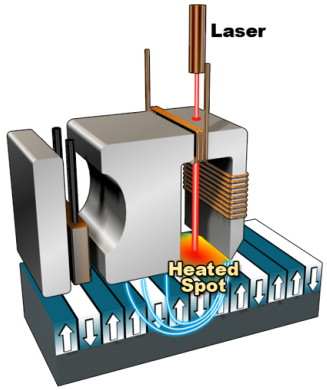
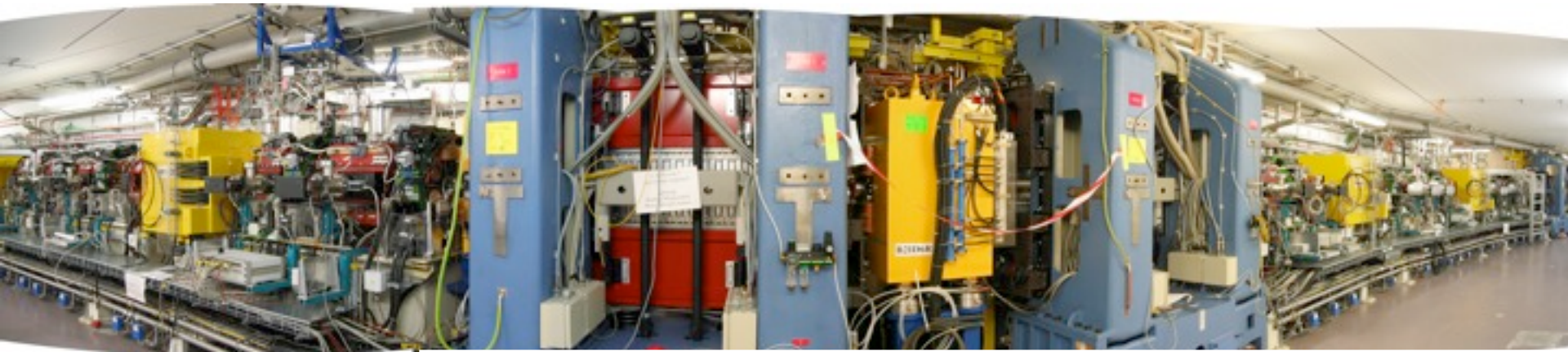
The X-Ray View of Magnetism

Hermann A. Dürr

SLAC National Accelerator Laboratory
Stanford University



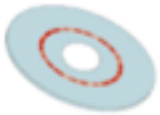


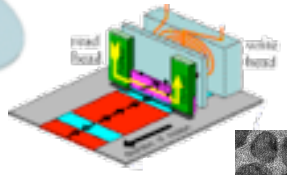
X-Rays Access the Ultra Small and Ultra Fast

