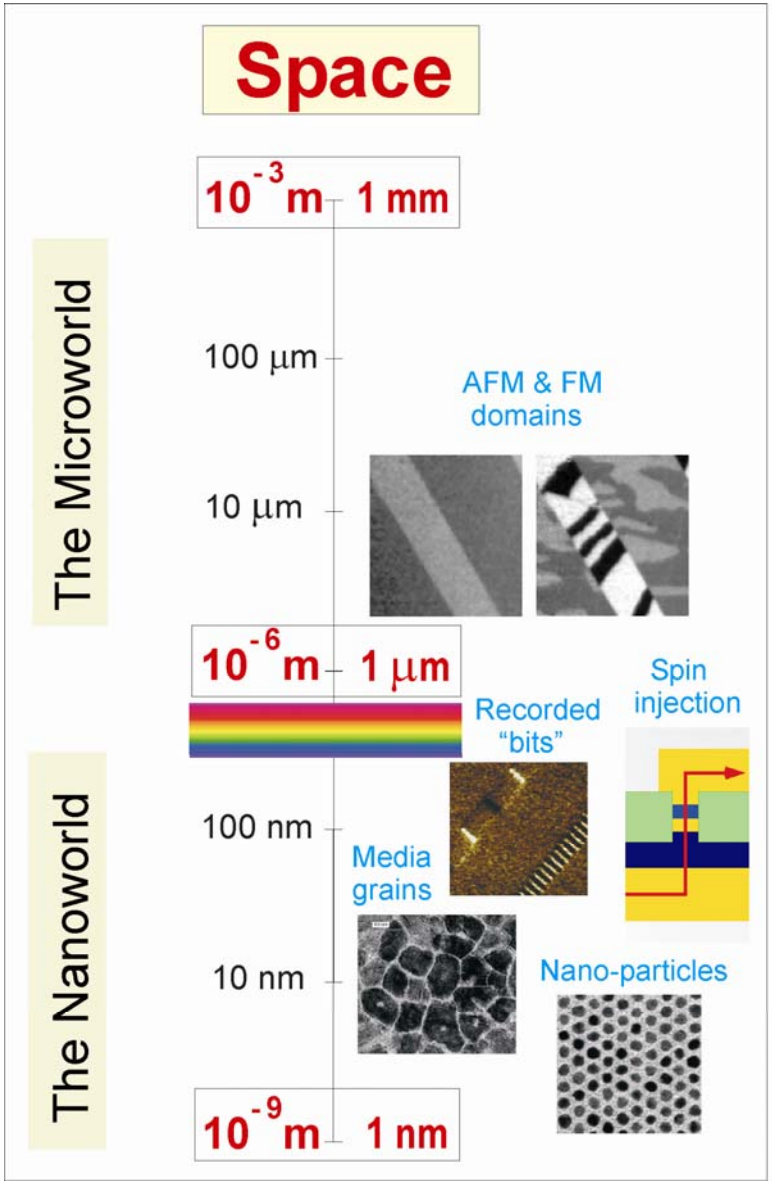
Berkeley - ALS:

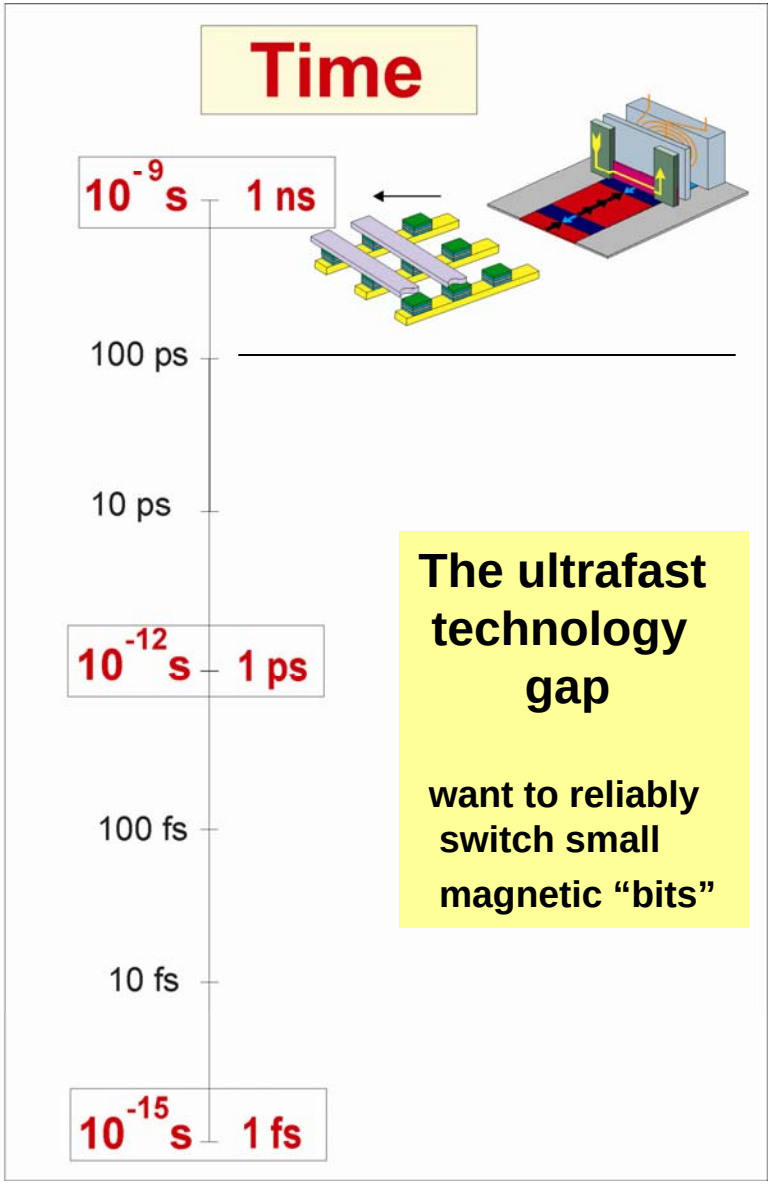
A. Scholl
S. B. Choe
A. Bauer (FU Berlin)

Berlin - BESSY:

S. Eisebitt
M. Lörgen
O. Hellwig
W. Eberhardt

The Technology Problem: Smaller and Faster





The ultrafast technology gap

want to reliably switch small magnetic "bits"

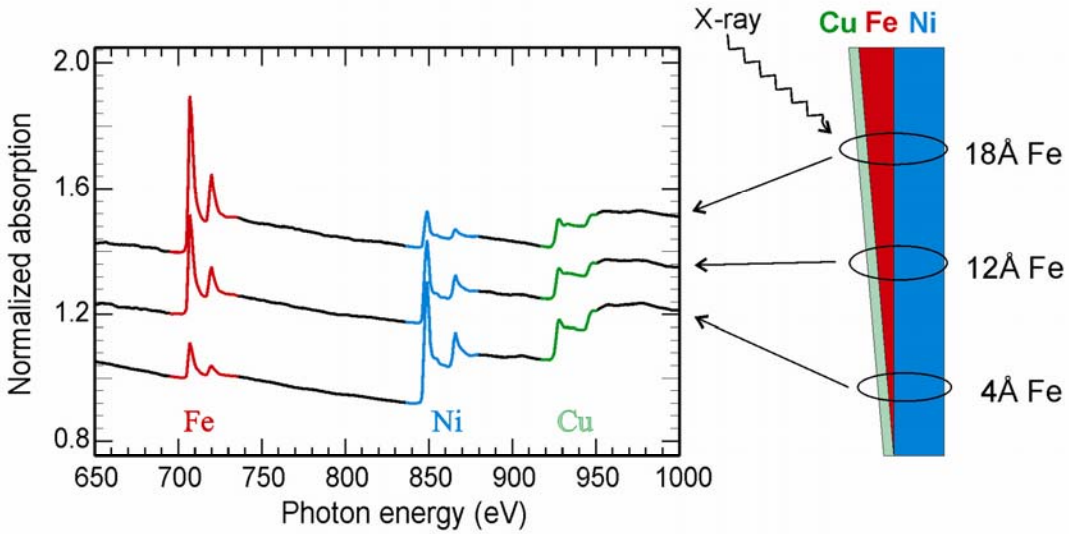
Capabilities of X-Rays
&
Experimental X-Ray Methods

What does it take to explore advanced magnetic materials and phenomena ?

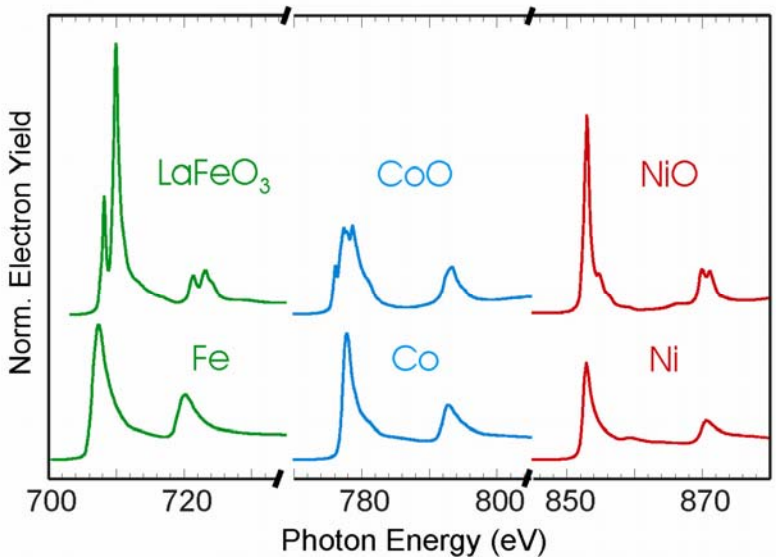
Need techniques that can:

see the invisible	spatial resolution < 300 nm
study thin films and interfaces	large cross section for “signal”
look below the surface	depth sensitivity
distinguish components	elemental (chemical) specificity
resolve dynamic motions	time resolution < 1 nanosecond

X-rays can pick materials apart: layer-by-layer

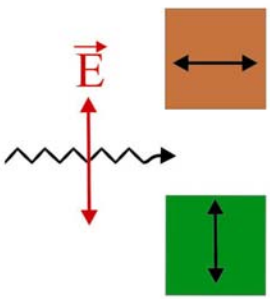


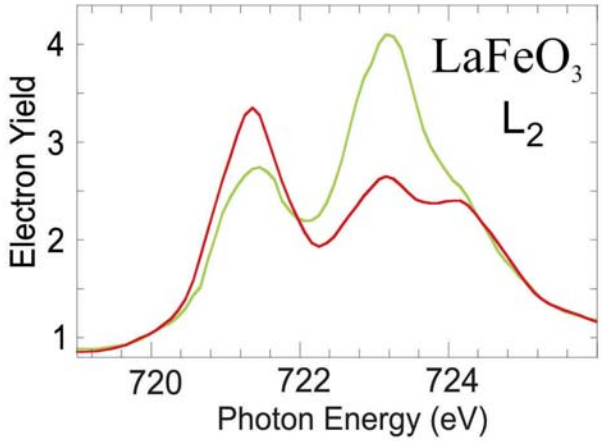
X-rays offer chemical sensitivity



Magnetic Spectroscopy and Microscopy

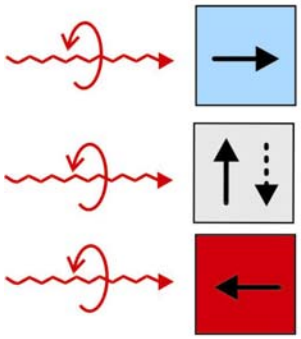
X-ray Magnetic Linear Dichroism: Antiferromagnets



