Magnetization dynamics studied by x-ray microscopy

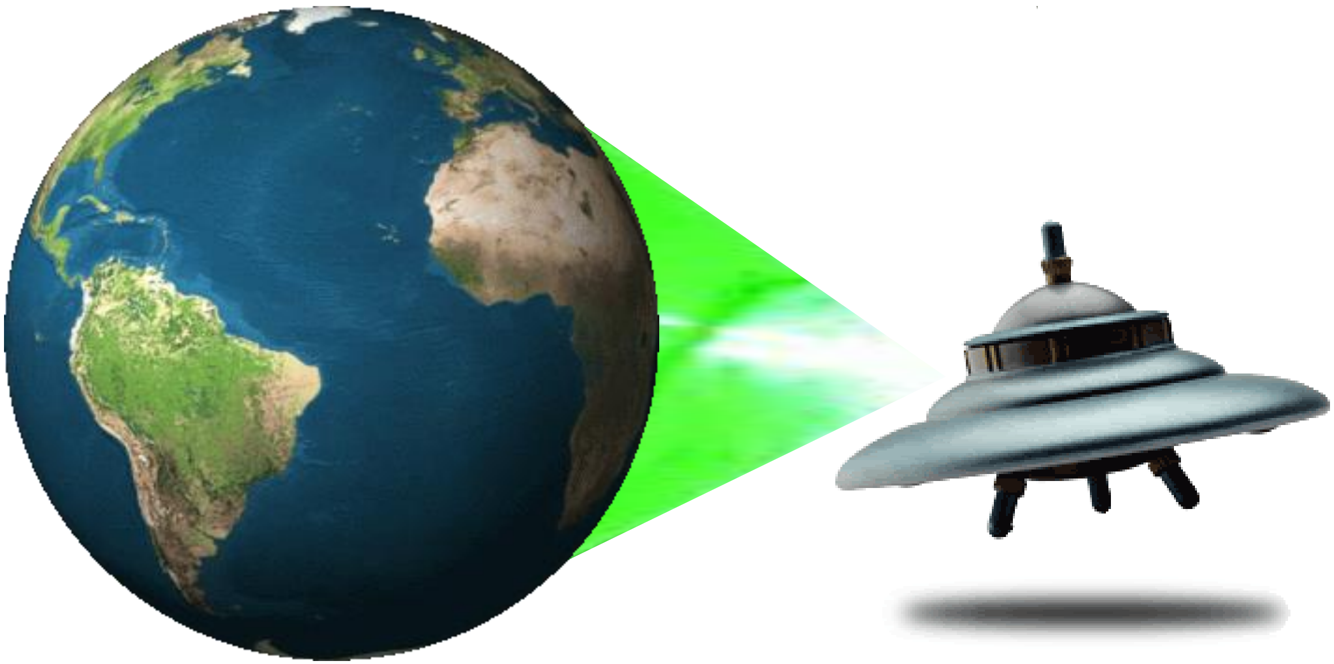
X-ray microscopy – how does it work?