ultra small

1mm

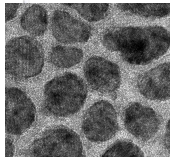
hard disc



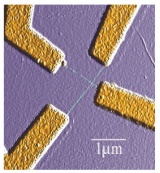


GMR heads

1μm

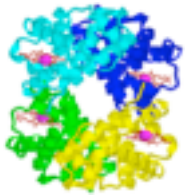


~10nm grains

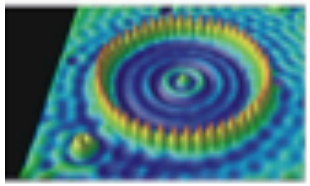


electrodes connected by nanotubes

1nm



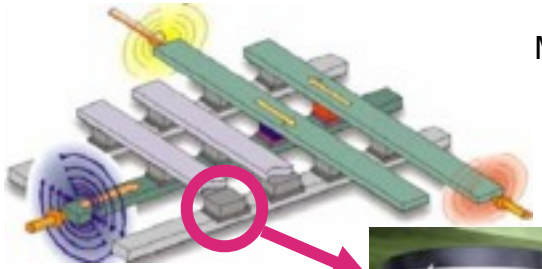
molecules



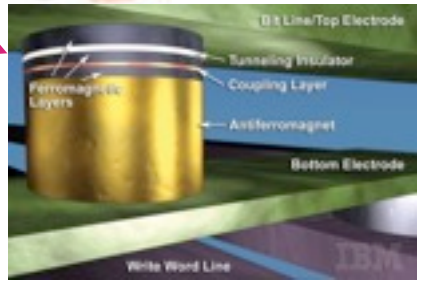
'atomic corral' ~14nm diameter

ultra fast

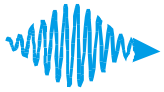
1ns



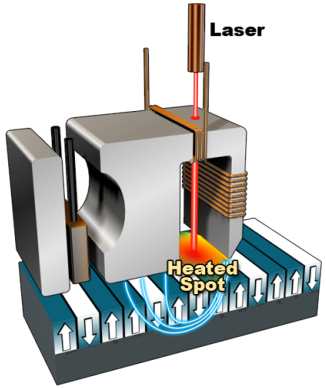
MRAM



1ps



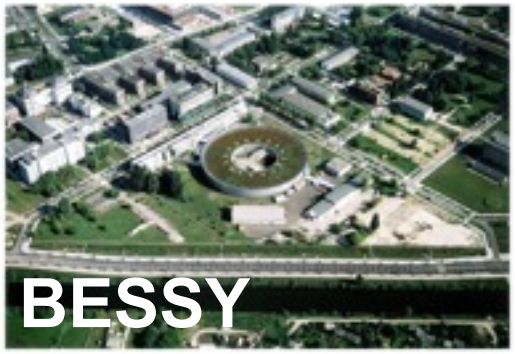
shortest laser pulse ~1fs



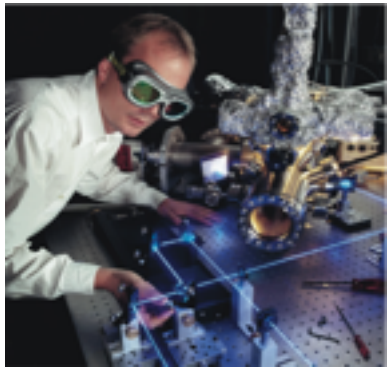
1fs

The X-Ray View of Magnetism

The Ultra Small

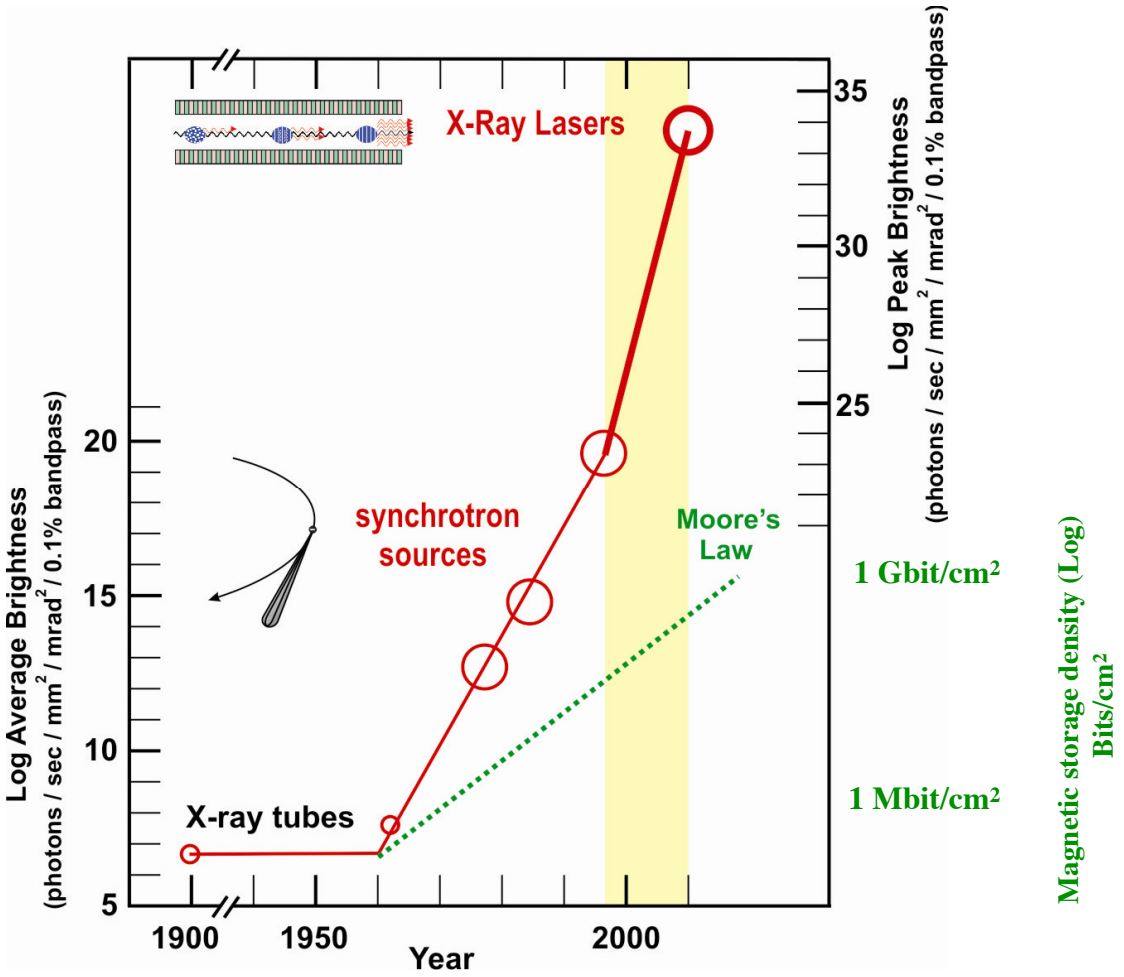


The Ultra Fast



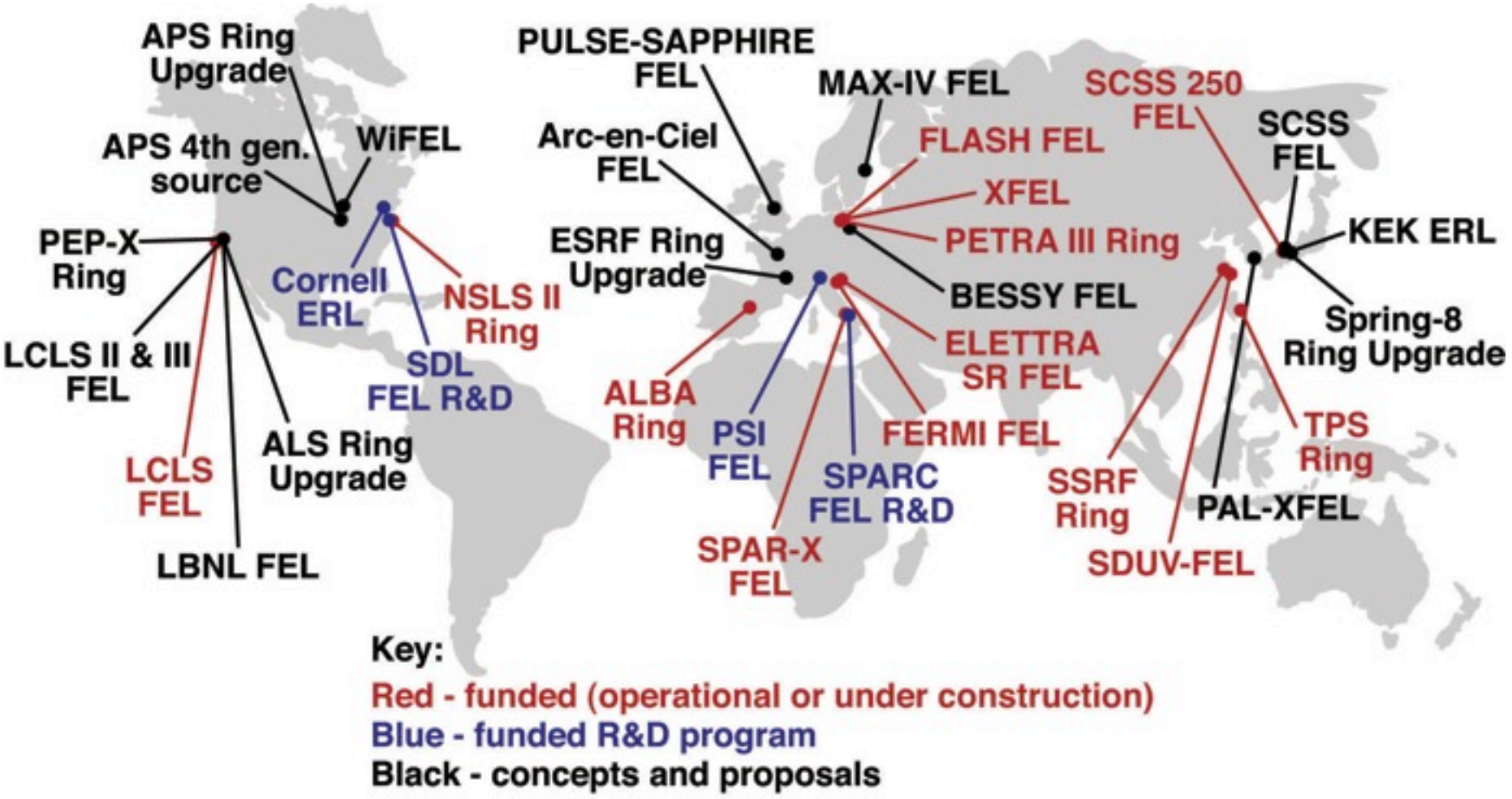
The Ultra Small & Ultra Fast

The X-Ray Revolution



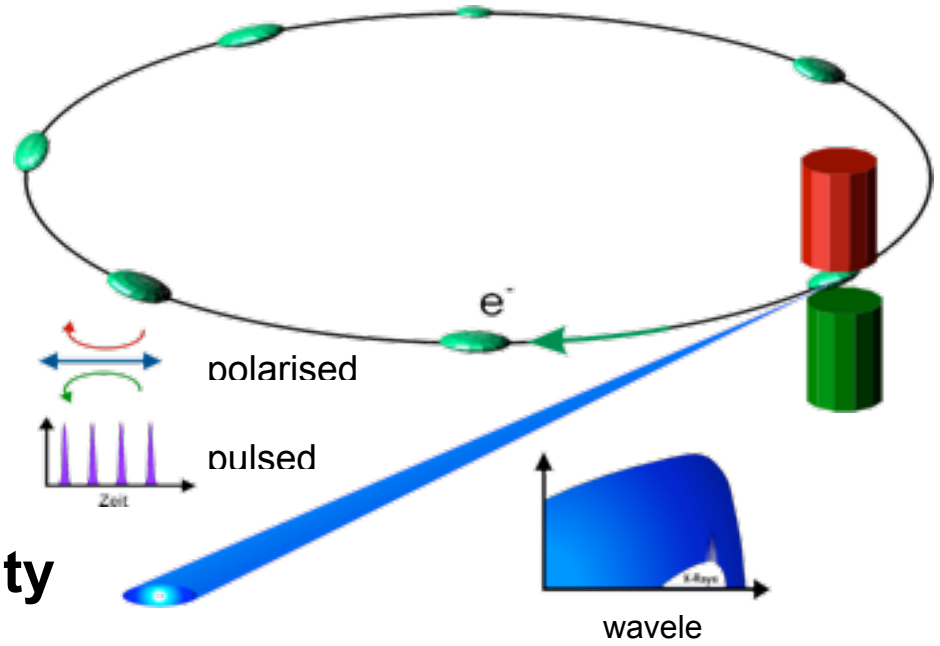
The development of x-ray sources easily outpaces the growth of the semiconductor and magnetic storage technology

Major Synchrotron Radiation Facilities Around the World

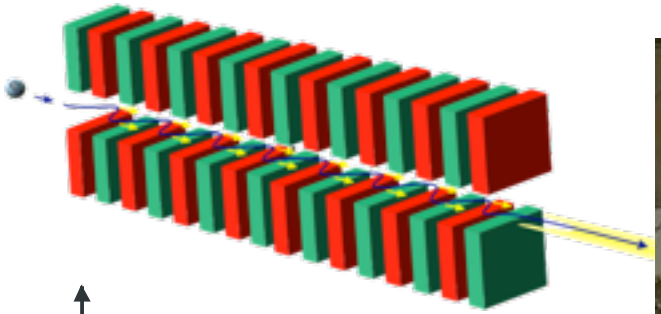


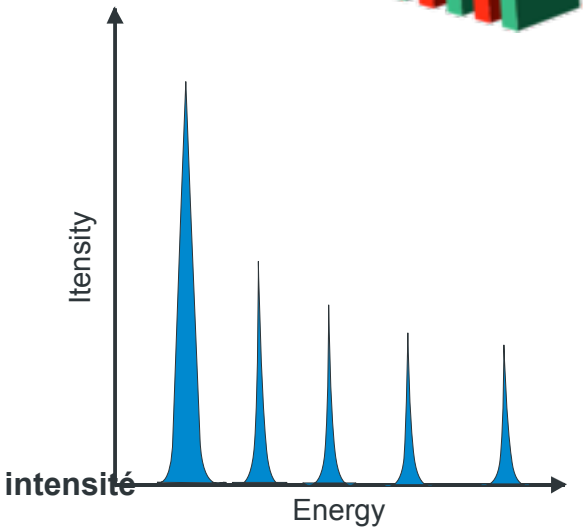
The power of conventional synchrotron radiation

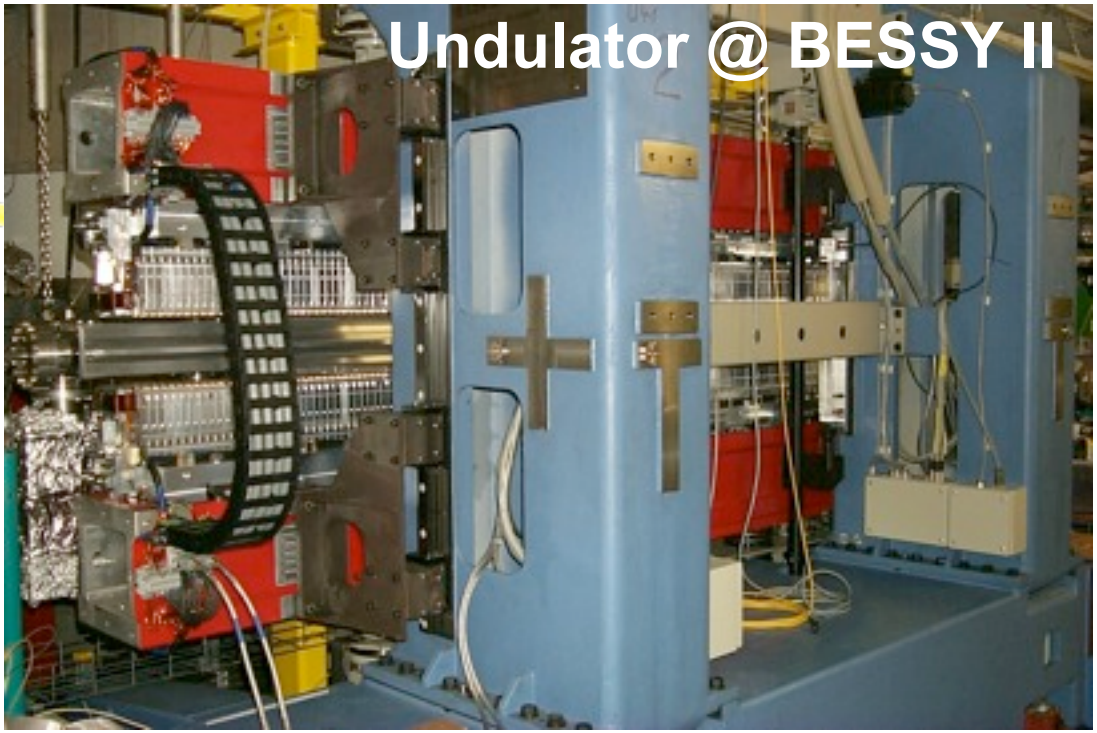
- high average intensity
- variable cross section & sample penetration
- element & chemical state specificity
- charge versus spin sensitivity through polarization
- spatial resolution down to atomic size
- temporal resolution to ~ 50 ps



The power of conventional synchrotron radiation







Each bunch contains $N_e \sim 10^9$ electrons

…but electrons emit spontaneously
photons not coherent

Intensity limited by independent photon emission – scales as N_e

The power of conventional synchrotron radiation

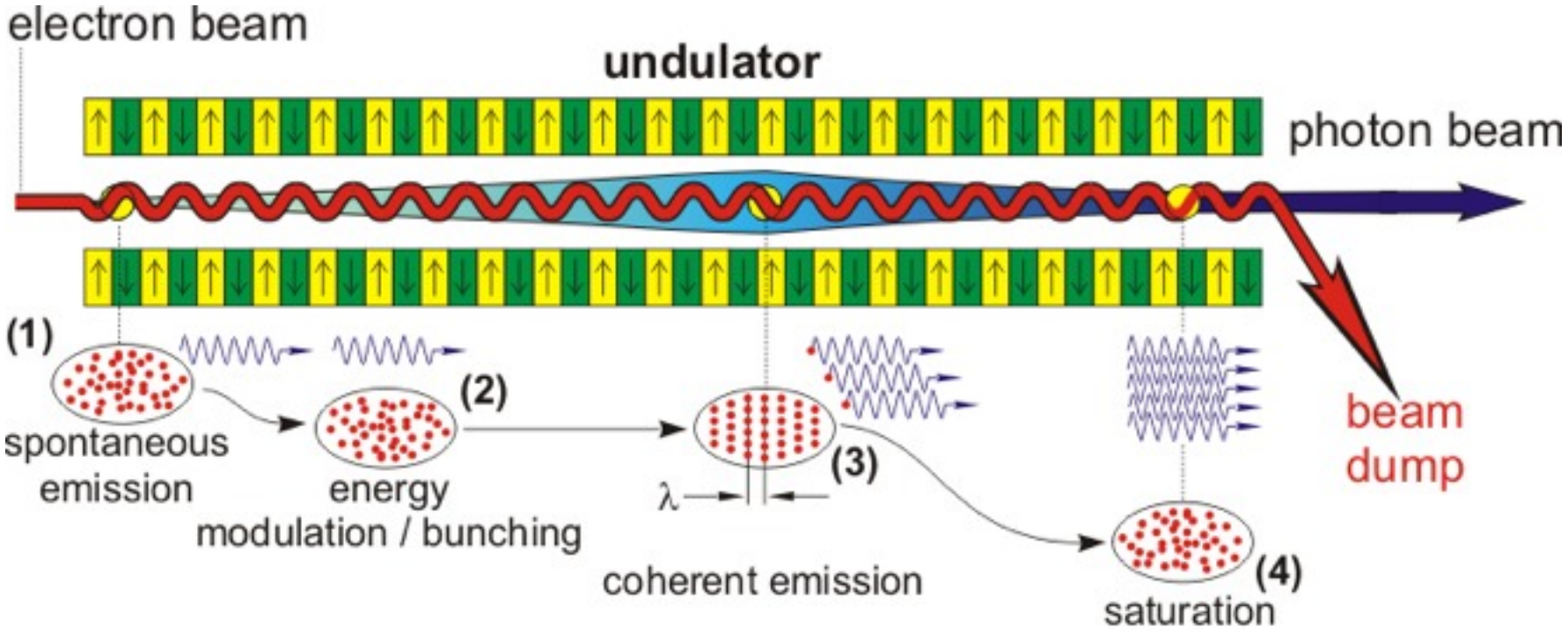
View of the BESSY II experimental hall with 46 beamlines in operation in 2004

many simultaneous experiments

Concept of a free electron x-ray laser

- Replace storage ring by a linear accelerator
  allows compression of electron bunch – use once, then throw away