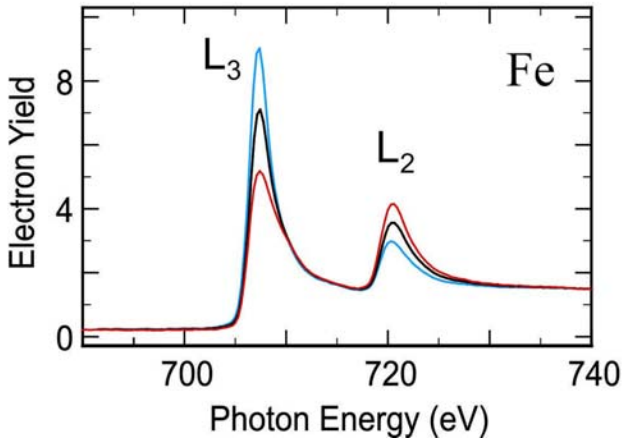


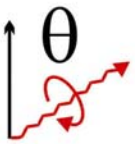
$I \sim \cos^2\theta$

X-ray Magnetic Circular Dichroism: Ferromagnets



x-ray "spin"





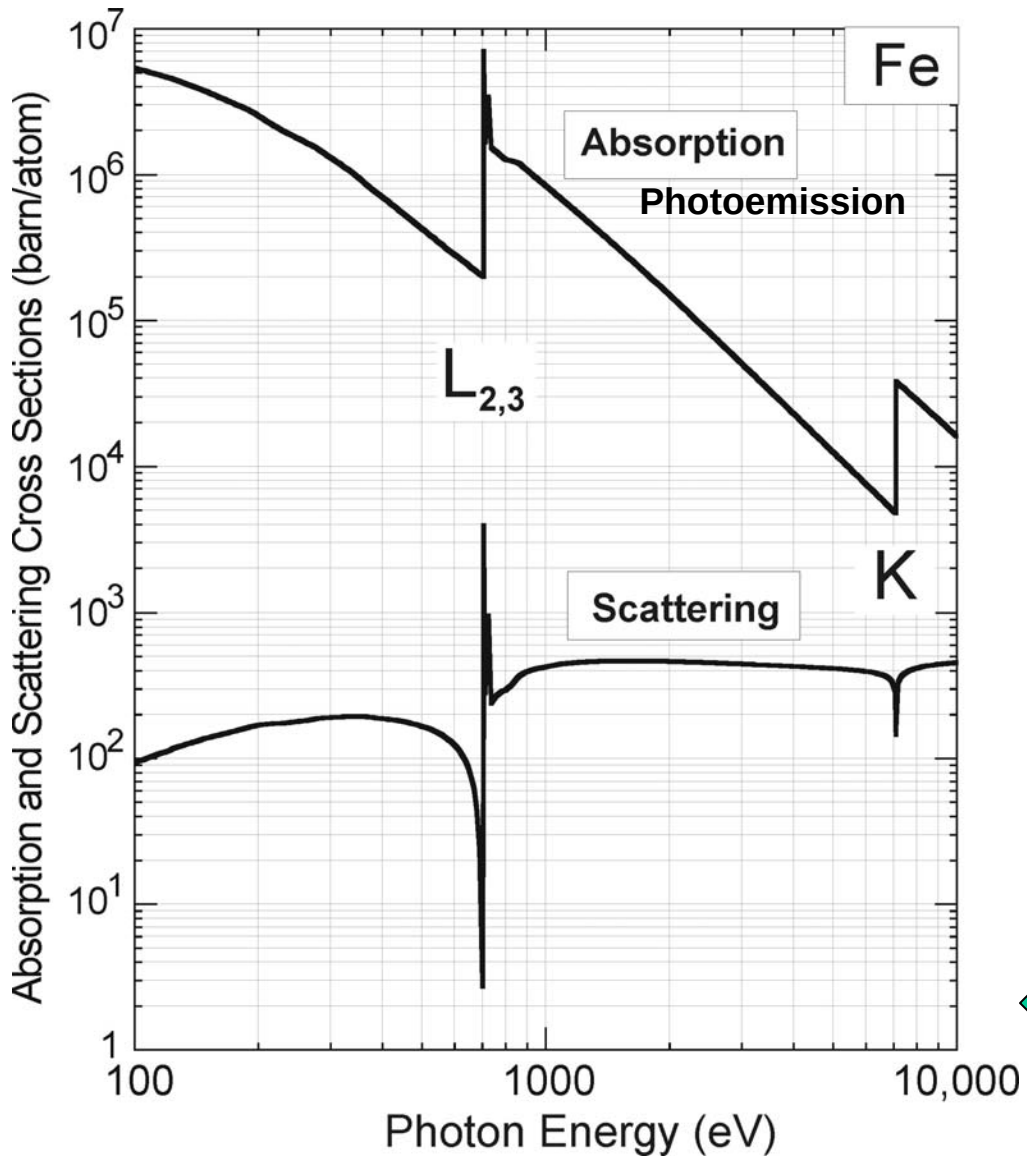
$I \sim \cos\theta$

Soft X-Rays are best for magnetism!

Tunable x- rays offer variable interaction cross sections

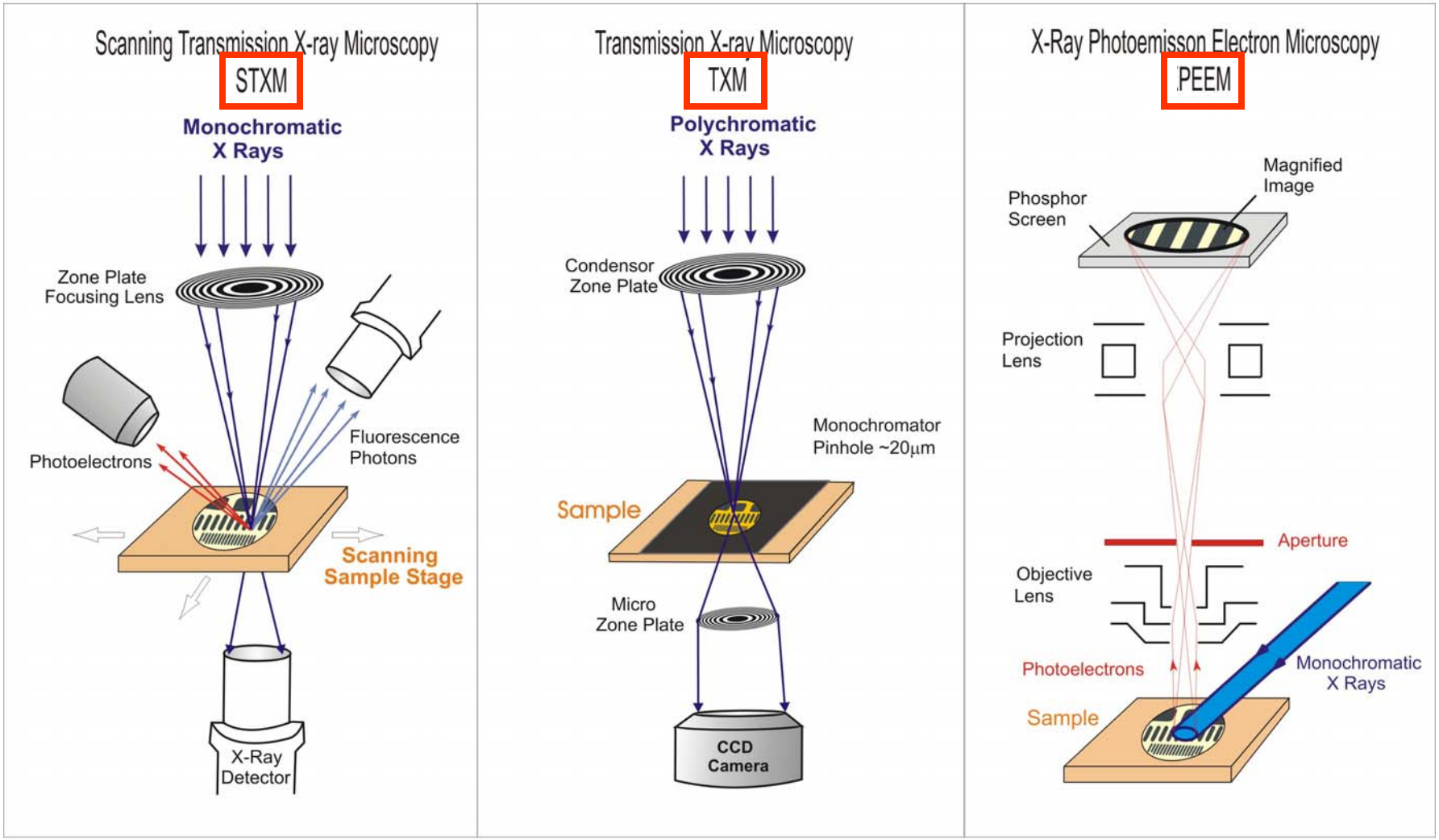
optical light

electrons



neutrons

Focusing of x-rays offers nanoscale resolution



Present resolution in the 20 - 40 nm range

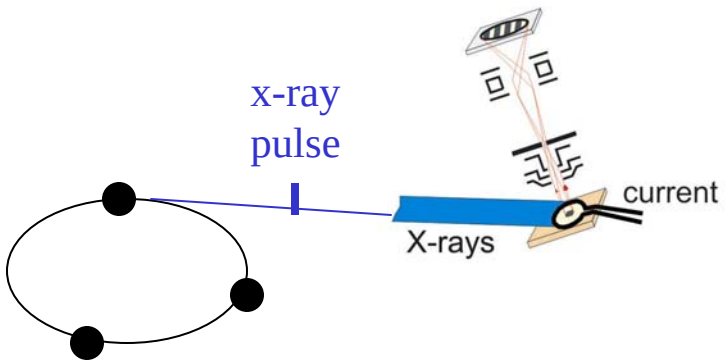
Experimental Results 1:

Time resolved imaging of magnetic structures

Time

Science

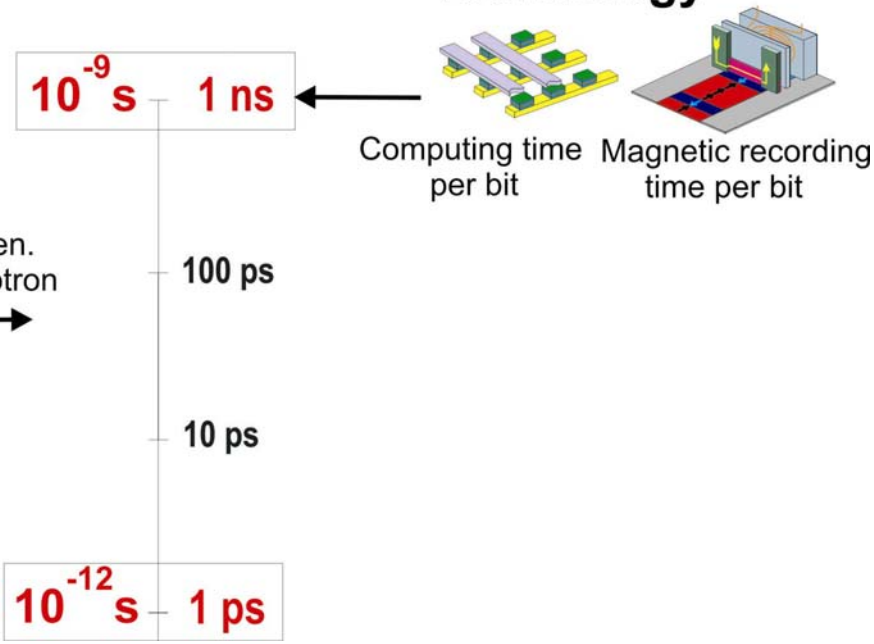
The length of probe pulses:



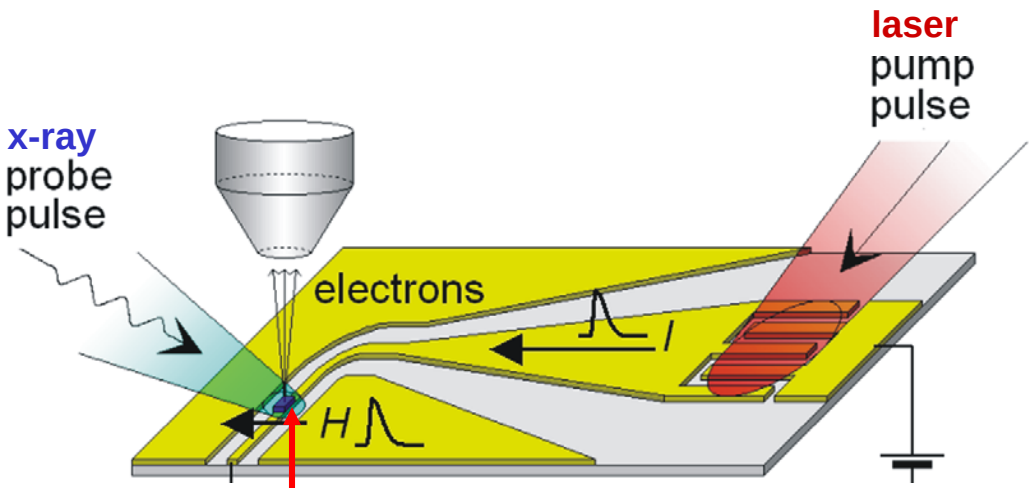
electron
storage
ring

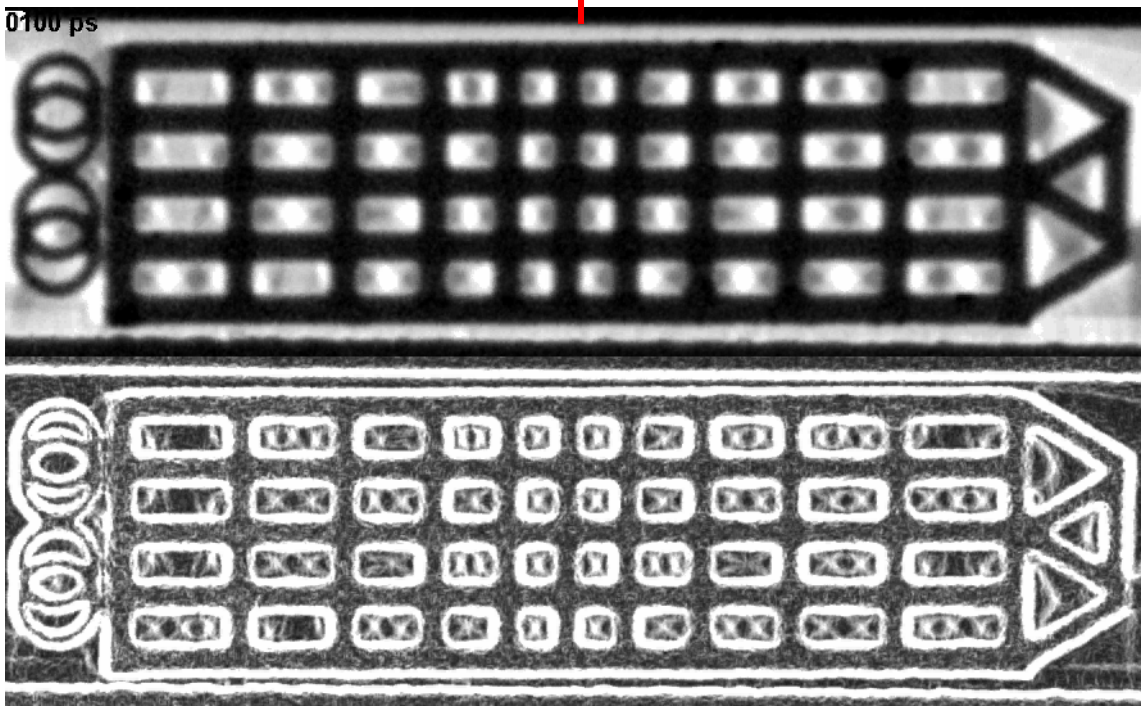
3rd gen.
synchrotron

Technology



Imaging of Motion of Nanoscale Domains (100 ps)

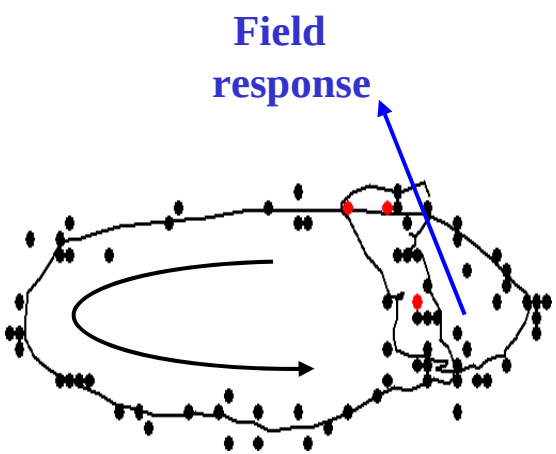


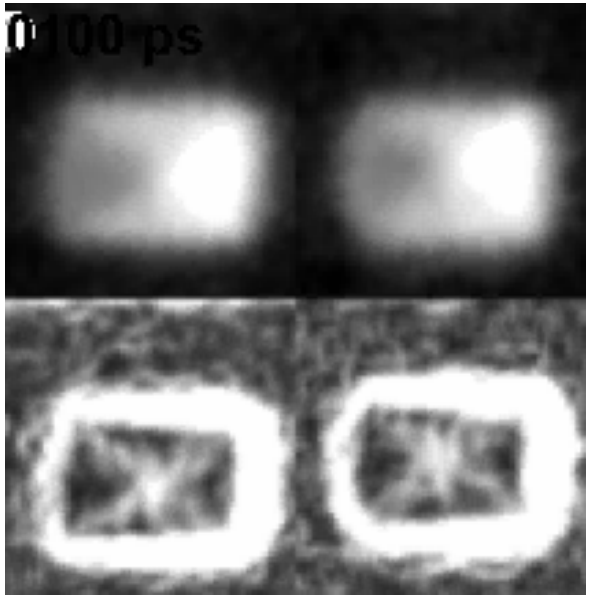


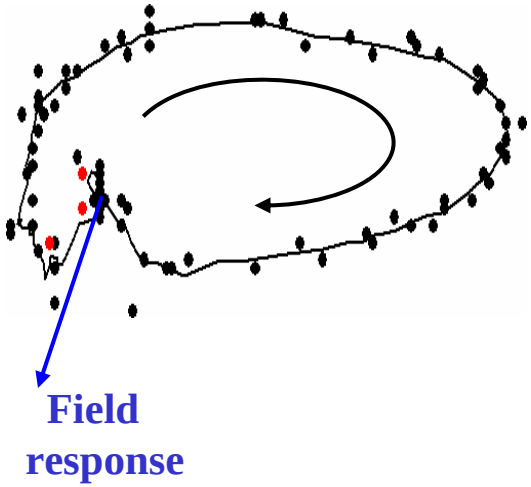
real image

differential image

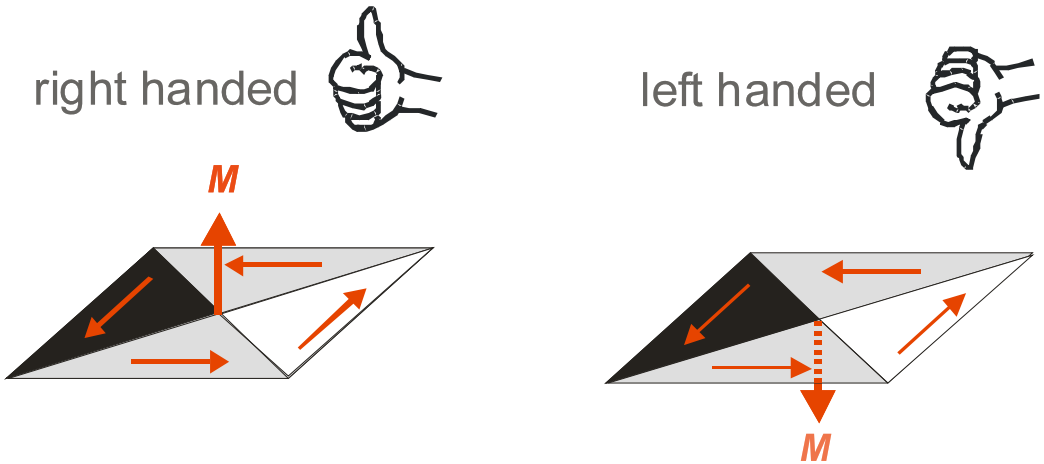
Two pattern with same static structure, but …..