Real time and stroboscopic imaging

Florian Kronast

Introduction

Earth



Introduction

Nationality: Chinese

Sex: Male

Age: 28 years old

Height: 165 cm

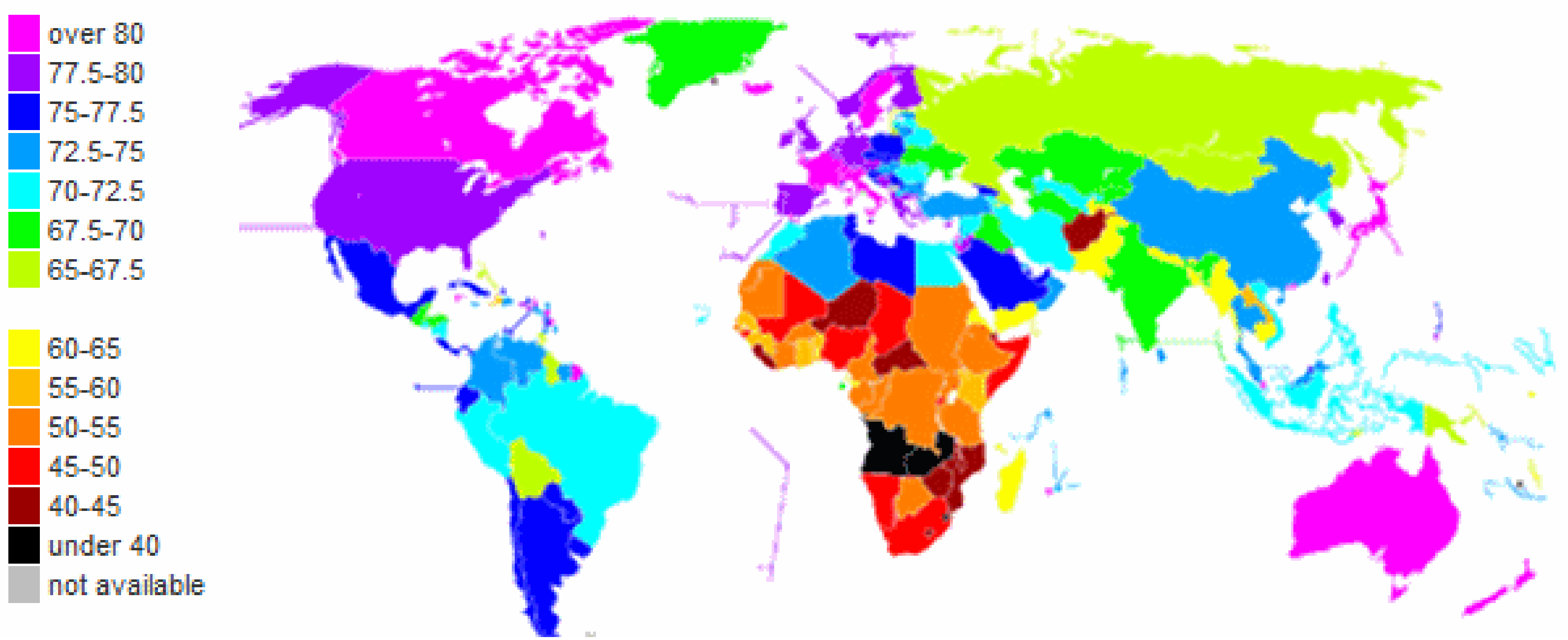
Weight: 62 Kg

Yearly income: 10.000 $

Life expectancy: 69 years

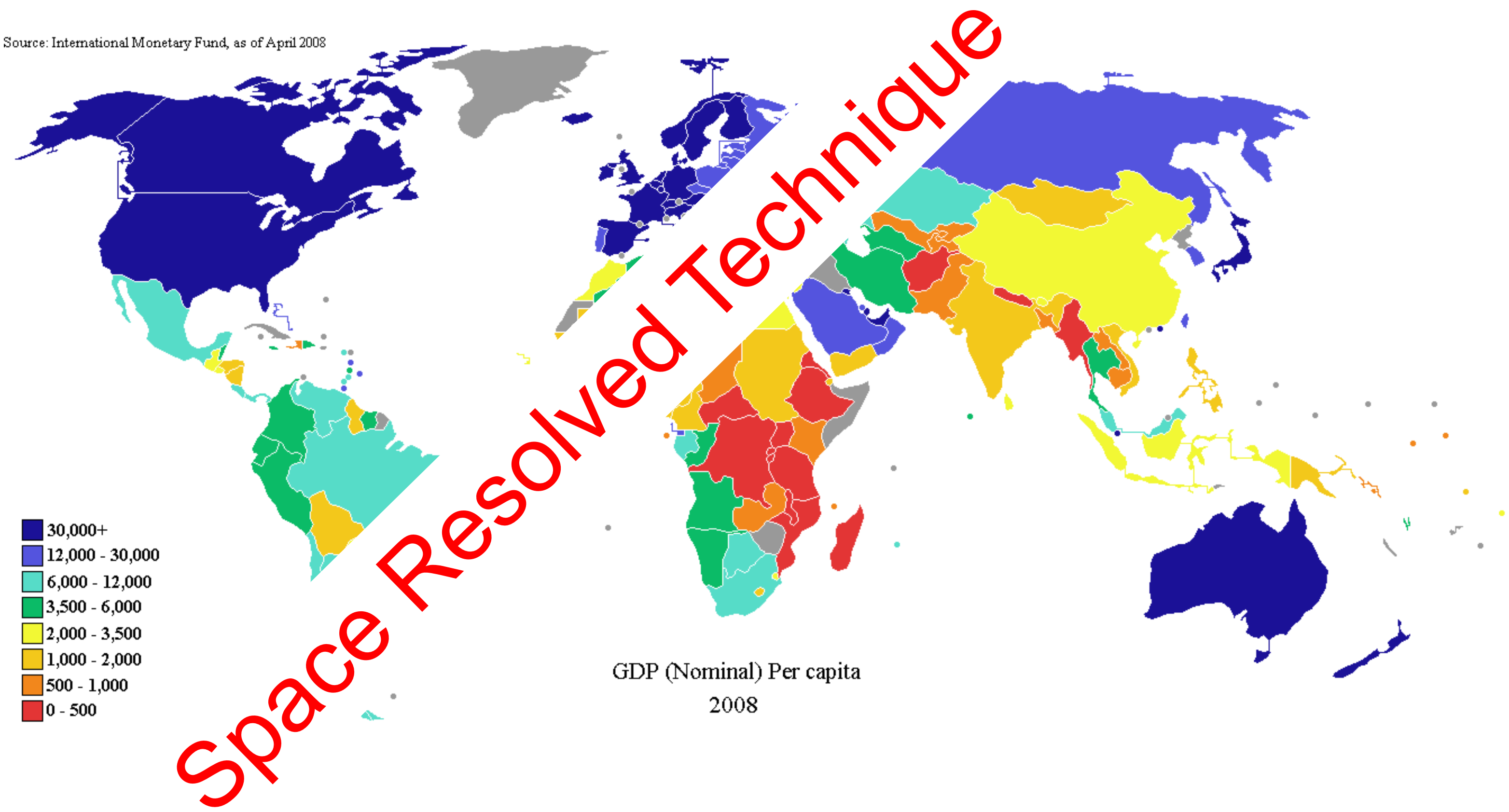