- Send electron bunch through a very long undulator

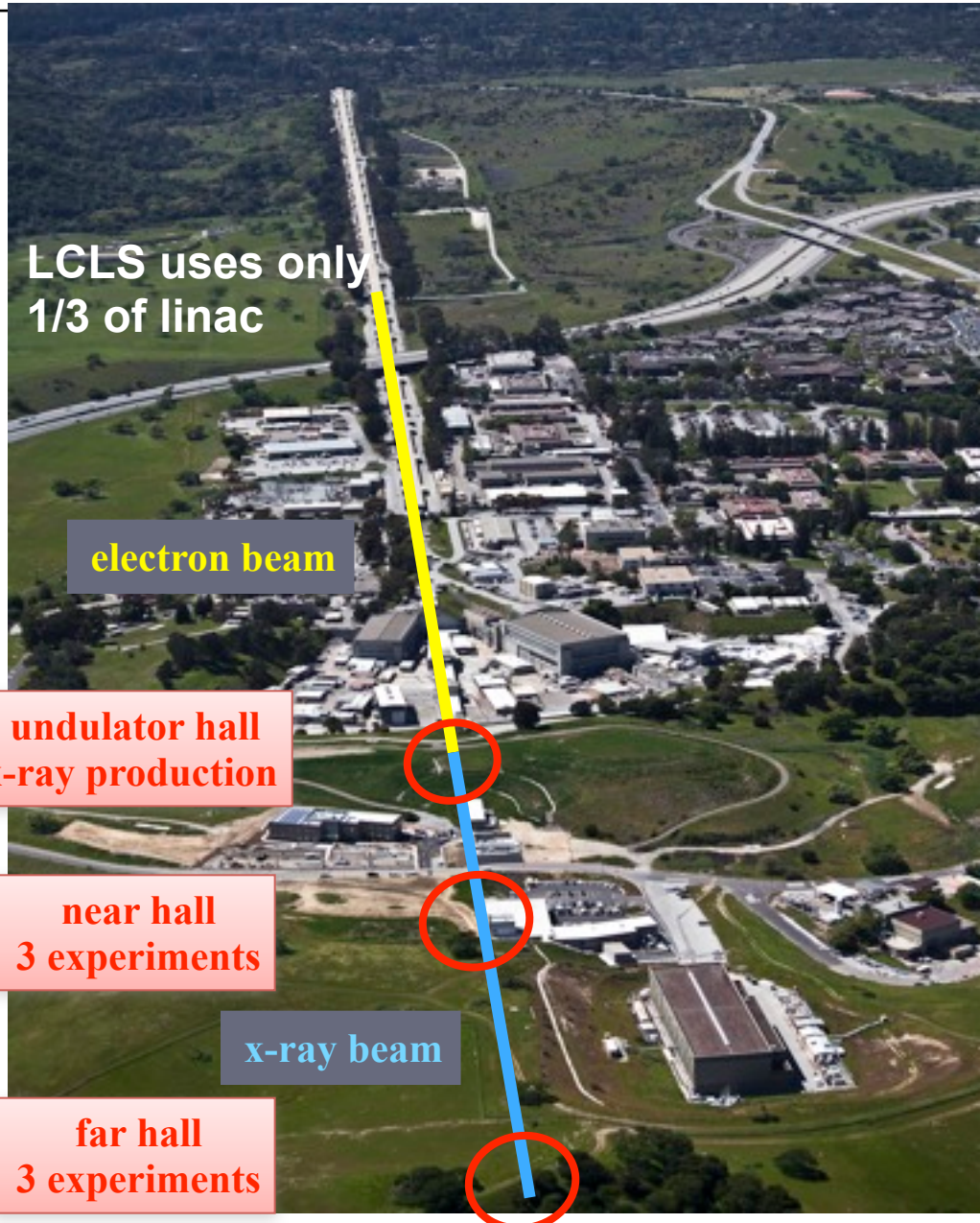


Intensity scales as N_e^2 or increased by 10^9

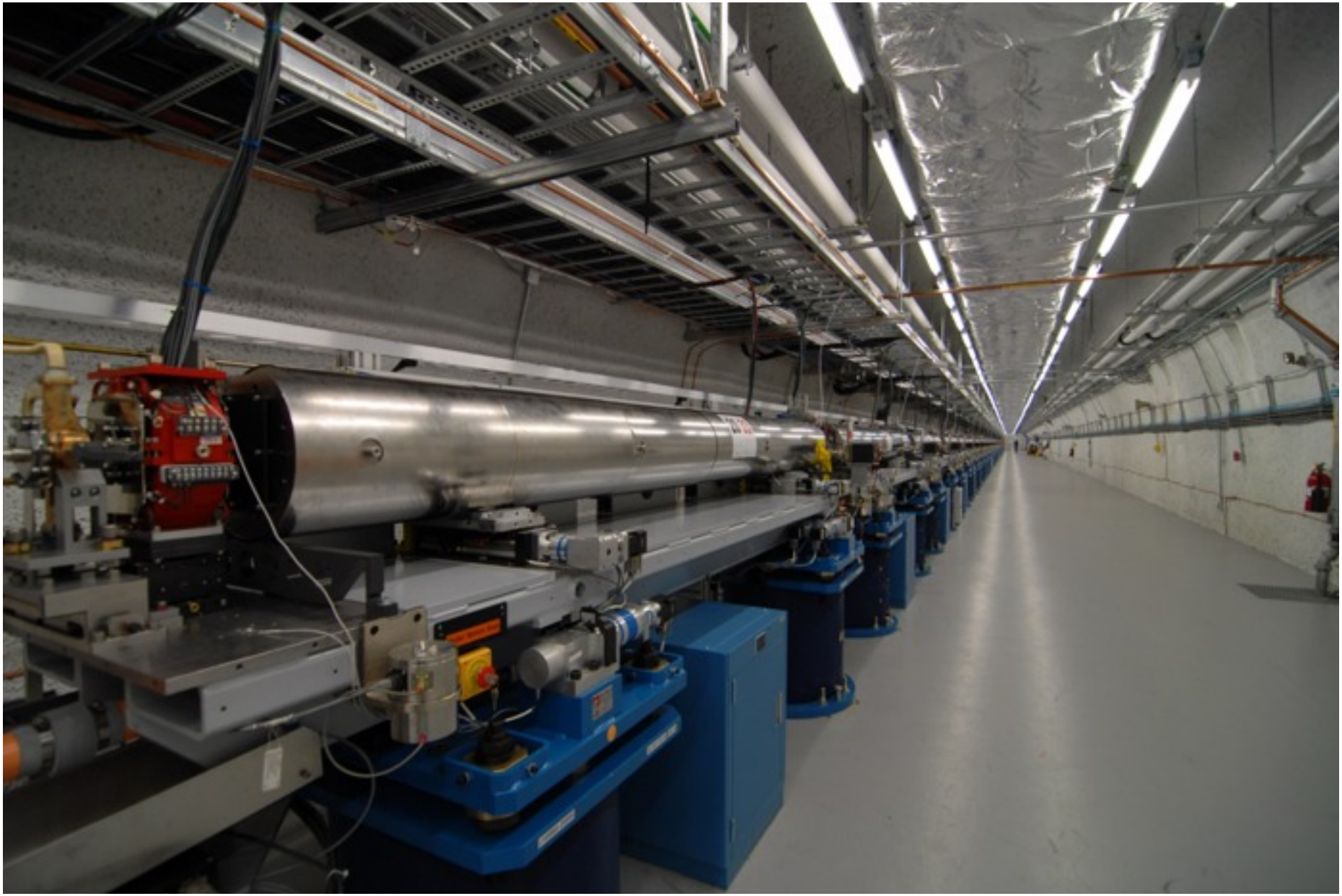
Linac Coherent Light Source or "LCLS" at SLAC
the world's first x-ray laser

- **X-rays**
  for atomic resolution
- **ultrafast flash**
  to study processes with femtosecond duration
- **ultrabright flash**
- **increased coherence**
  to study disordered system without lenses

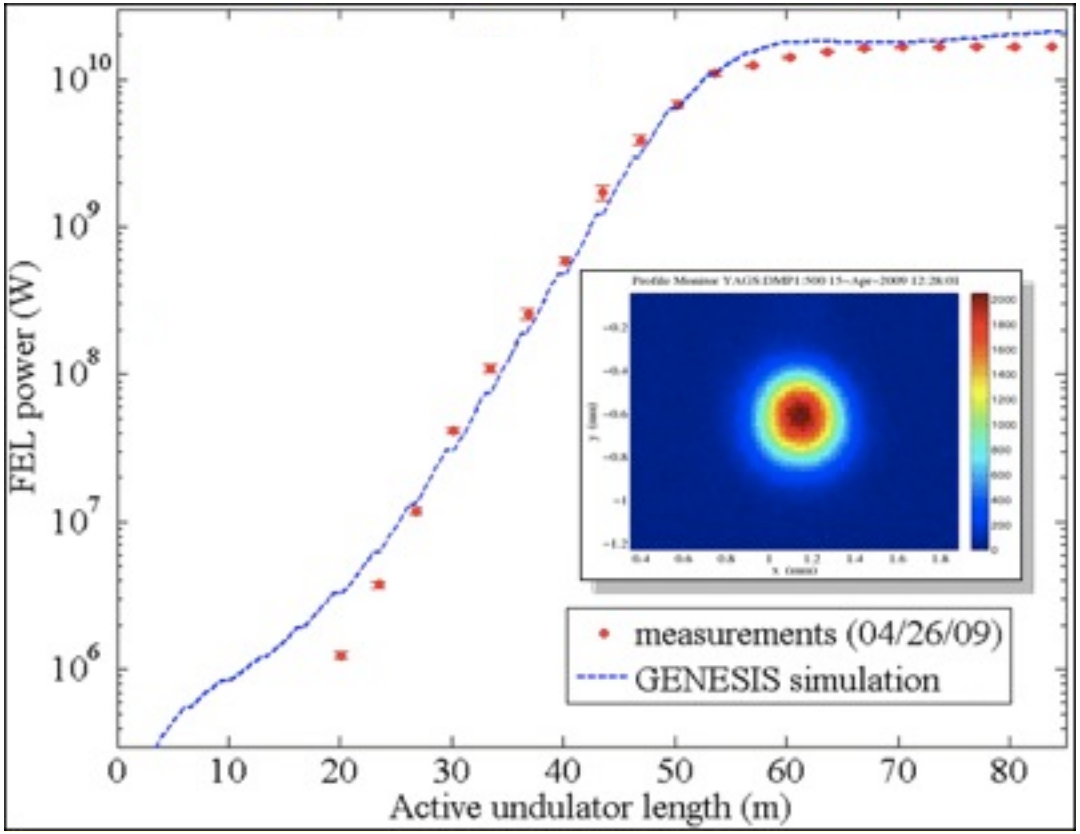
... but only one experiment at a time



132 meters of FEL undulators



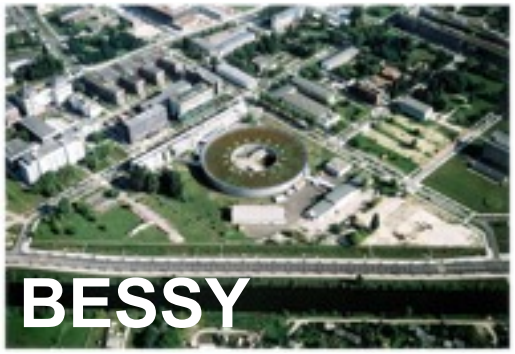
LCLS lases at 1.5 Å



- Typical x-ray beam energy **> 1 mJ** or **> 10^{12}** photons per pulse
- Typical x-ray pulse duration at 300pC charge **~ 100 fs** (FWHM).
- X-ray pulse duration at 20 pC charge < **10 fs**