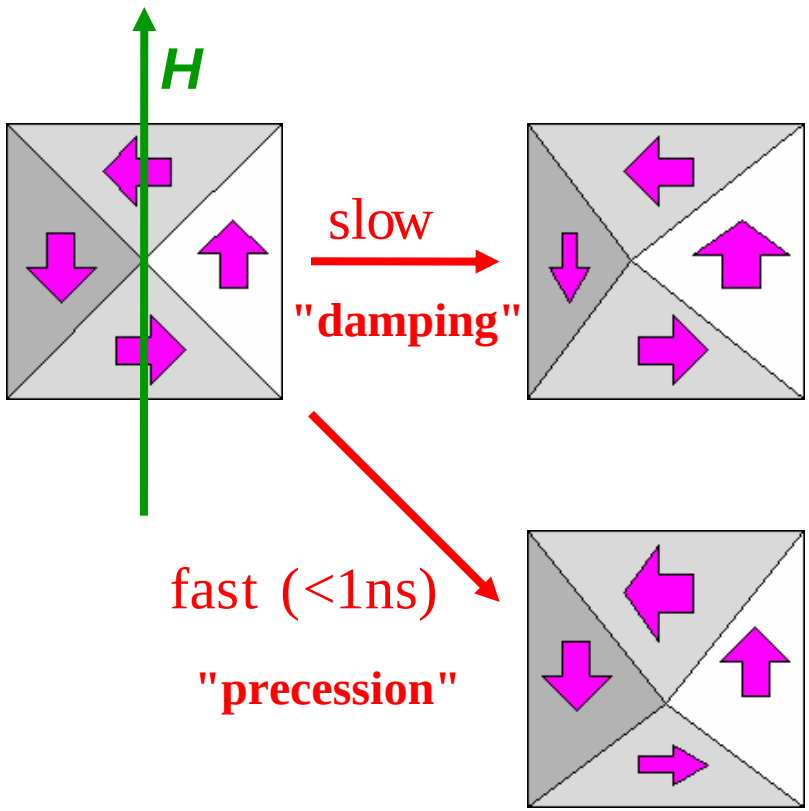




Opposite rotation is caused by direction of vortex core magnetization, i.e. chirality

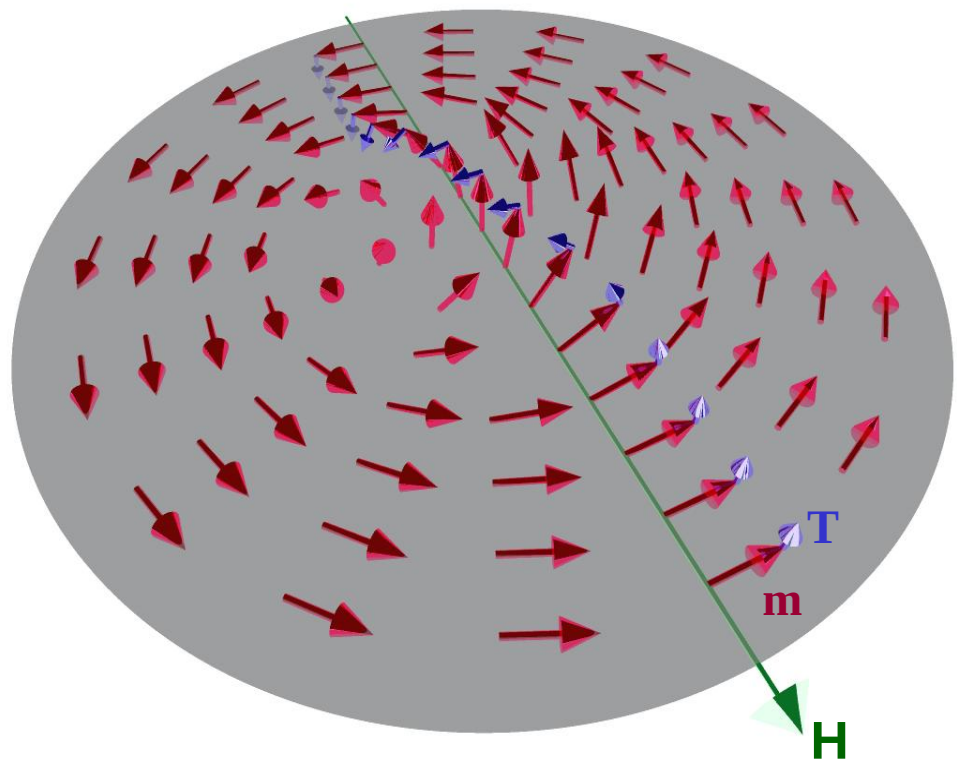


Response to a fast field pulse



Instanteneous precession determined by torque:

T = **H** x **m**



Tiny vortex core determines fast dynamics of the whole domain structure!

Experimental Results 2:

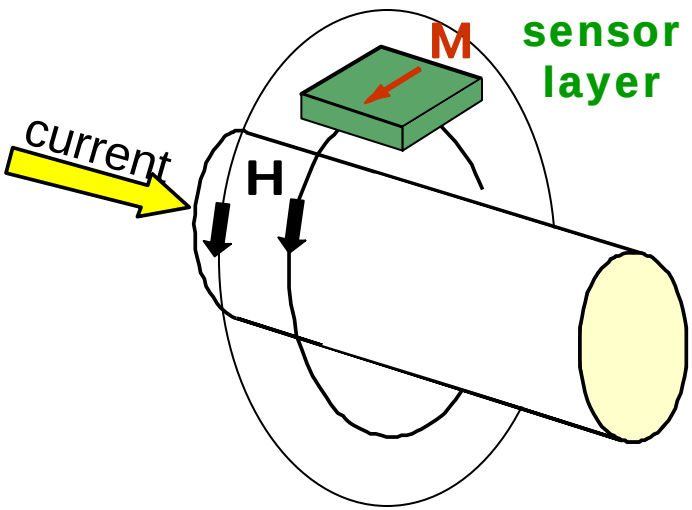
Beyond “Oersted switching” and “ballistic switching”….

Magnetic switching by spin currents

Spin currents: a new way of magnetic switching:

electric current creates magnetic field

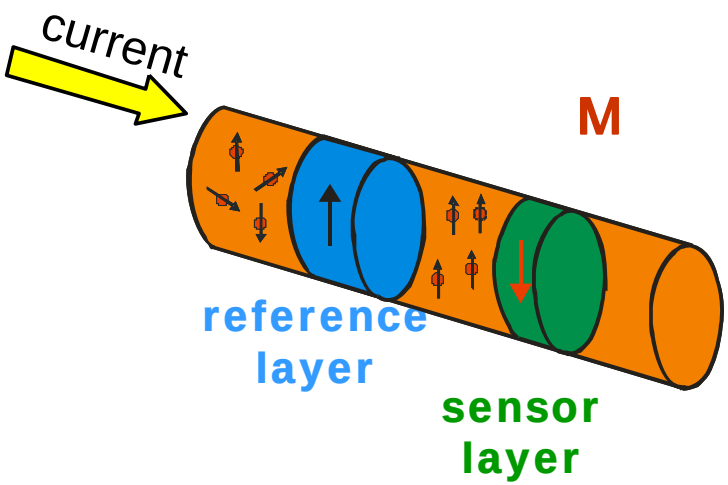
"Oersted field"



Weak, long range

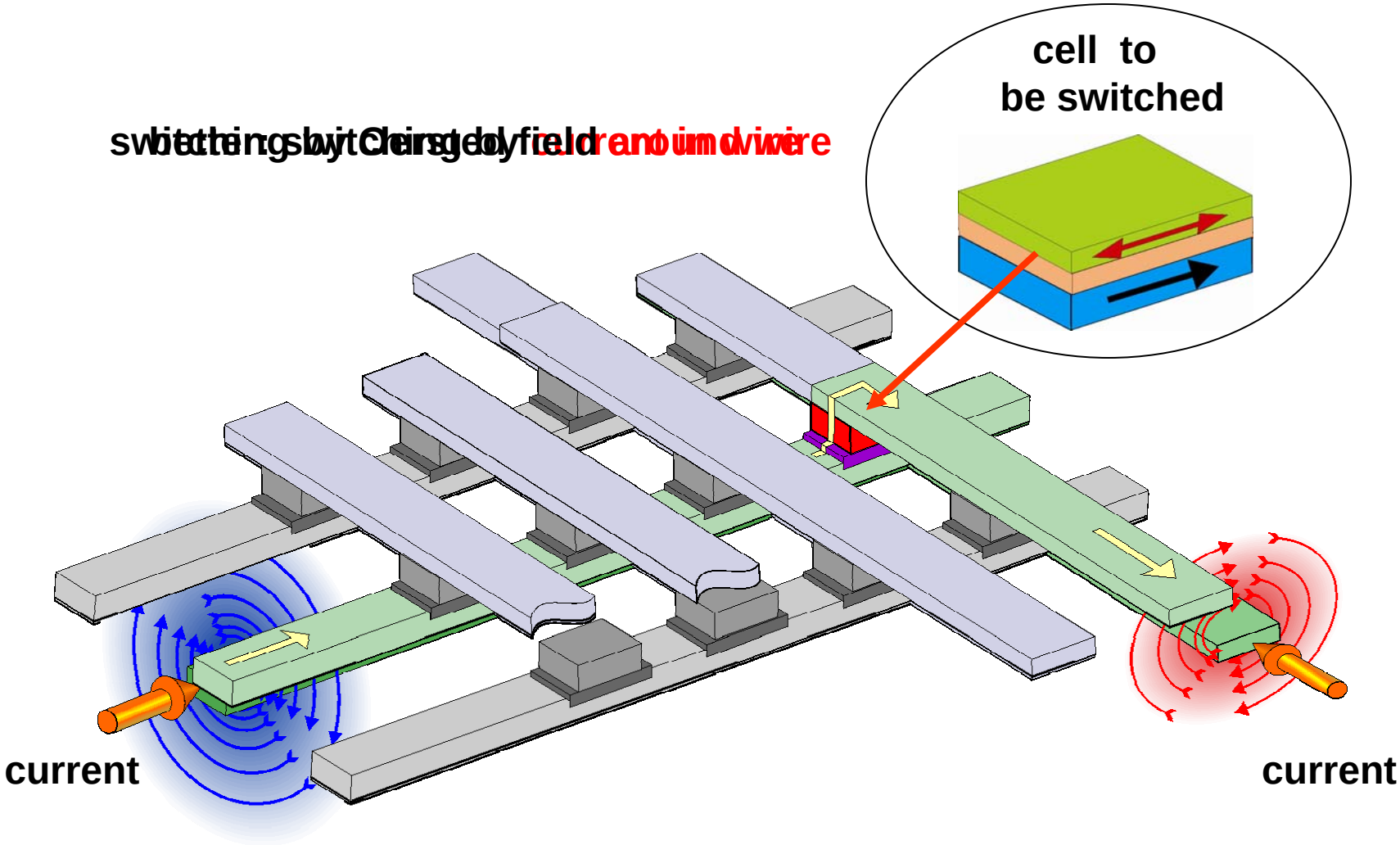
spin current acts like an

"Exchange field"