Introduction

Earth



Introduction

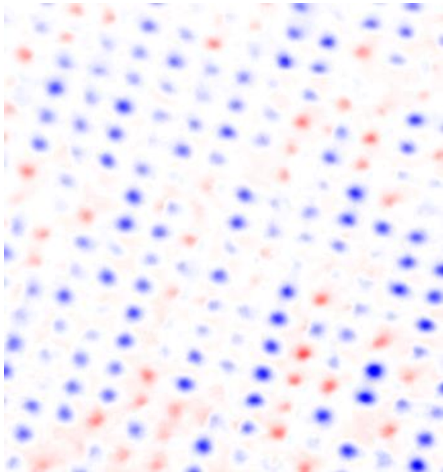
Earth

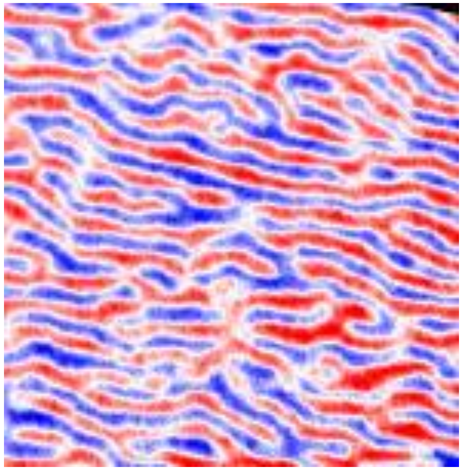


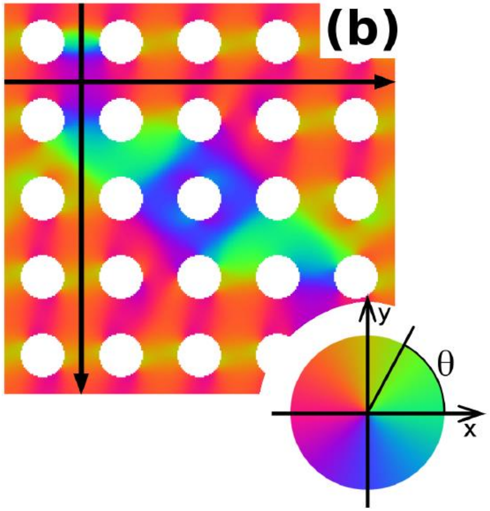
Swizerland 80,500

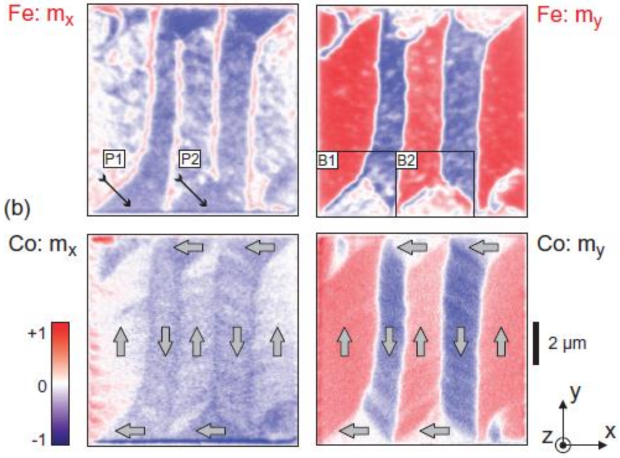
Introduction

Magnetic domain imaging



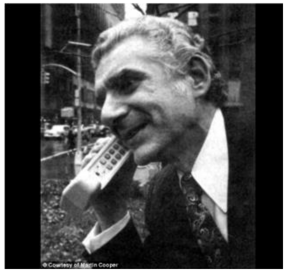