The X-Ray View of Magnetism

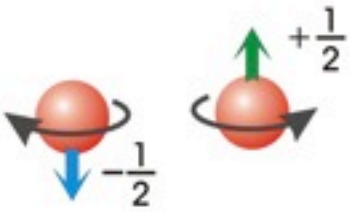
The Ultra Small



The Ultra Small & Ultra Fast

The Ultra Fast

Magnetism in a Nutshell

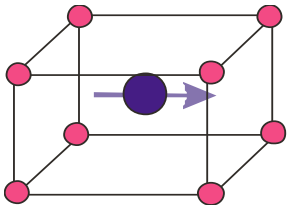


long-range ferromagnetic order

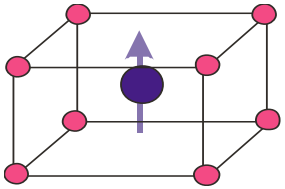
↕

exchange interaction

hard axis

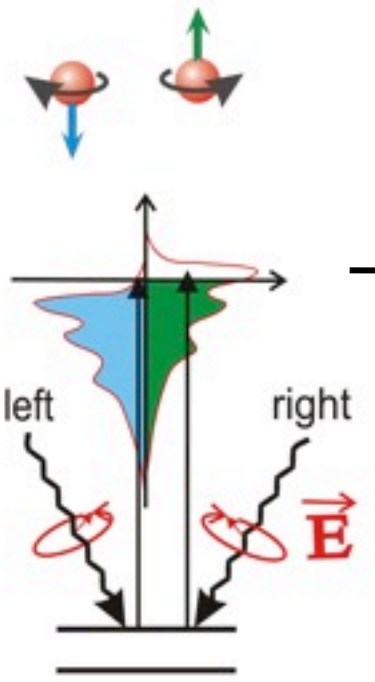


easy axis



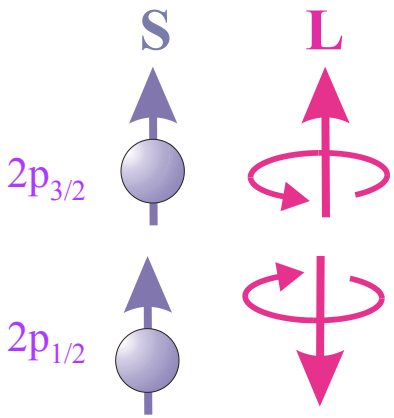
magnetic anisotropy is caused by spin-orbit coupling & crystalline field

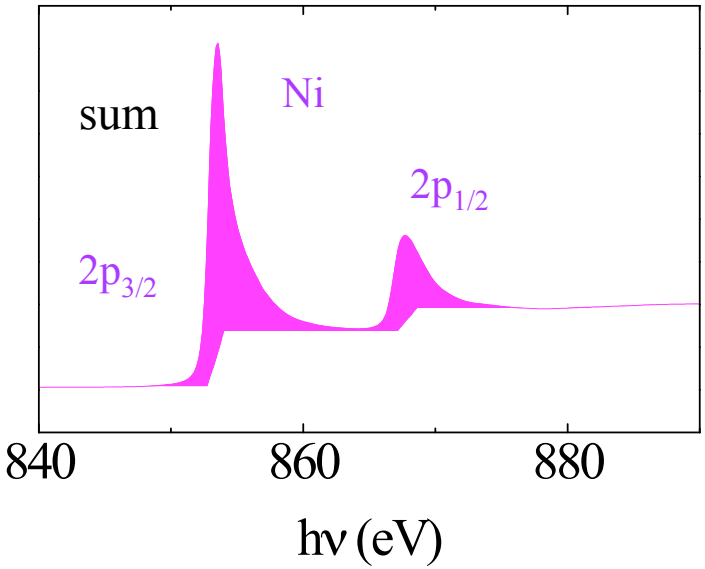
X-Ray Magnetic Circular Dichroism

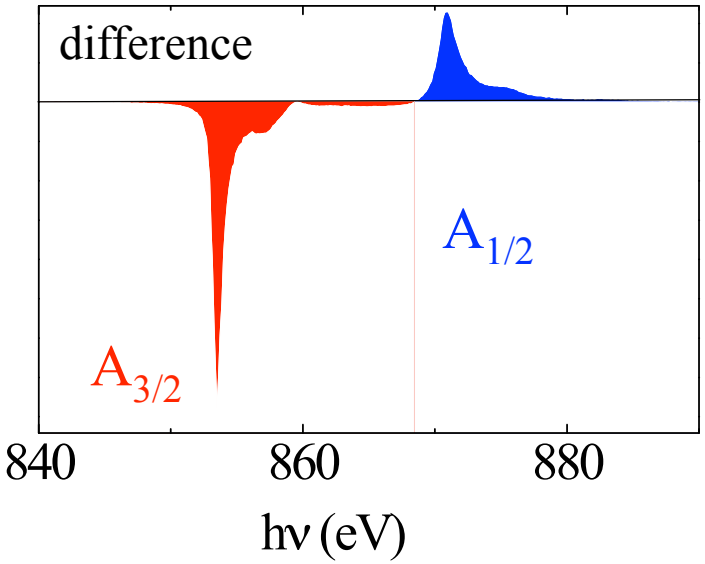


$2p_{3/2}$ l + s
$2p_{1/2}$ l - s

empty 3d states
(exchange split
in ferromagnets)



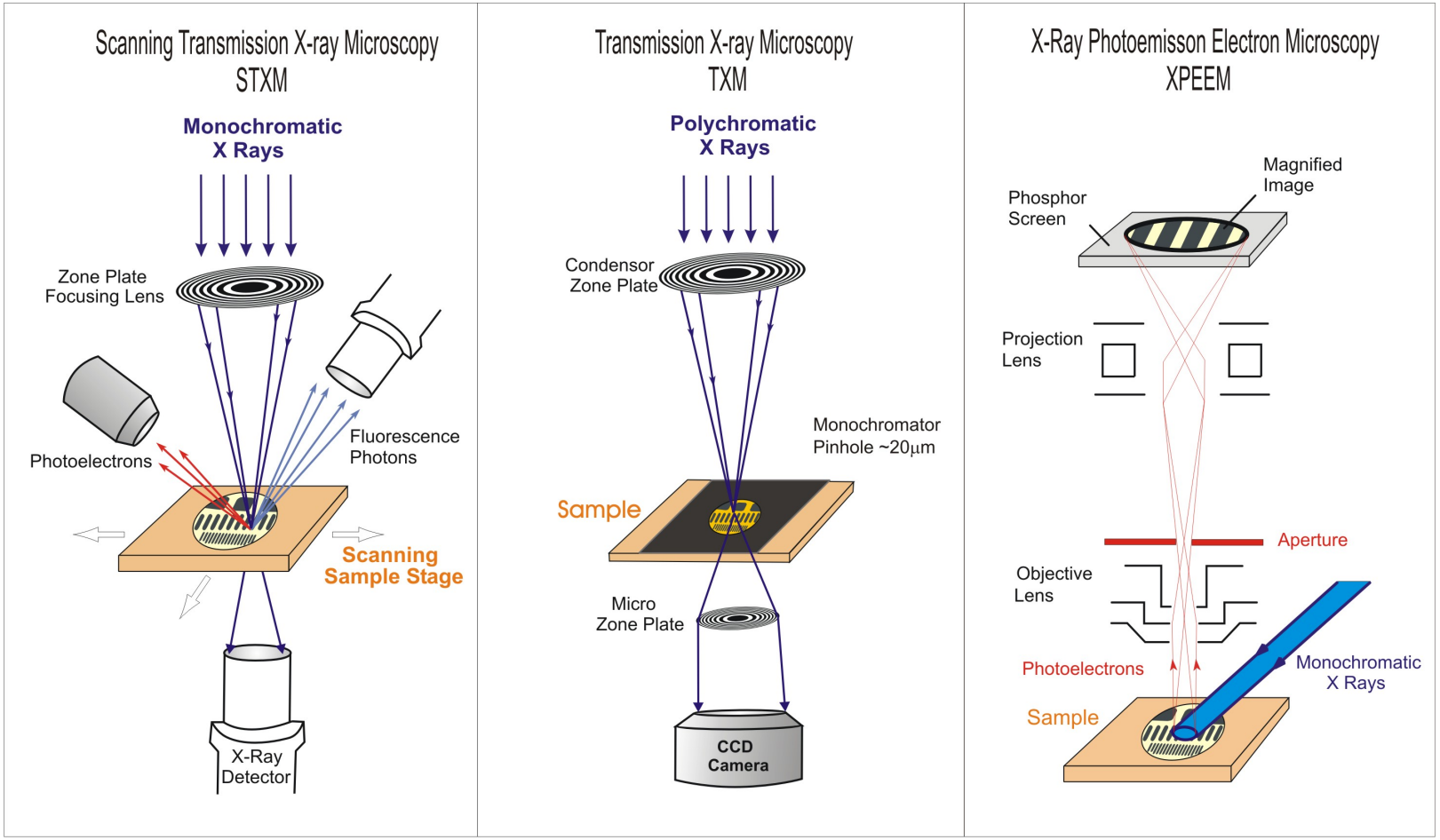




separation of
orbital, $L \sim A_{3/2} + A_{1/2}$ and
spin moment, $S + 7/2\ T \sim A_{3/2} - 2A_{1/2}$

Thole, Carra, Sette, van der Laan, Phys. Rev. Lett. **68,** 1943 (1992)
Carra, Thole, Altarelli, Wang, Phys. Rev. Lett. **70,** 694 (1993)

Imaging Nanoscale Magnetism

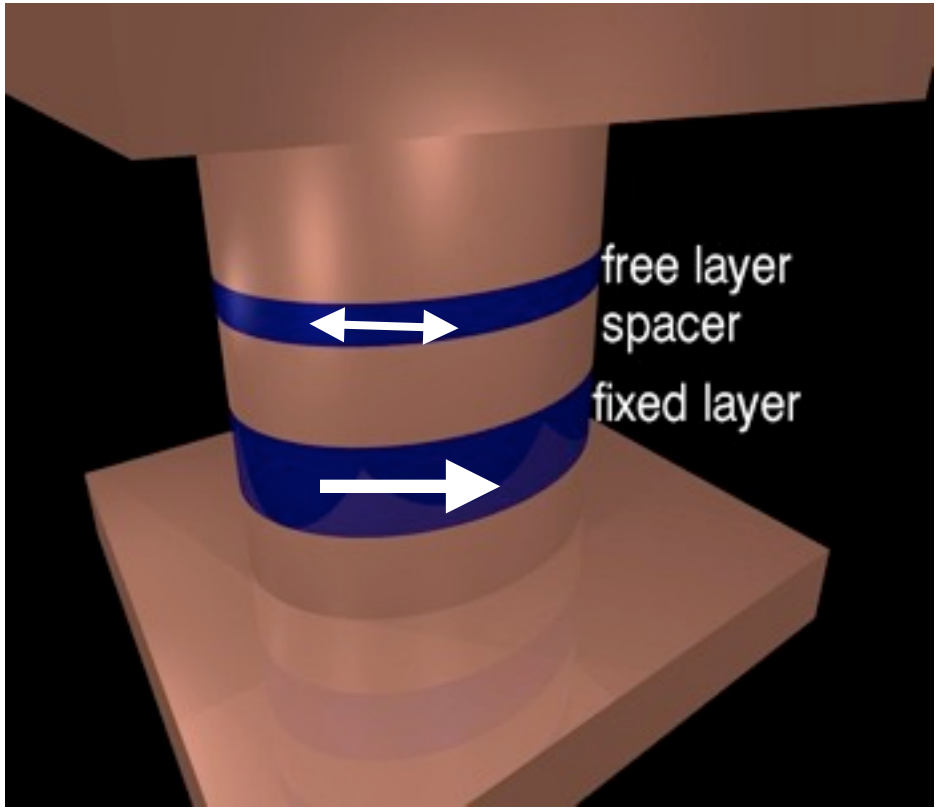


Spatial resolution presently 20 - 40 nm

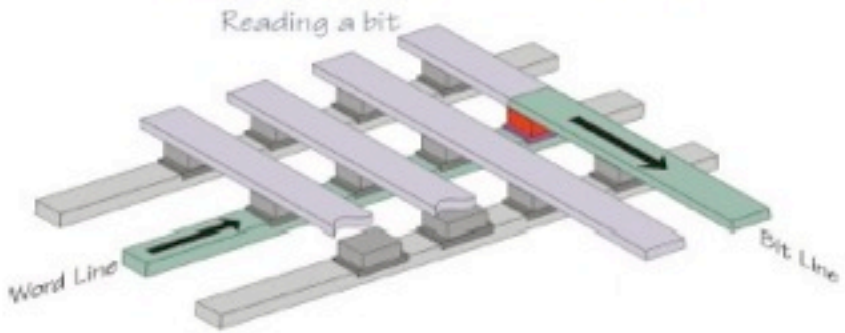
H. A. Dürr, Zakopane 2011

Magnetic switching by spin injection

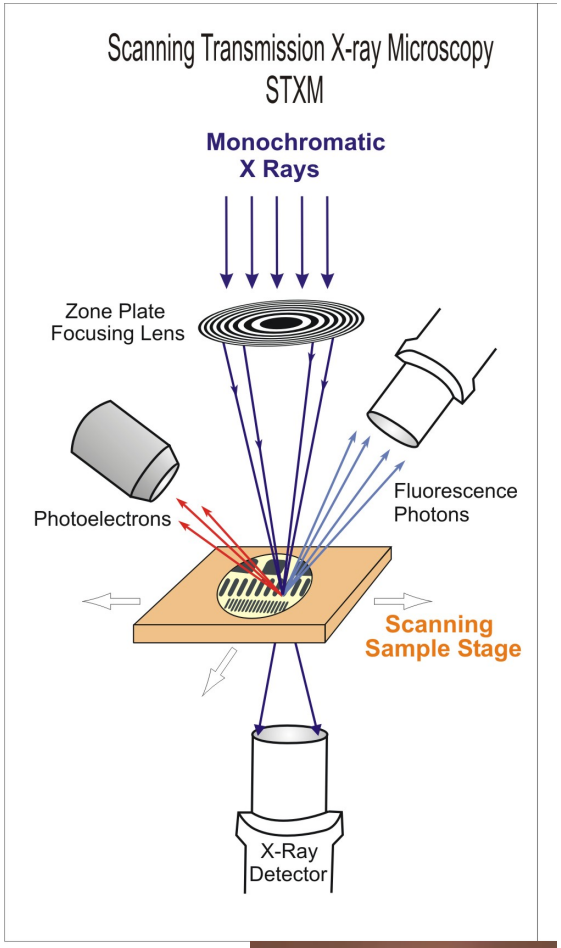
Y. Acremann (ETH Zurich)