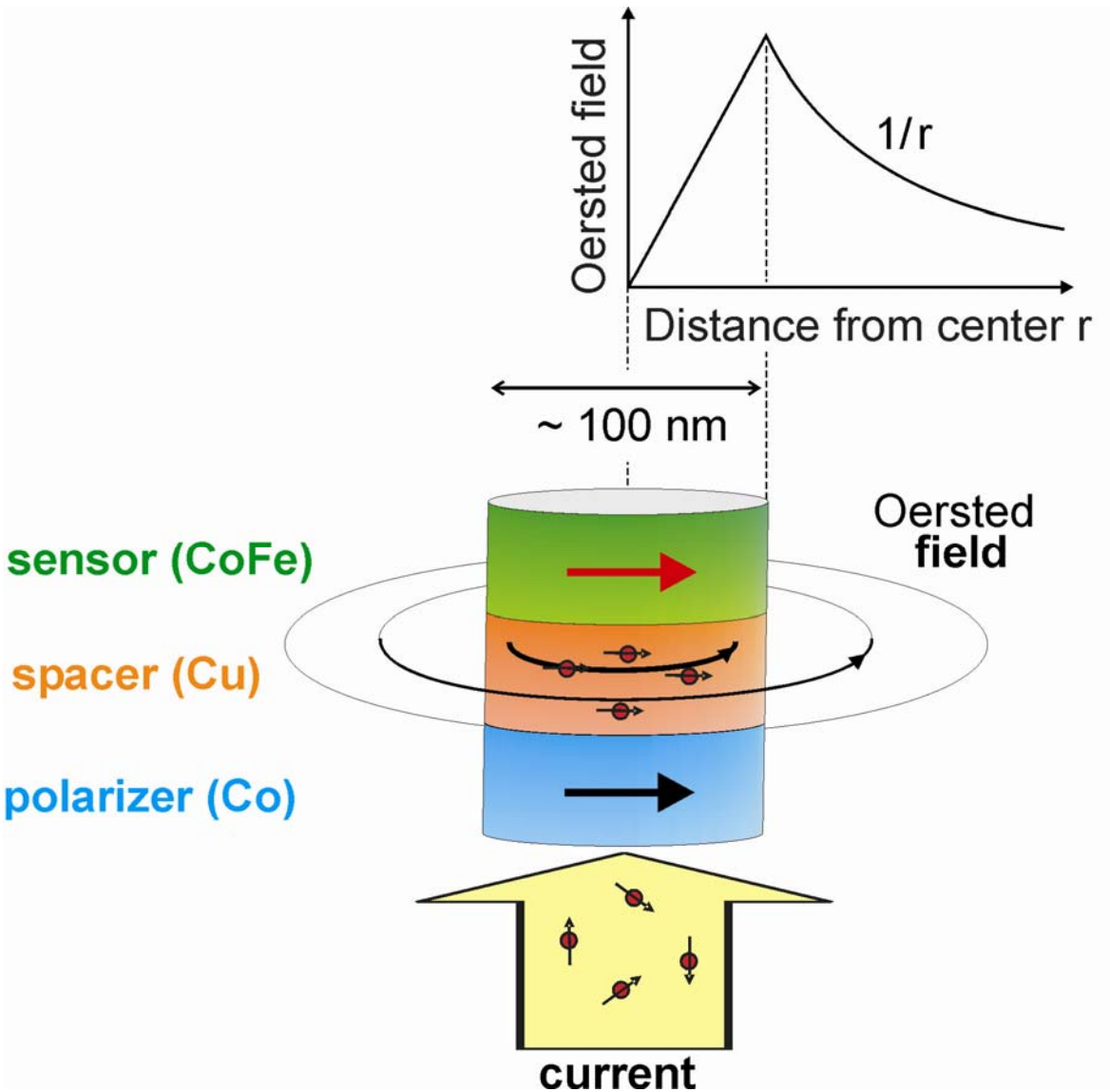


Strong, short range

Switching of magnetic memory cells (MRAM)



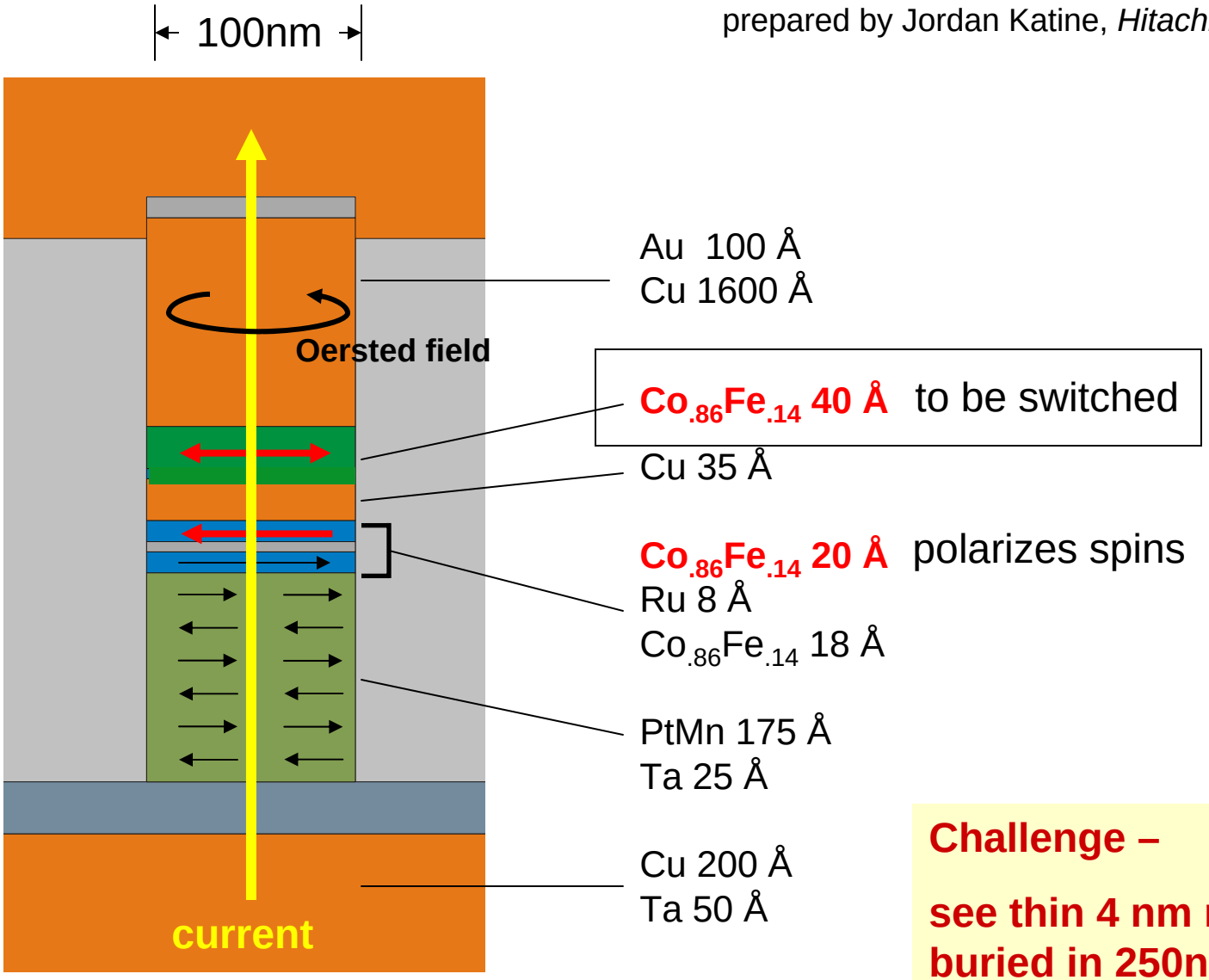
A new way of magnetic switching: spin injection



current becomes spin-polarized

Samples for spin-injection studies – e-beam lithography

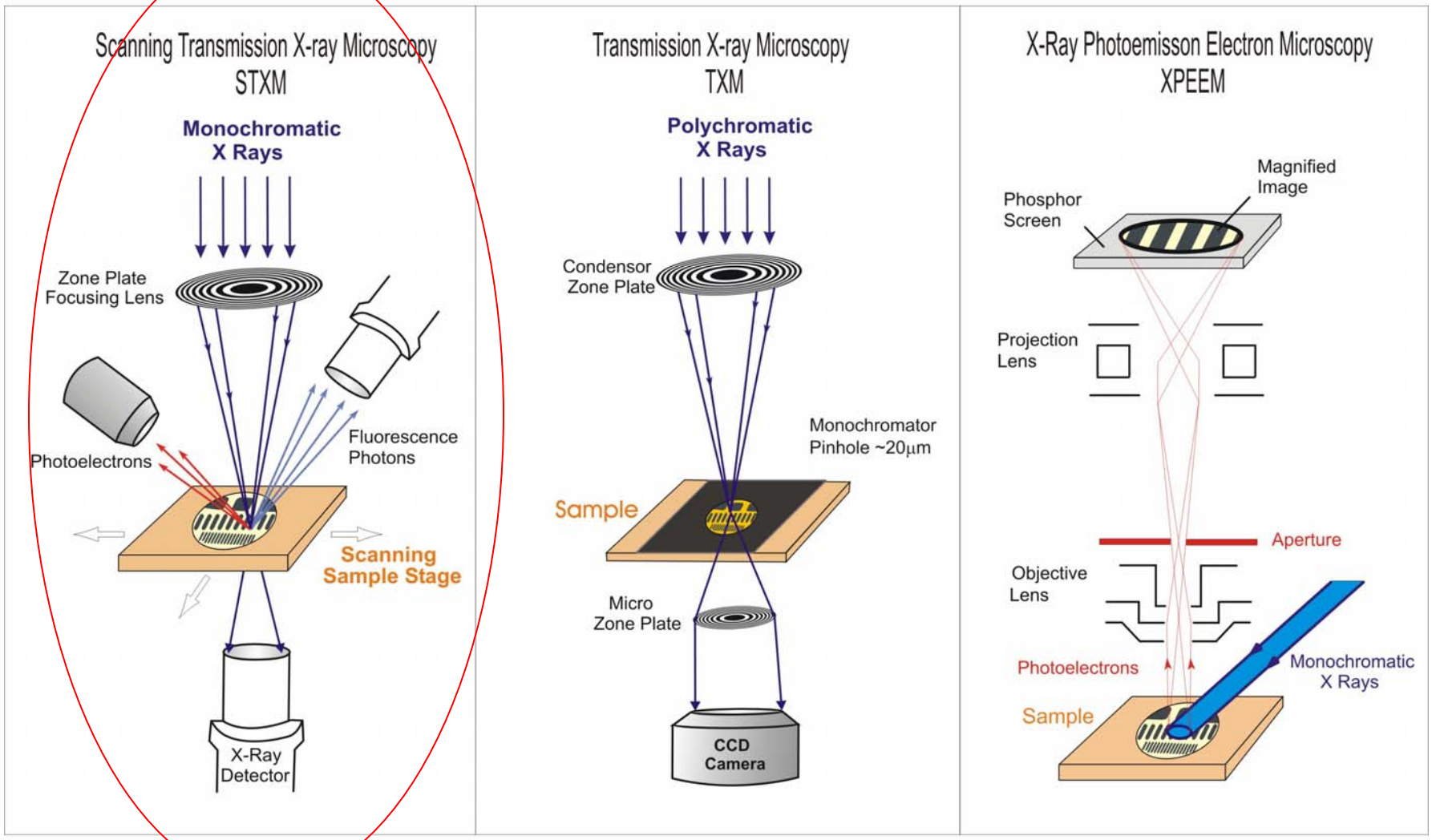
prepared by Jordan Katine, *Hitachi Global Storage*