Introduction

Miniaturization



1st phone: DynaTAC „the brick" or the „shoe" phone

1kg and ca. 25 cm

Battery lifetime: 20 minutes

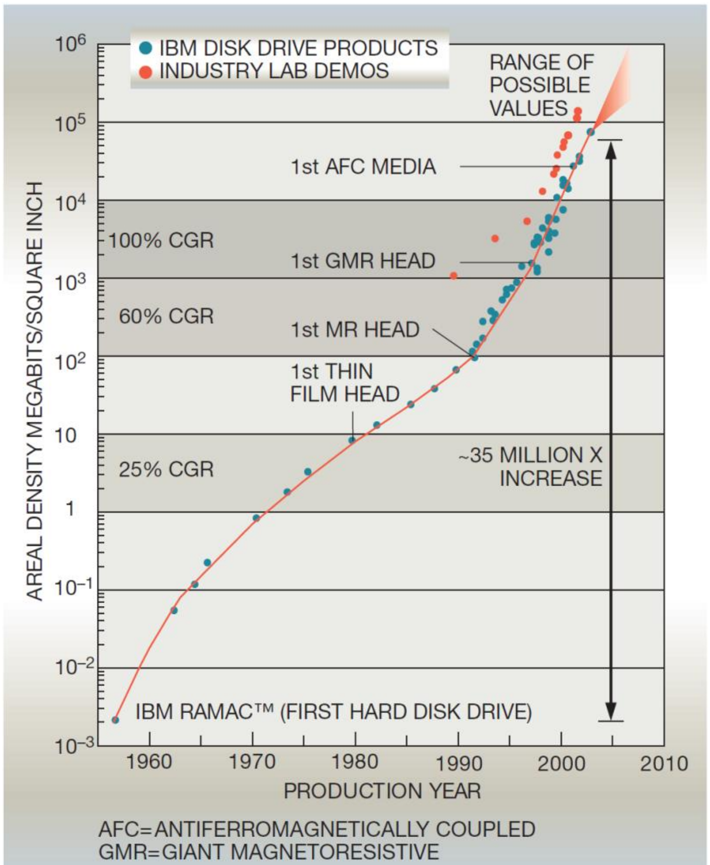
"The battery lifetime wasn't really a problem because you couldn't hold that phone up for that long!"