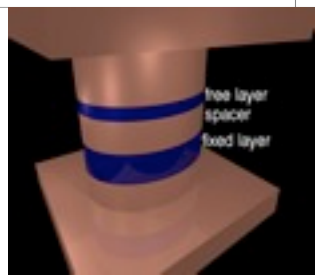


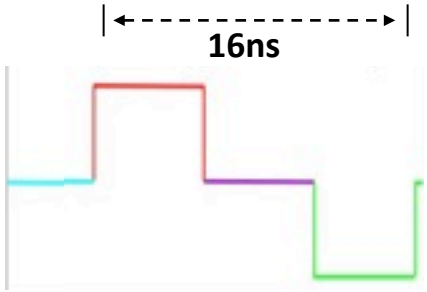
MRAM cells



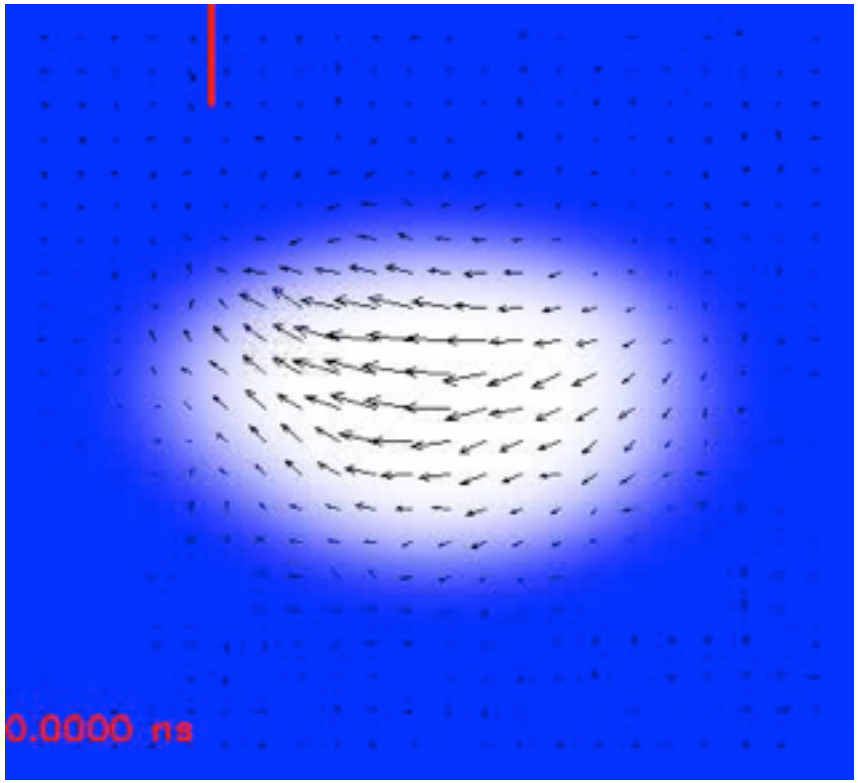
Movie of Magnetization







Images taken every 200ps



100x200nm
2nm free layer

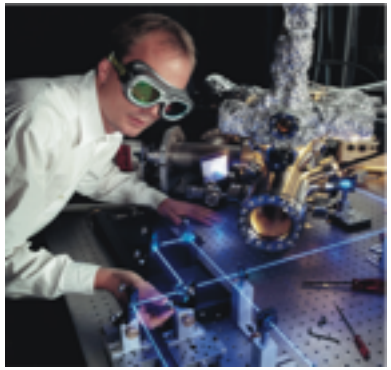
Y. Acremann, et al., Phys. Rev. Lett. **96**, 217202 (2006)

The X-Ray View of Magnetism

The Ultra Small

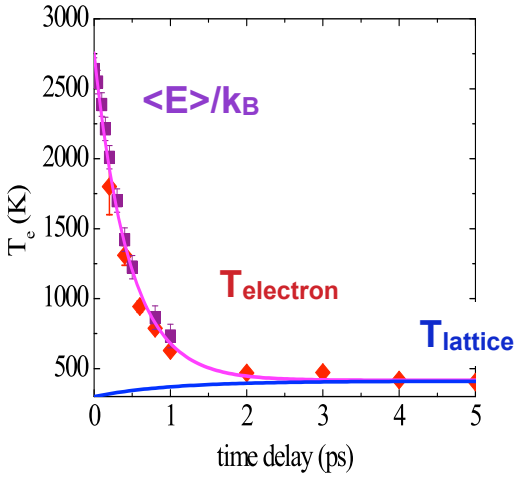
The Ultra Small & Ultra Fast

The Ultra Fast



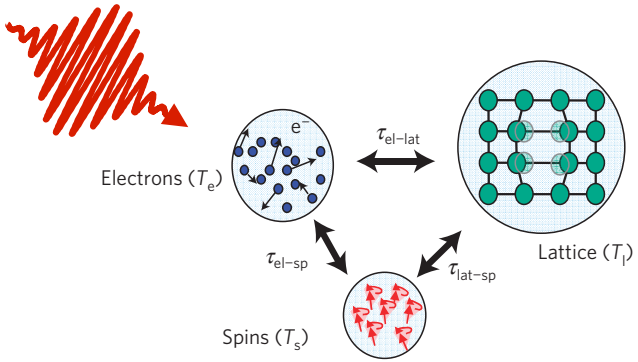
Can we speed up and simplify magnetic switching ?

Control Energy and Angular Momentum in Magnetic Materials



laser excitation increases electron temperatures > 1000 K

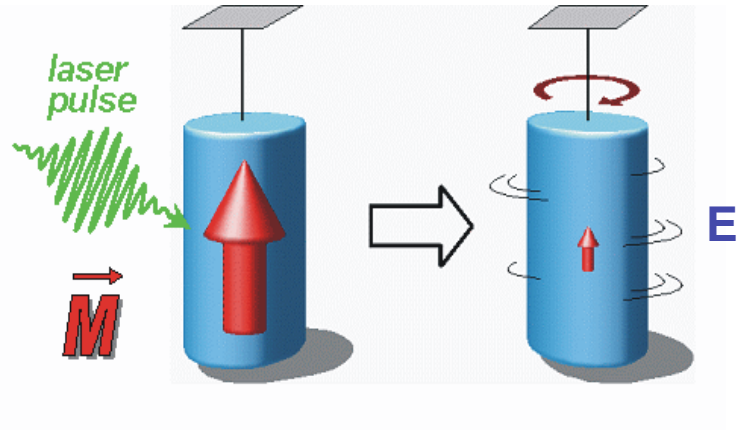
Rhie, Dürr, Eberhardt, PRL **90**, 247201 (2003);
Dürr, NIM (2009)



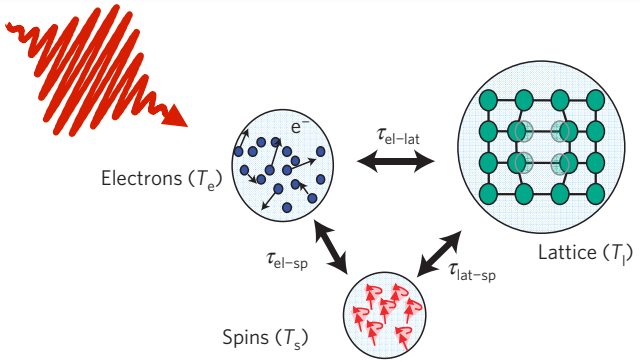
Control Energy and Angular Momentum in Magnetic Materials

conserve total angular momentum

$$J = S_e + L_e + L(\text{lattice}) + L(\text{photon})$$

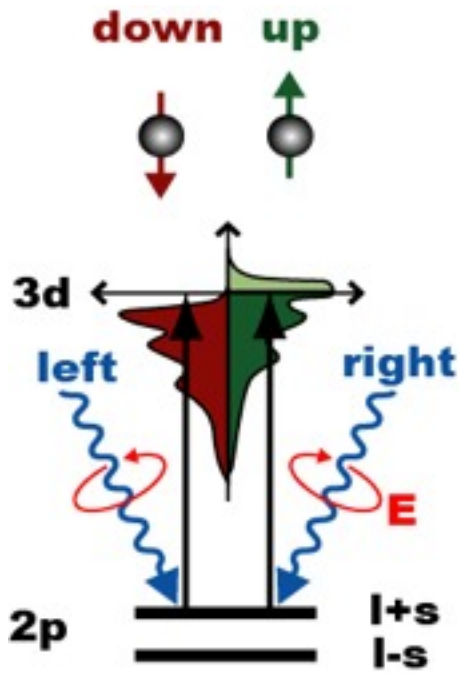


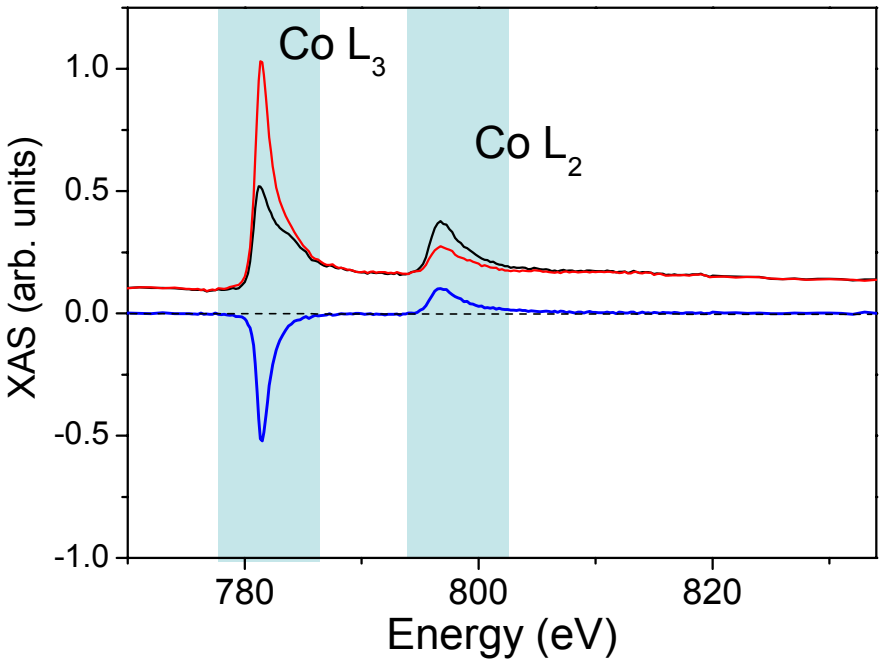
ultrafast
Einstein – de Haas effect ?