Challenge –

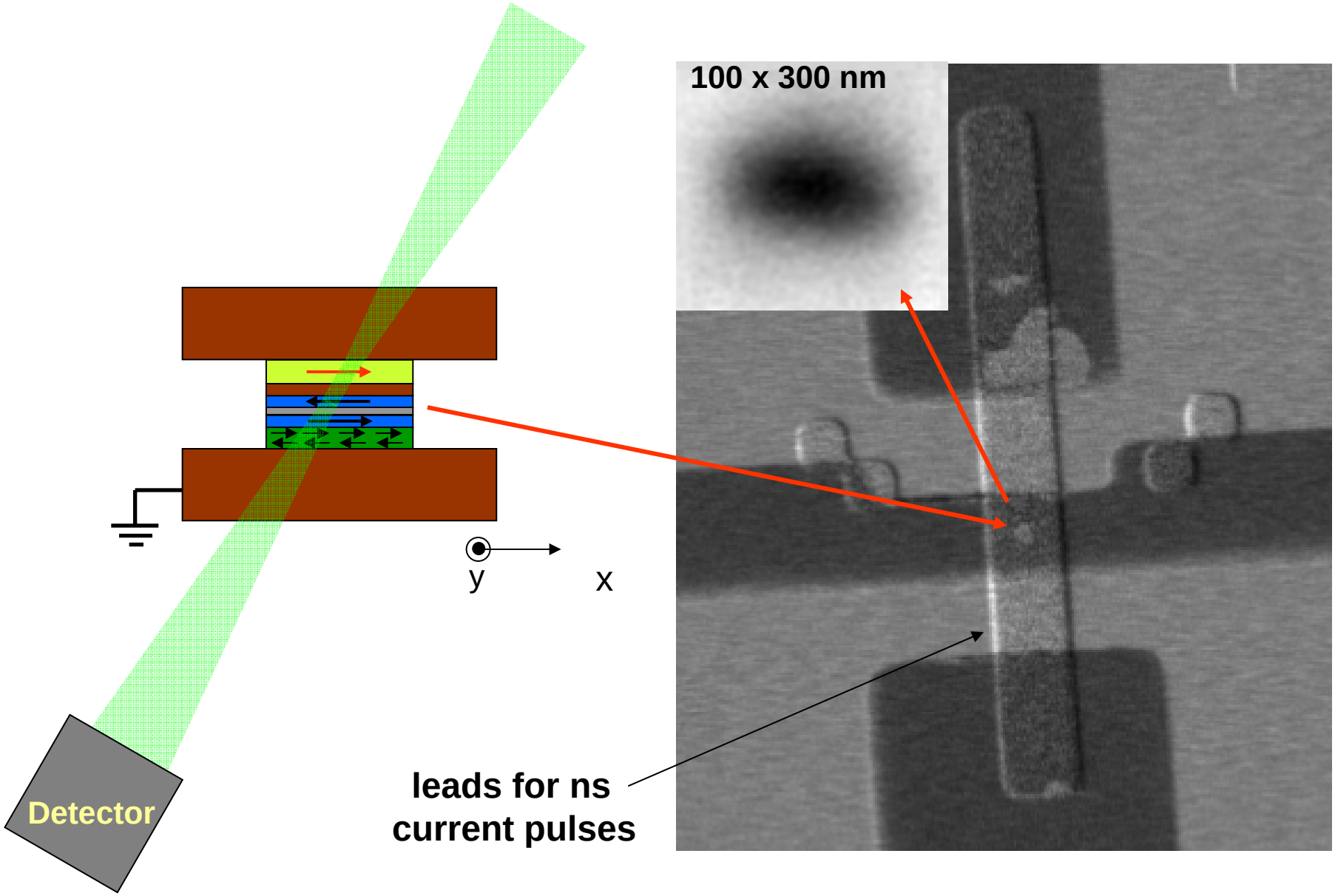
see thin 4 nm magnetic layer buried in 250nm of metals!

X-Ray Microscopy Methods - toward Nanometer Resolution

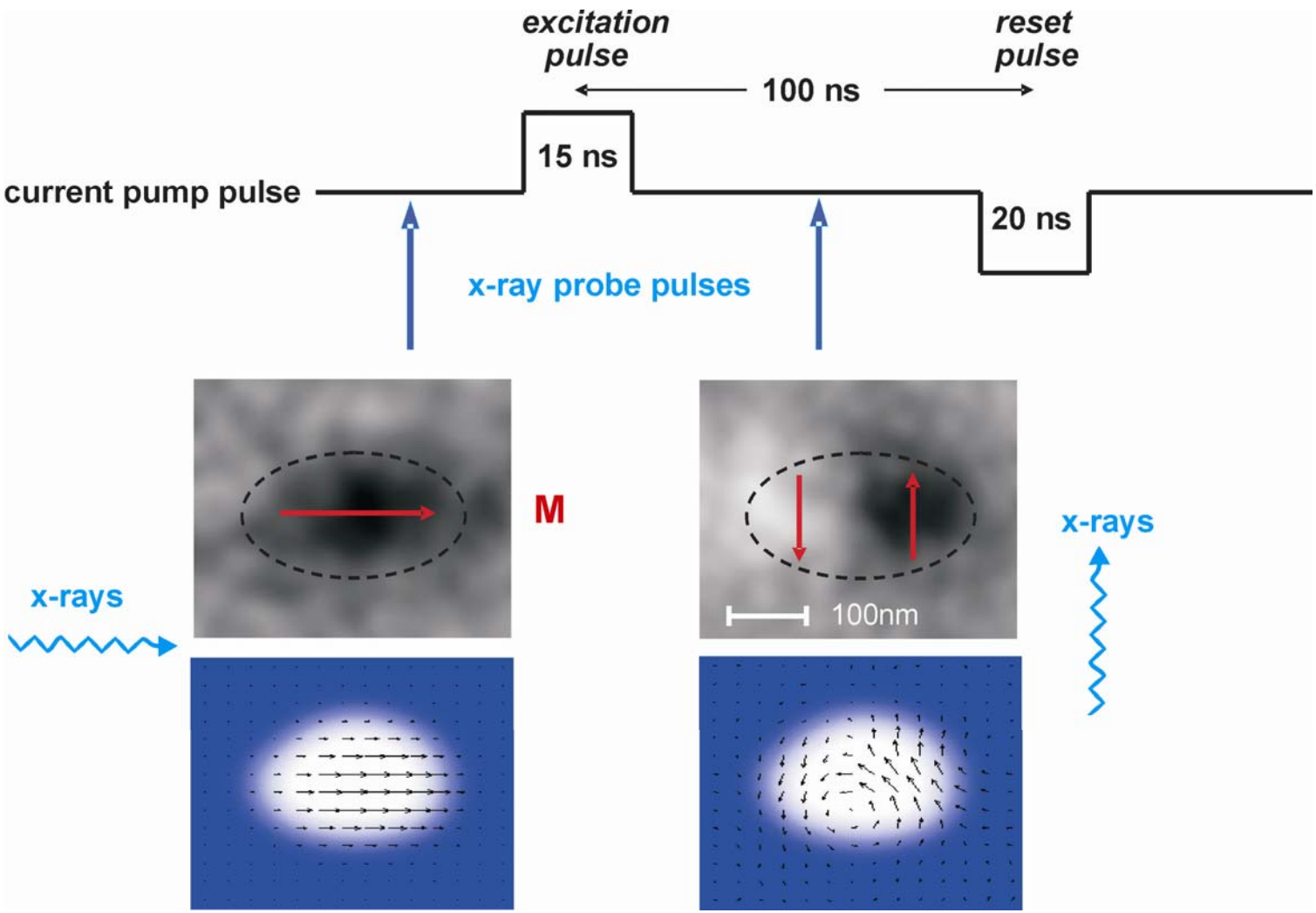


Present resolution in the 20 - 40 nm range

STXM image of spin injection structure



Images before and after spin injection pulse



magnetization has complicated "**C**" state
both **electrical current** and **spin current** contribute

A Vision of the Future……..

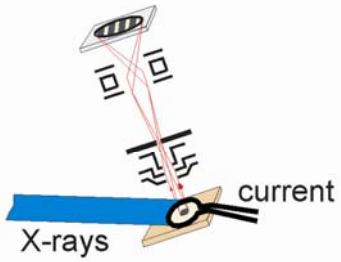
Ultrafast pictures -

single shot images with x-ray lasers (XFEL)

Time

Science

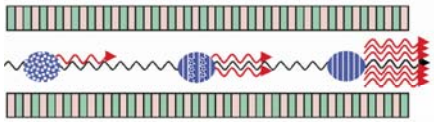
The length of probe pulses:



3rd gen. synchrotron

not enough intensity –

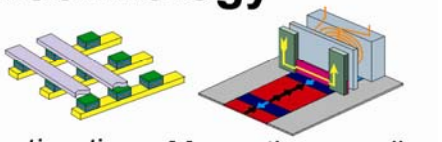
cannot do microscopy



Slicing

X-Ray Lasers

Technology



Computing time per bit

Magnetic recording time per bit

10^{-9} s — 1 ns

100 ps

10 ps

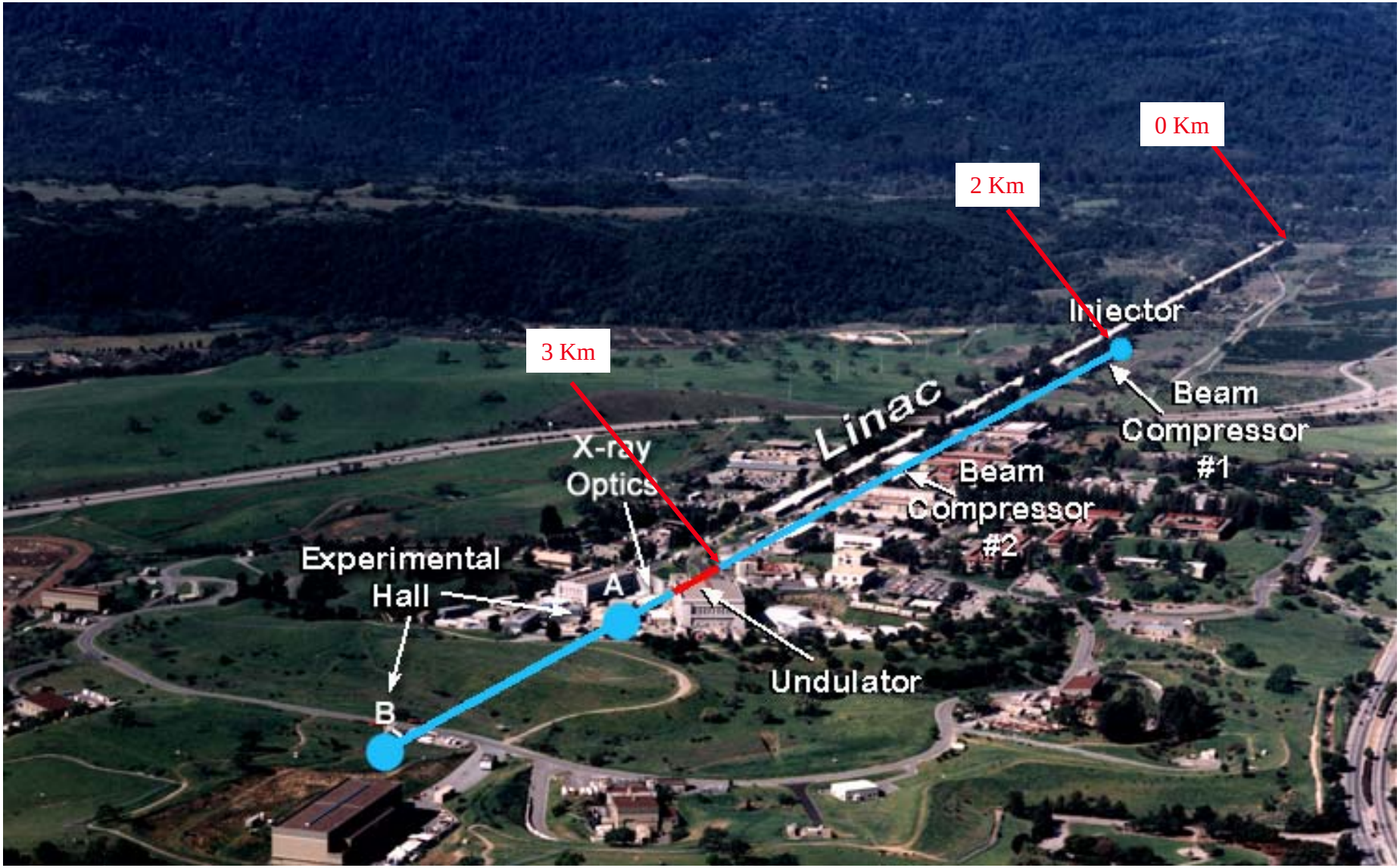
10^{-12} s — 1 ps

100 fs

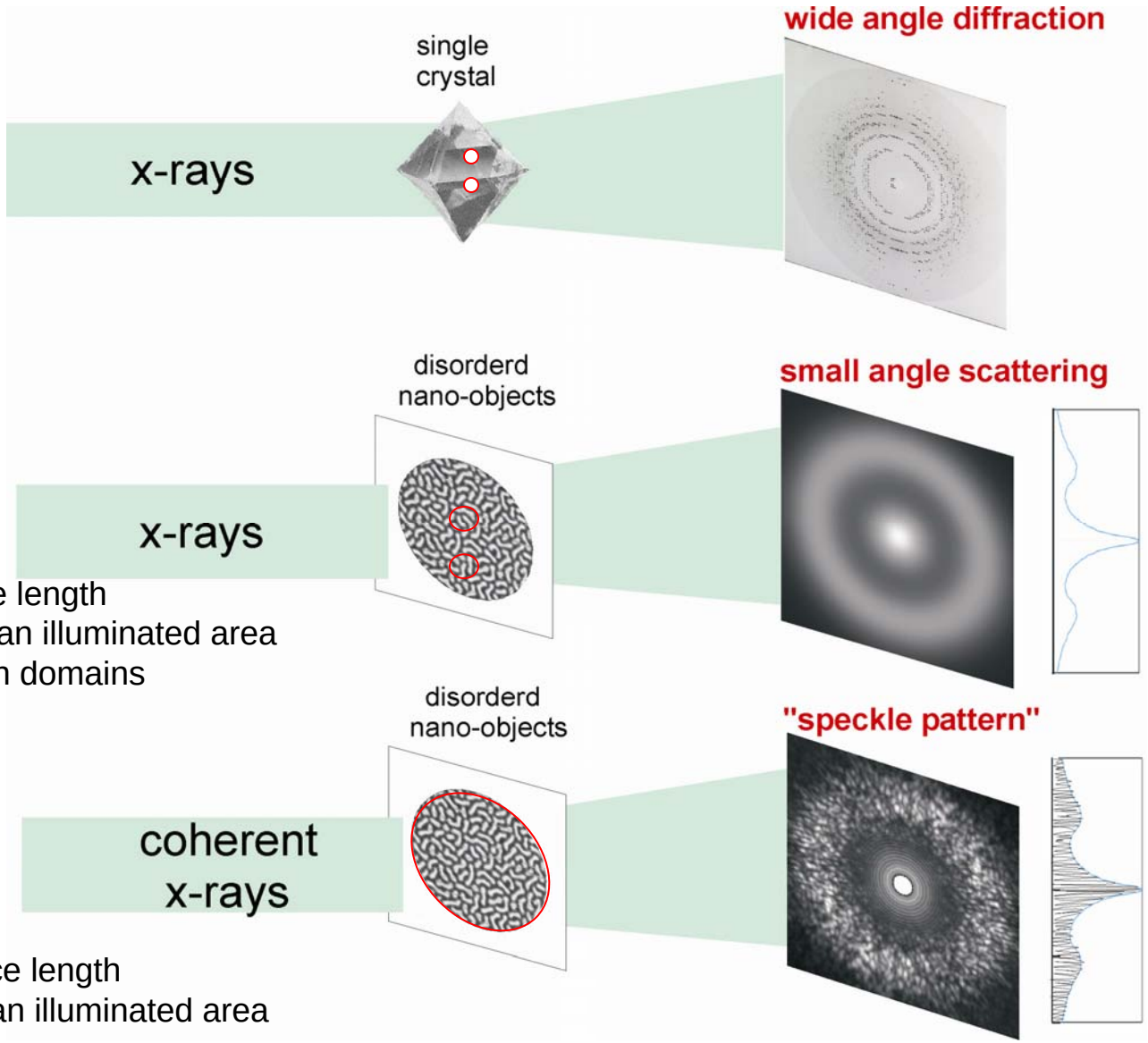
10 f s

10^{-15} s — 1 fs

Coming to Stanford … in 2008:
The first x-ray laser - LINAC COHERENT LIGHT SOURCE (LCLS)



A new way to take fast images – no lenses !

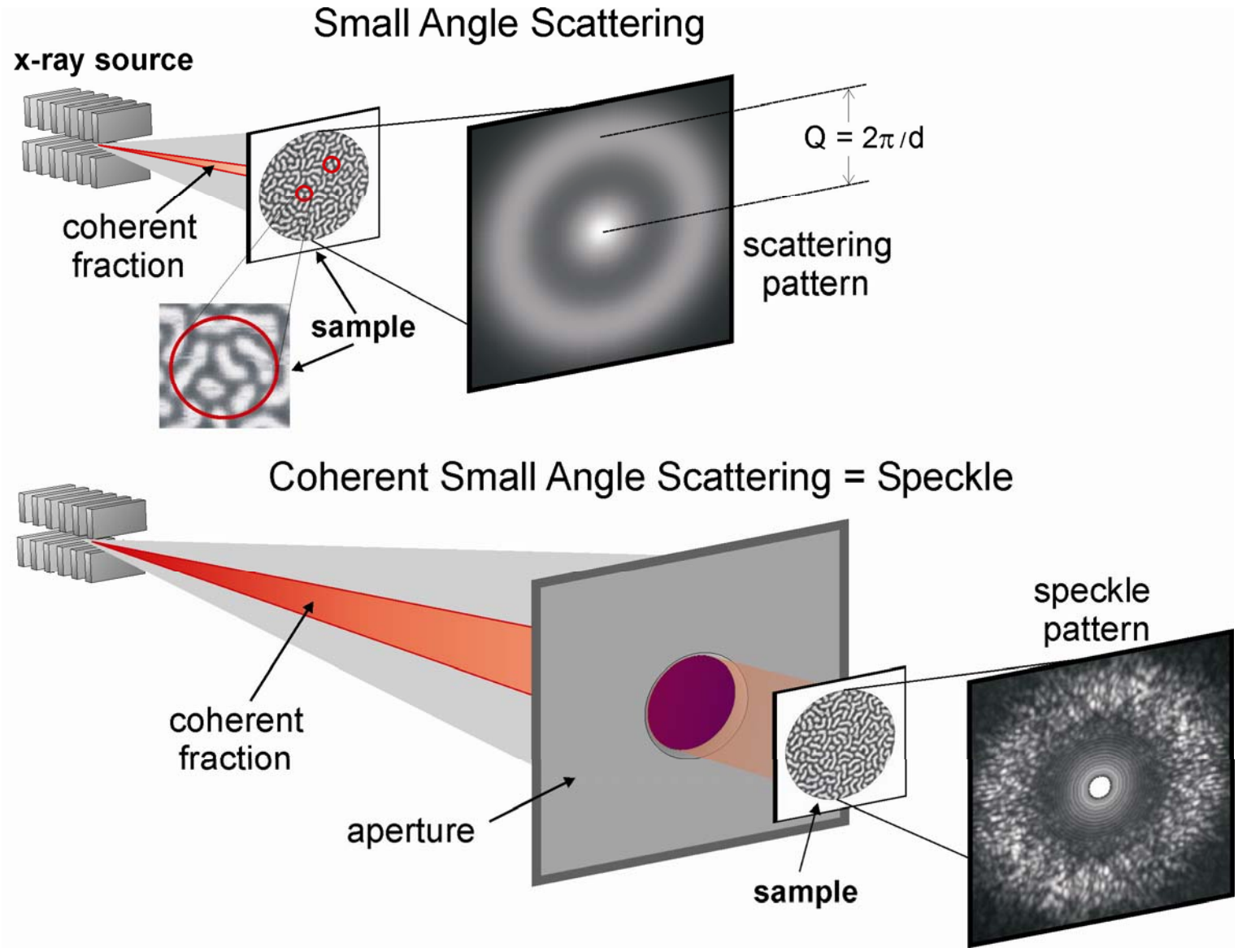


coherence length
smaller than illuminated area
larger than domains

coherence length
larger than illuminated area

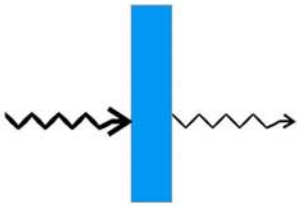
Can the reciprocal space pattern be inverted ?