Martin Cooper

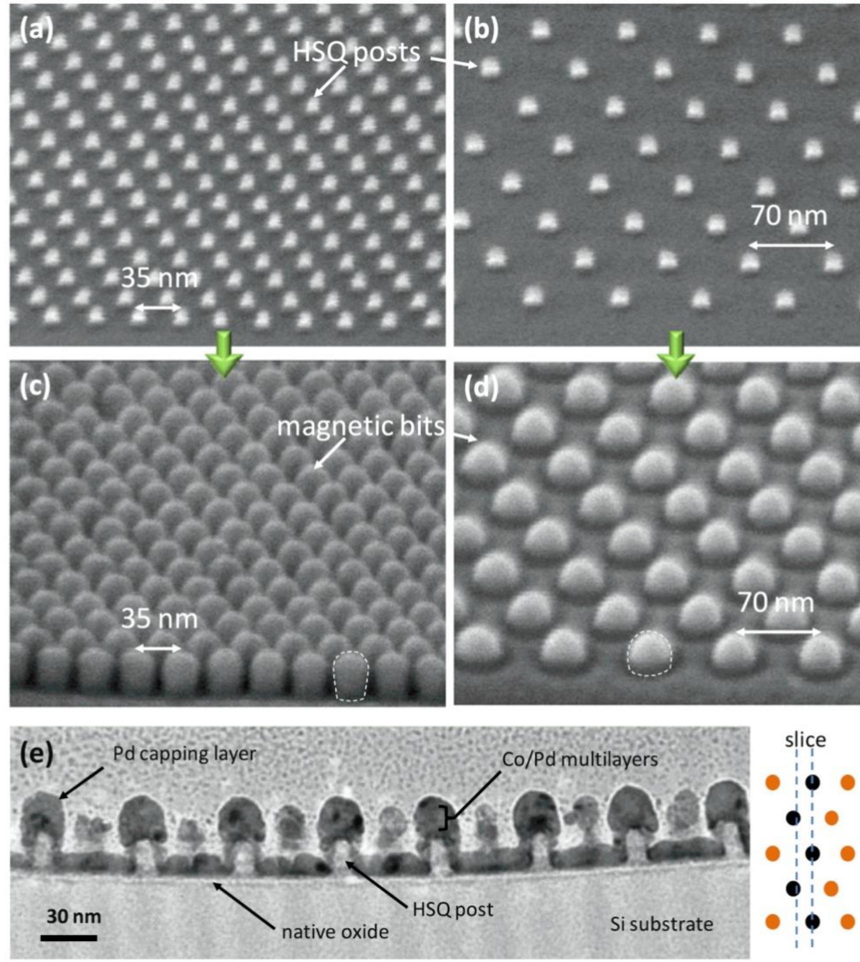
Introduction

Miniaturization

Figure 1 Hard disk drive areal density trend



E. Grochowski and R.D.Halem, IBM