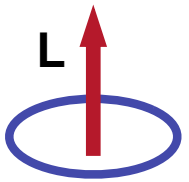
Angular Momentum Probed With X-Rays

X-ray Magnetic Circular Dichroism





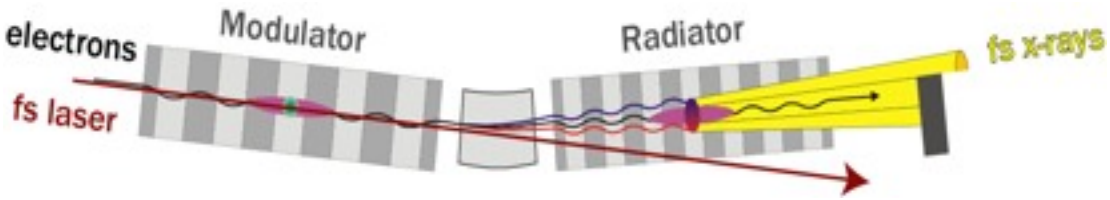
XMCD sum rules:



$S \sim -(L_3-2L_2)$ $L \sim -4/3(L_3+L_2)$

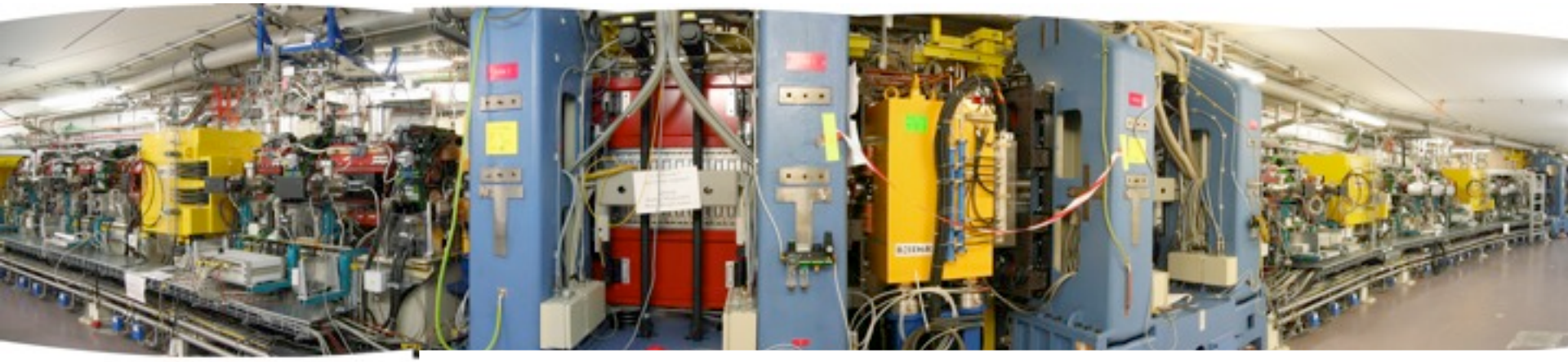
Thole, Carra, Sette, van der Laan, Phys. Rev. Lett. **68,** 1943 (1992)
Carra, Thole, Altarelli, Wang, Phys. Rev. Lett. **70,** 694 (1993)

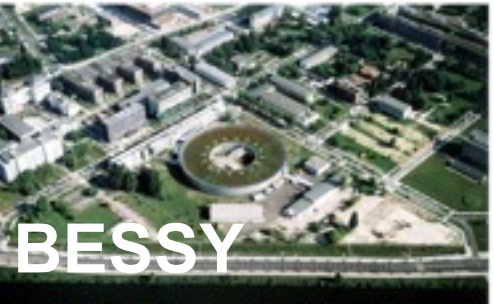
The BESSY Femtosecond Slicing Facility



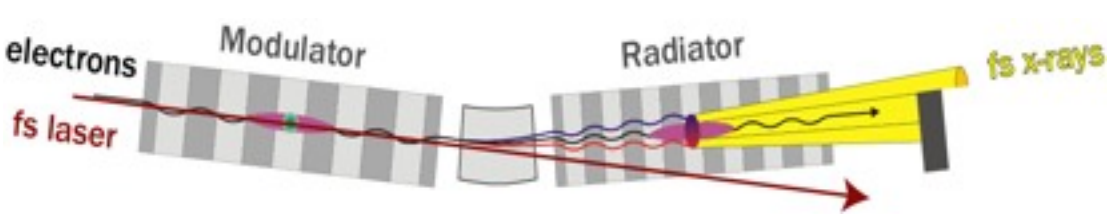
~ 100 fs duration

K. Holldack et al., PRL **96**, 054801 (2006);
PR ST Accel. Beams **8**, 040704 (2005)



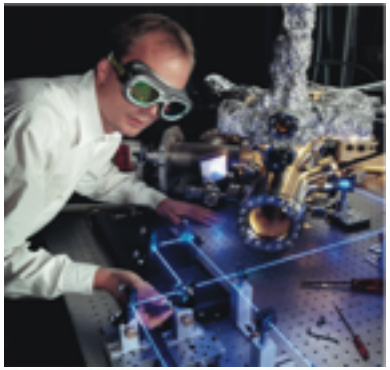


The BESSY Femtosecond Slicing Facility



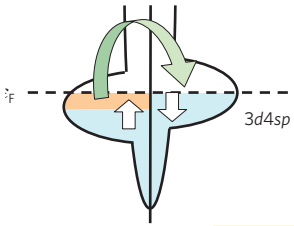
~ 100 fs duration

K. Holldack et al., PRL **96**, 054801 (2006);
PR ST Accel. Beams **8**, 040704 (2005)



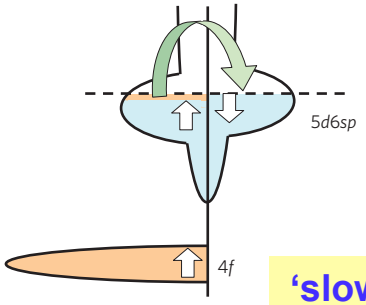
‘Standard’ model of fs magnetism

3d transition metals

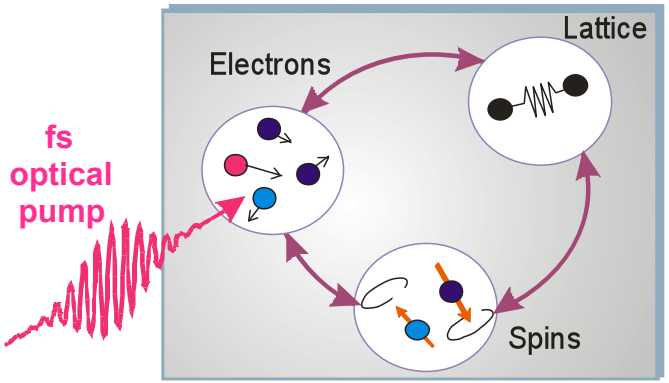


‘fast’

4f rare earth metals



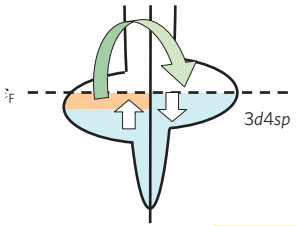
‘slow’



Koopmans et al., Nature Materials (2009)

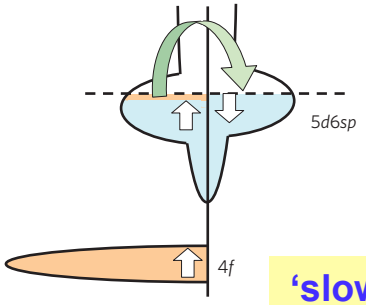
‘Standard’ model of fs magnetism & its experimental test

3d transition metals



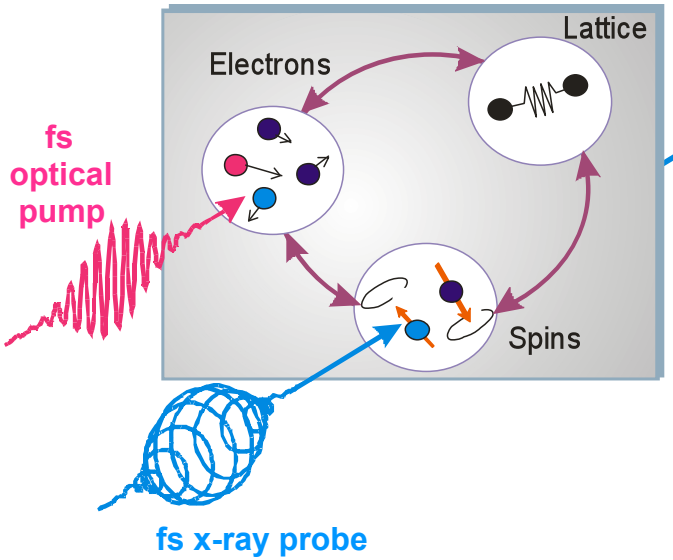
‘fast’

4f rare earth metals

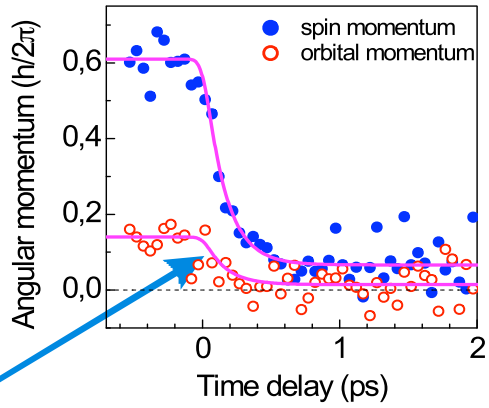


‘slow’

10nm Ni / 200 nm Al



Ni
150 +- 50 fs

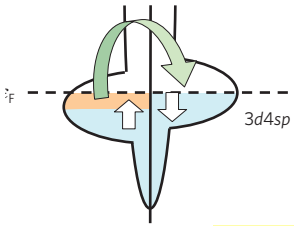


Stamm, Durr, et al., NM (2007); PRB (2010)

Koopmans et al., Nature Materials (2009)

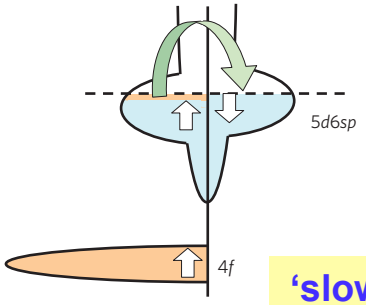
‘Standard’ model of fs magnetism & its experimental test

3d transition metals

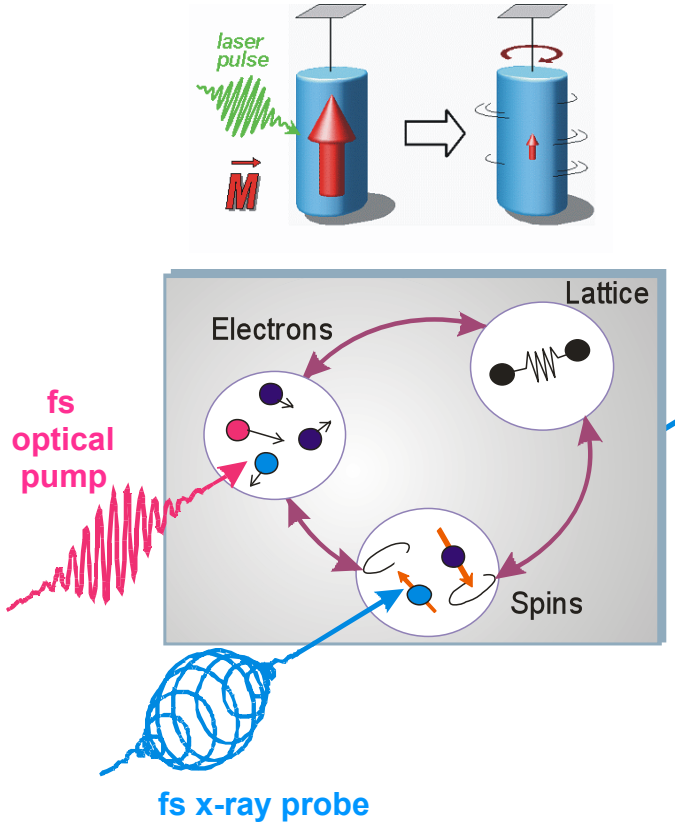


‘fast’