Towards single shot imaging



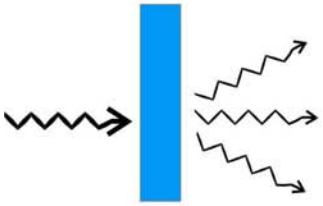
X-Ray Dichroism in Absorption and Scattering

Absorption



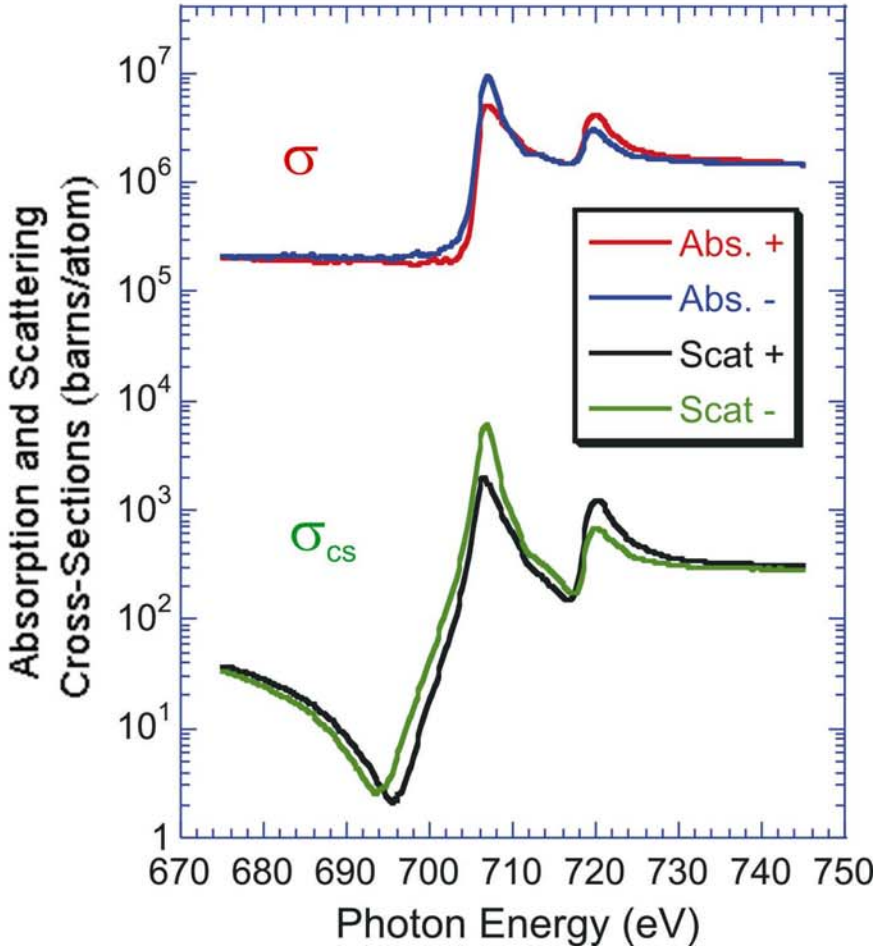
$\sigma_{abs} \propto f_2$

Resonant Elastic Scattering



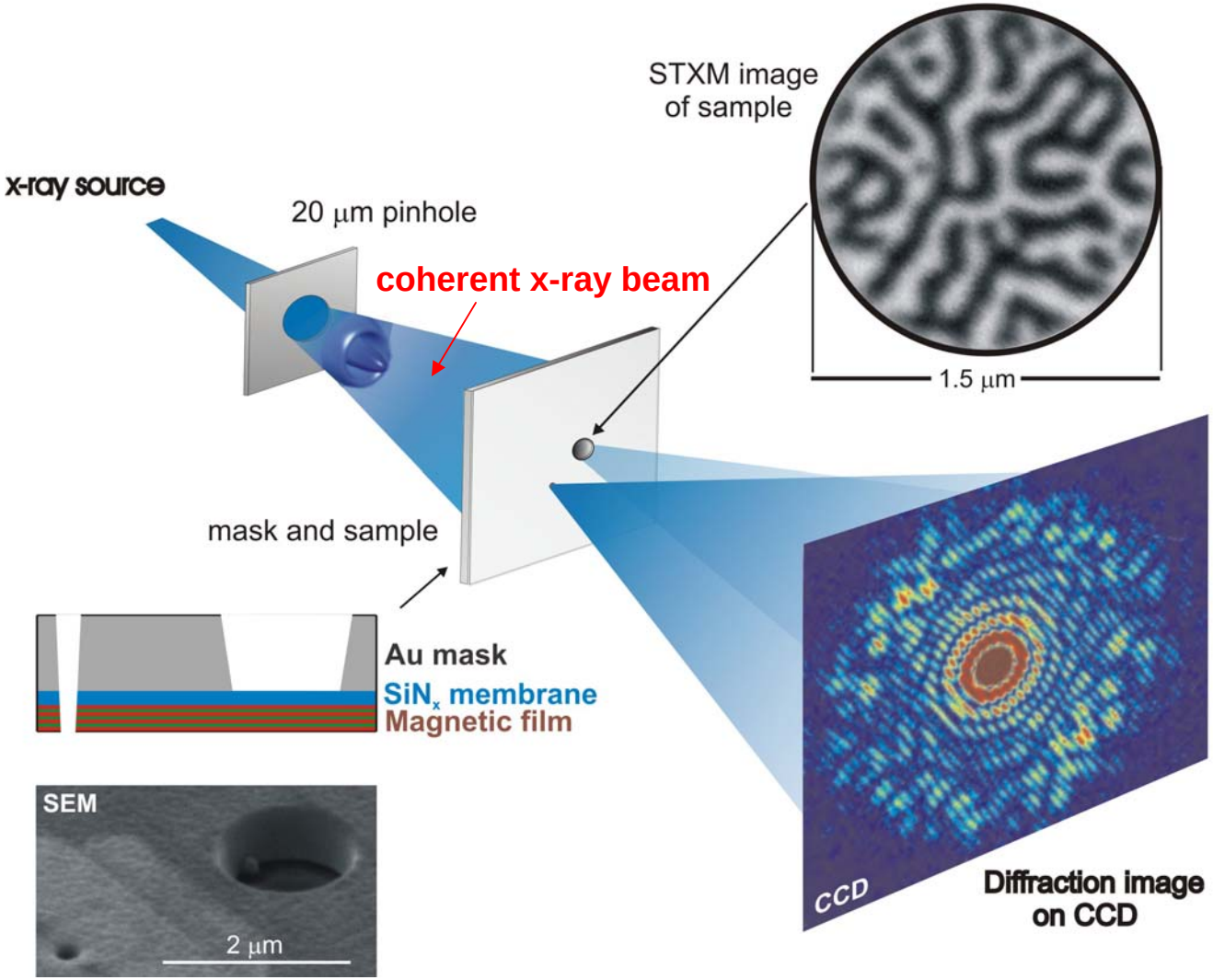
$\sigma_{scat} \propto | f_1 + i f_2 |^2$

Fe metal – L edge



Kortright and Kim, Phys. Rev. B **62**, 12216 (2000)

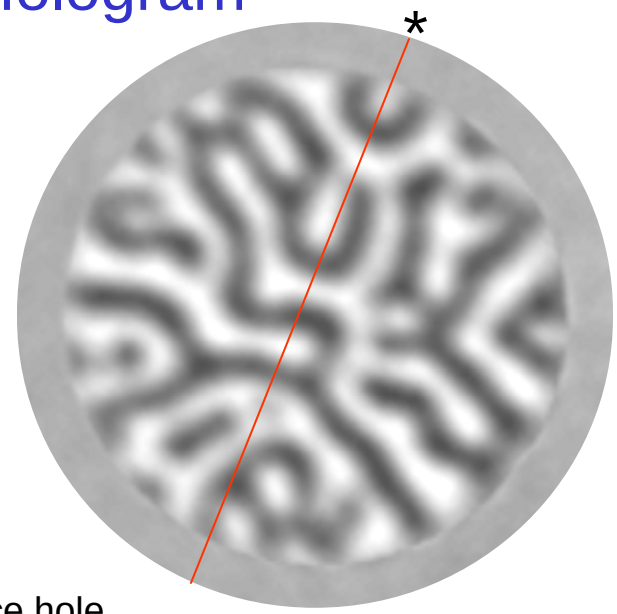
True images! - soft x-ray spectro-holography



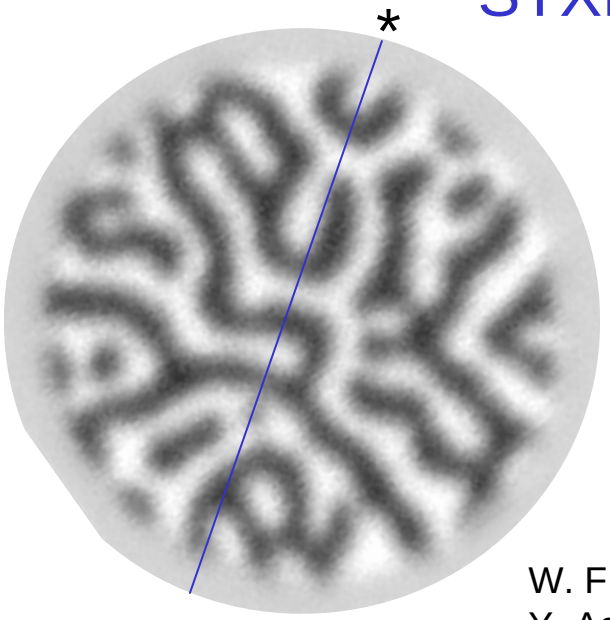
Eisebitt, Lüning, Schlotter, Lörgen, Hellwig, Eberhardt and Stöhr, *Nature* ***432****, 885 (2004)*

Is it real?

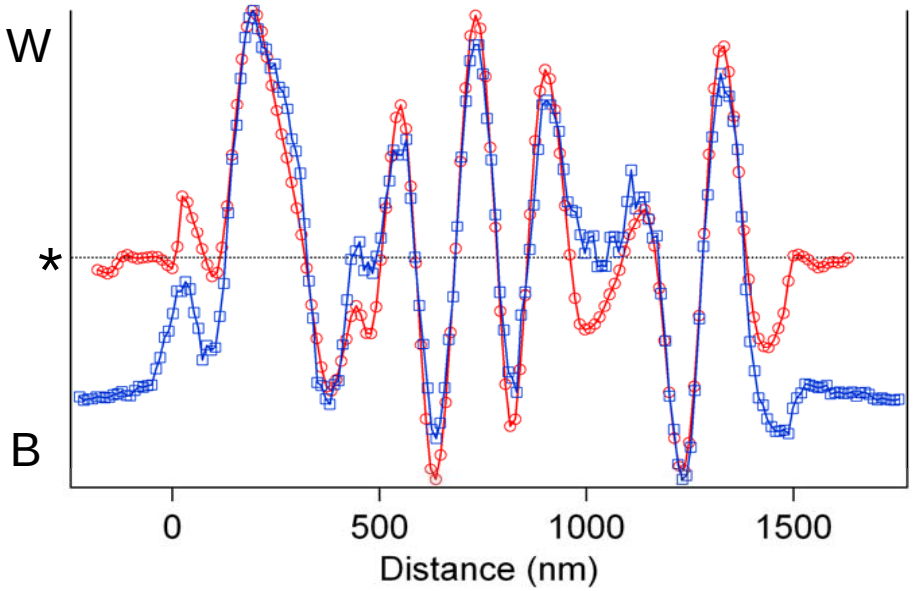
FT Hologram



STXM



Reference hole
∅ 100 nm



W. F. Schlotter
Y. Acremann

Resolution
30 - 40 nm

Conclusions

- X-rays have become an important probe of magnetic materials and phenomena
- X-rays offer **elemental**, **chemical** and **magnetic** specificity with nanoscale spatial resolution
- Transmission experiments probe **bulk**, electron yield experiments probe **surfaces** and **interfaces**
- X-rays allow **time-dependent studies**, paving the way for picosecond nanoscale technology
- **Future x-ray sources, new techniques and instrumentation will allow the complete exploration of magnetic phenomena in space and time**

For more, see: http://www-ssrl.slac.stanford.edu/stohr

and new textbook (820 pages)

J. Stöhr and H. C. Siegmann
Magnetism: From Fundamentals to Nanoscale Dynamics
Springer Verlag, February/March 2006