Syst. J. 42, 338 (2003)

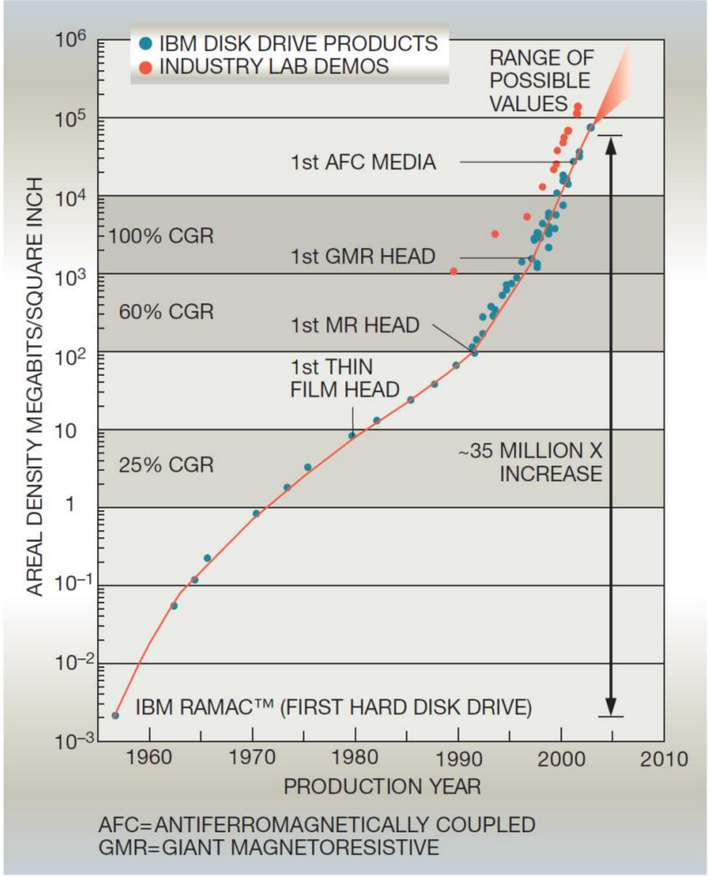


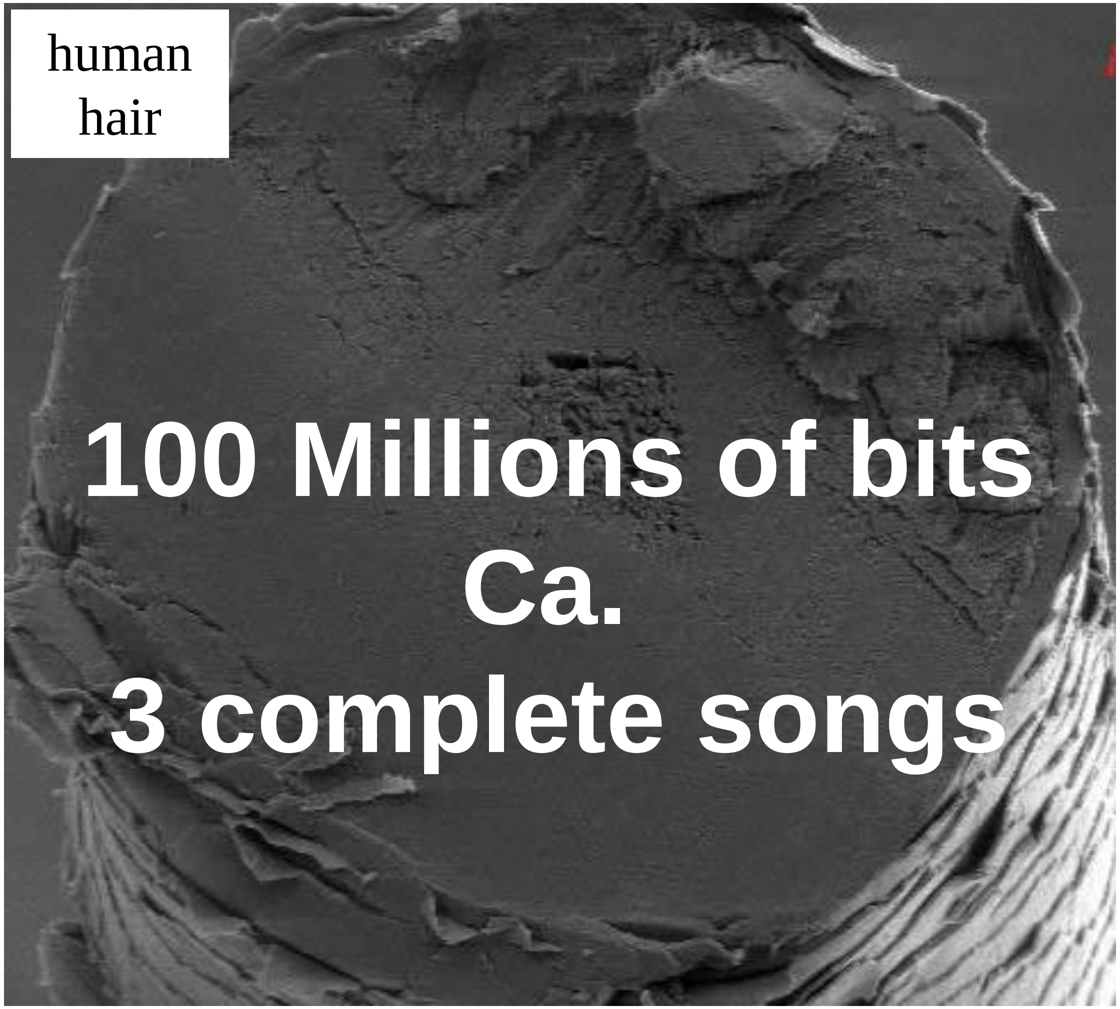
J.K.W Yang et al. Nanotechnology 22, 385301 (2011)