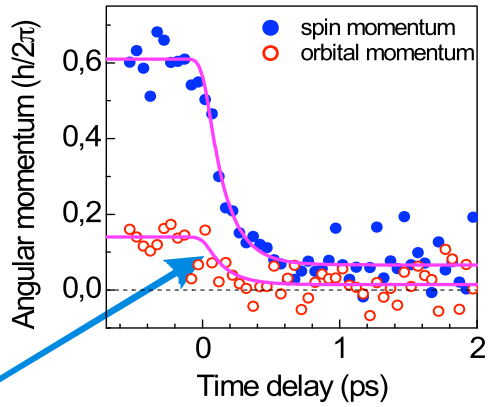
4f rare earth metals



‘slow’



Ni
150 +- 50 fs

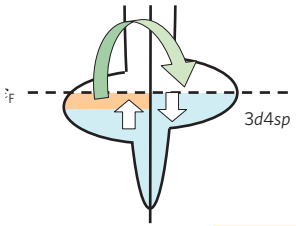


Stamm, Durr, et al., NM (2007); PRB (2010)

Koopmans et al., Nature Materials (2009)

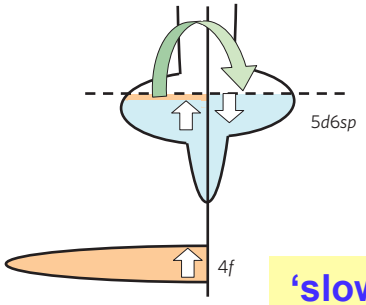
‘Standard’ model of fs magnetism & its experimental test

3d transition metals

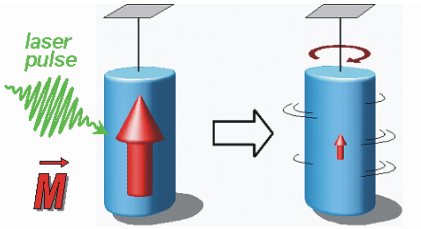


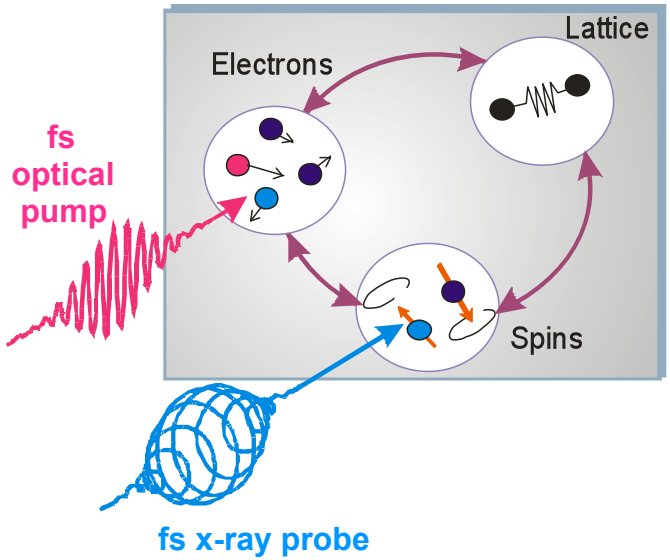
‘fast’

4f rare earth metals

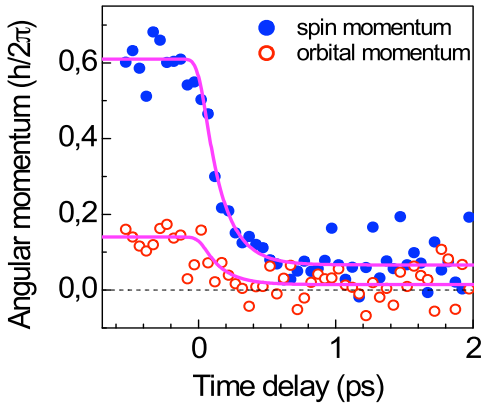


‘slow’



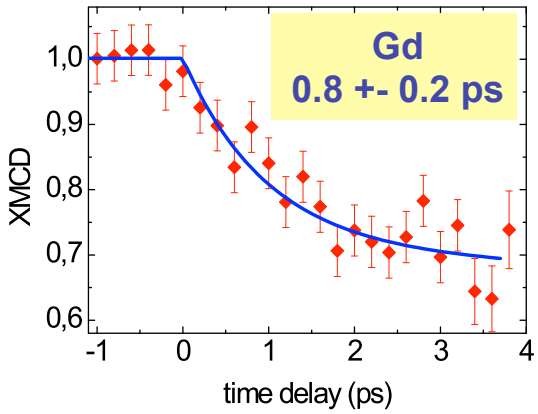


Ni
150 +- 50 fs



Stamm, Durr, et al., NM (2007); PRB (2010)

Gd
0.8 +- 0.2 ps

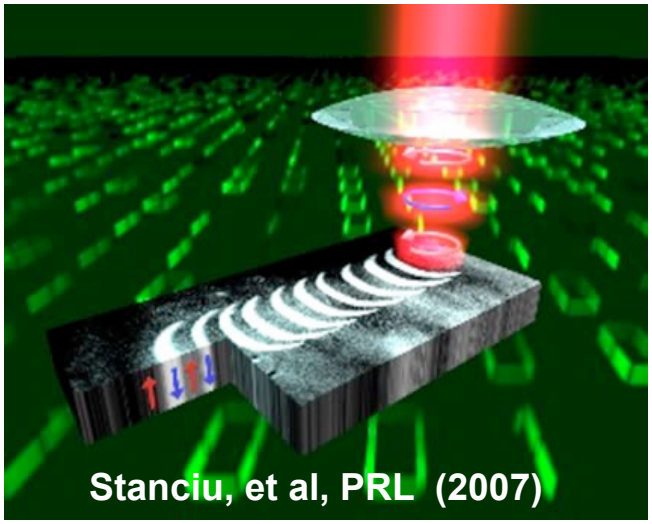


Koopmans et al., Nature Materials (2009)

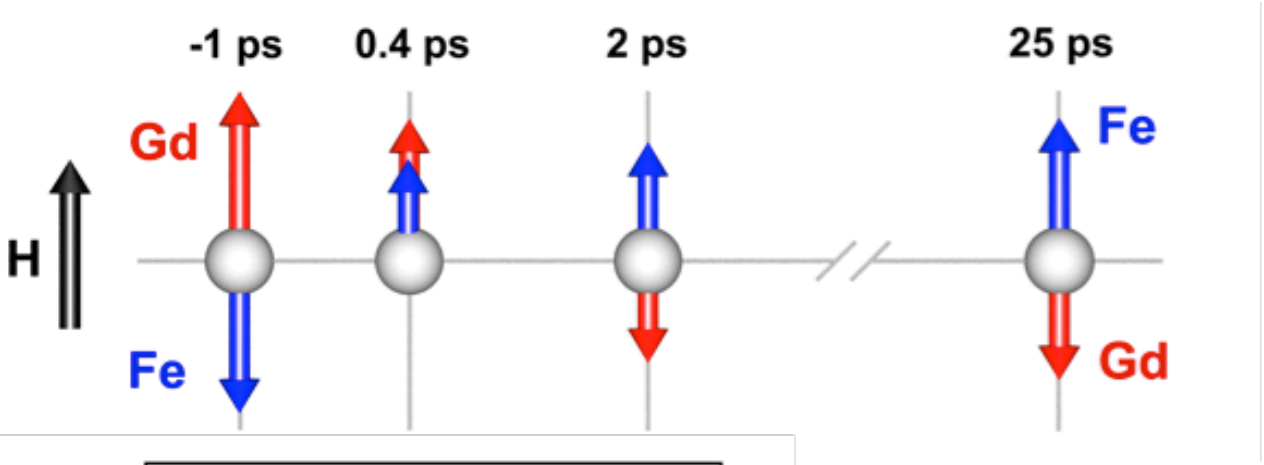
Wietstruk, Durr, Bovensiepen, et al., PRL (2011)

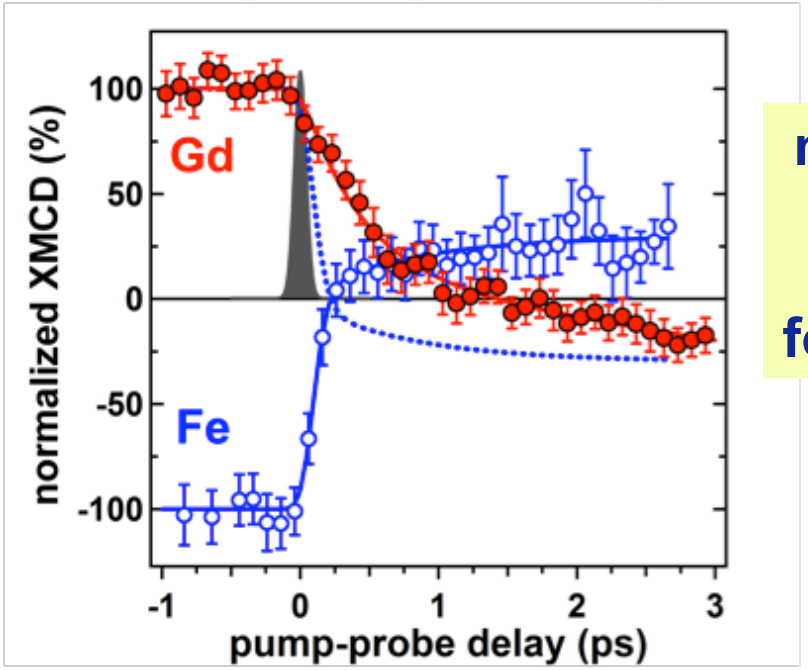
Combine 3d and 4f spins and something surprising happens ...

... all optical switching



Fs Control of Exchange Coupling

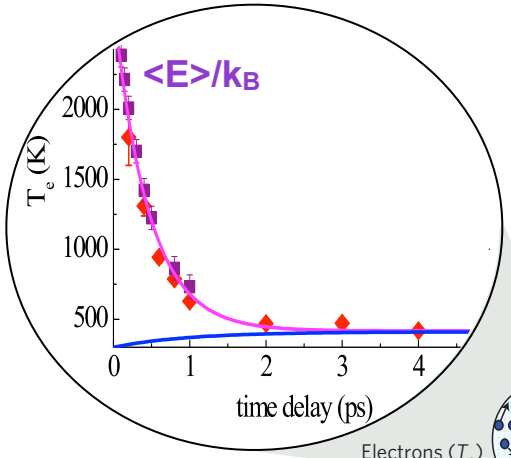


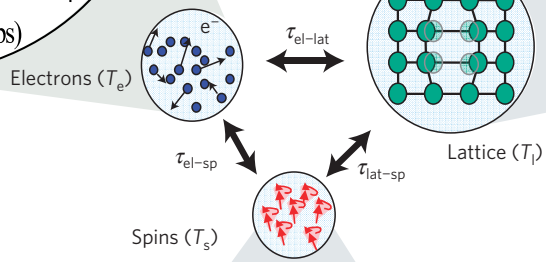


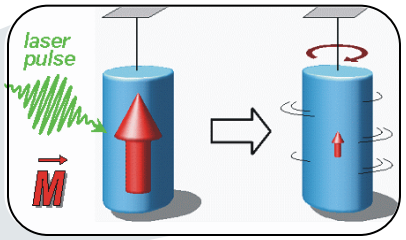
novel transient ferromagnetic angular momentum recoupling following exchange beakdown

I. Radu, K. Vahaplar, C. Stamm, T. Kachel, N. Pontius, H. A. Dürr, T. A. Ostler, J. Barker, R. F. L. Evans, R. W. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, Th. Rasing, A. V. Kimel, Nature (2011)

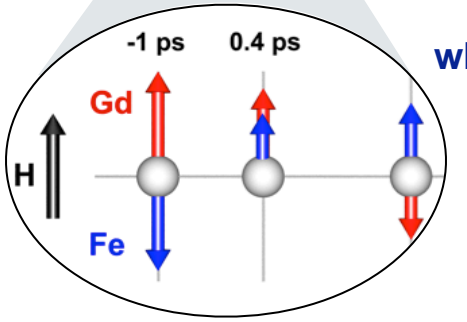
Summary:
optical control of fs magnetism







what is the microscopic mechanism behind a fs Einstein - de Haas effect ?



what is the lenght scale of the transient Fe and Gd angular momentum recoupling ?

The X-Ray View of Magnetism

The Ultra Small

The Ultra Fast

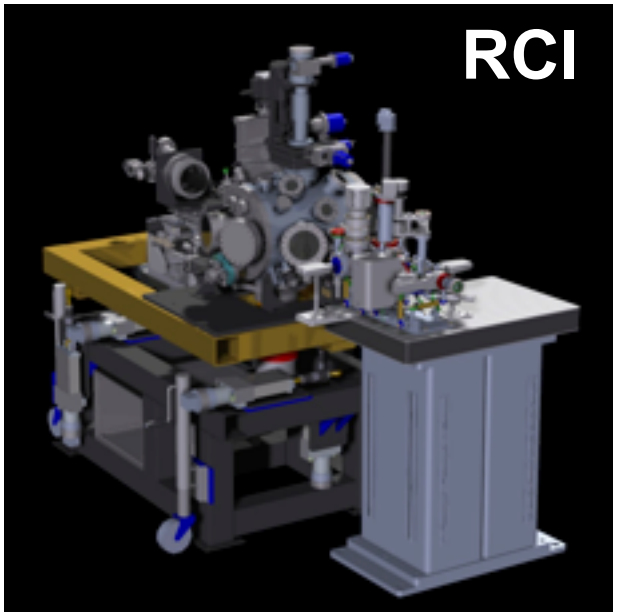
The Ultra Small & Ultra Fast

Can we image magnetic bits with one XFEL pulse ?

Femtosecond Magnetic Imaging @ LCLS

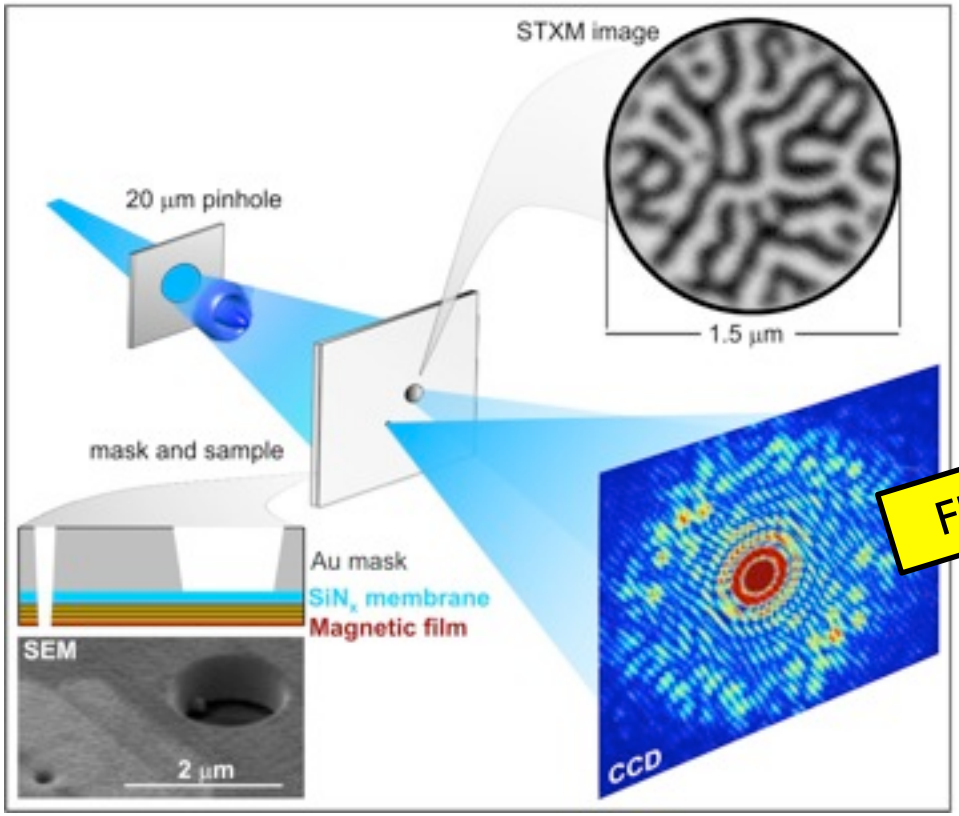
we built & operate a holography & coherent scattering endstation for LCLS and SSRL

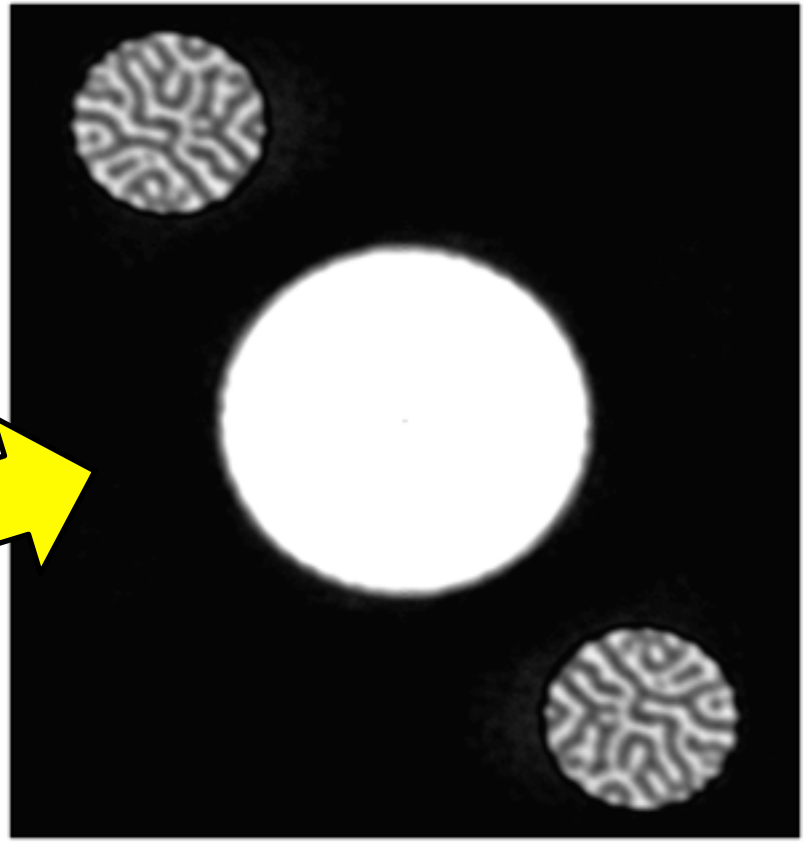
instrument responsible: A. Scherz



Fourier Transform Holography

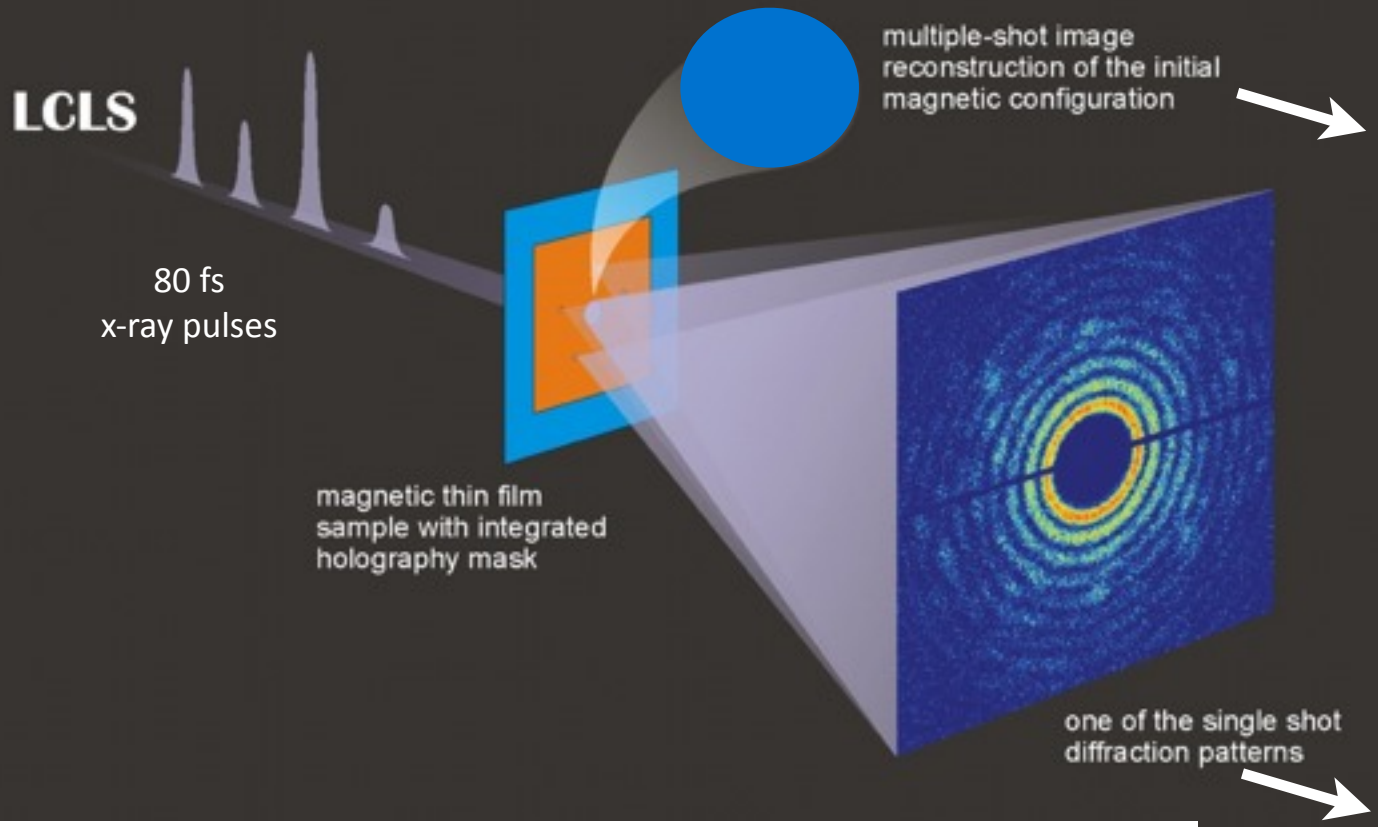
- Detectors record intensity → Phase information is lost.
- With FTH, reference holes encode phase information in the diffraction.



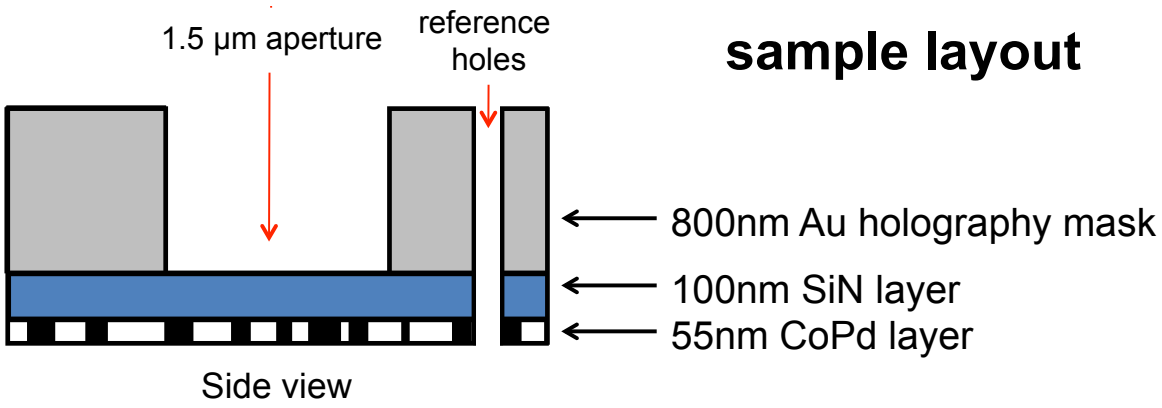


Eisebitt et al, Nature (2004)

Single Shot Magnetic Imaging @ LCLS



FFT images
to be published



sample layout

800nm Au holography mask

100nm SiN layer

55nm CoPd layer

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