Introduction

Miniaturization

Figure 1 Hard disk drive areal density trend



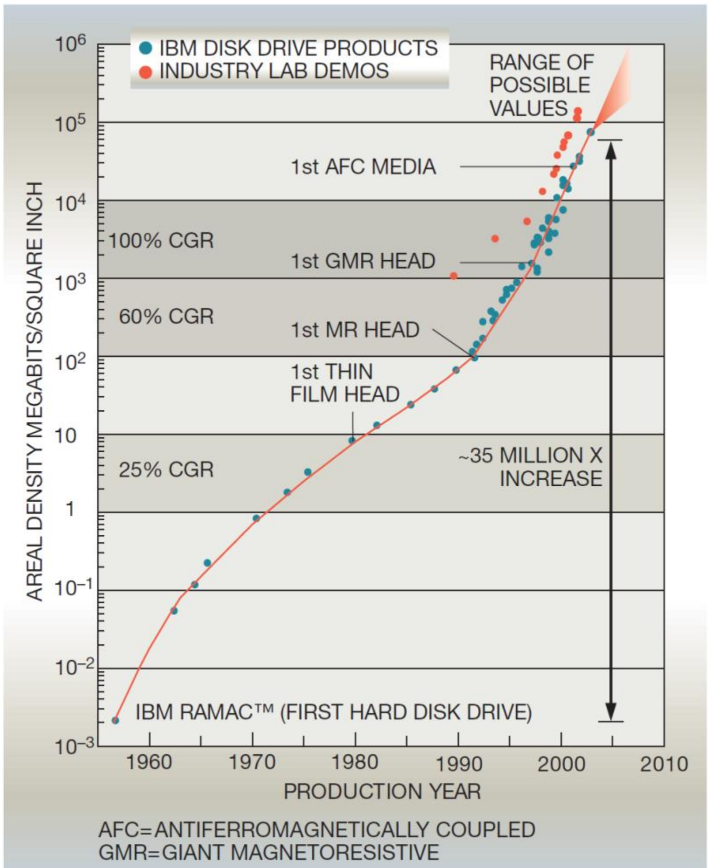


E. Grochowski and R.D.Halem, IBM Syst. J. 42, 338 (2003)

Introduction

Miniaturization

Figure 1 Hard disk drive areal density trend



E. Grochowski and R.D.Halem, IBM Syst. J. 42, 338 (2003)

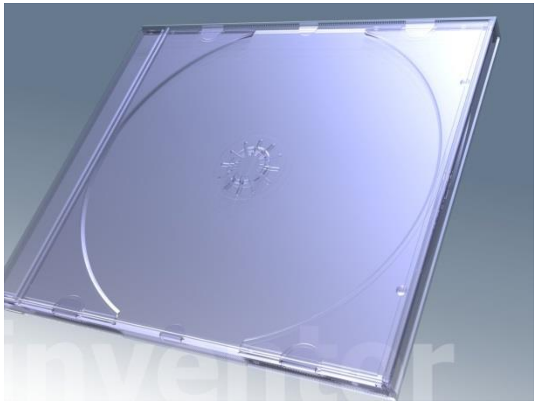
Floor space required to store 10 Terabyte of information

(USA Congress library with 138 Millions of documents)

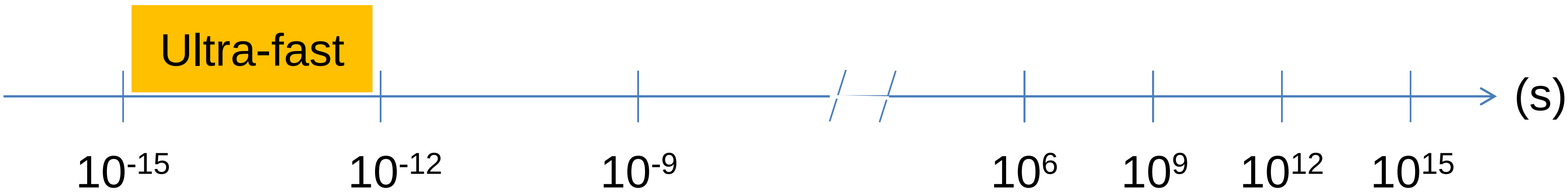
1953

1200 football fields

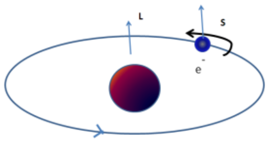
2011

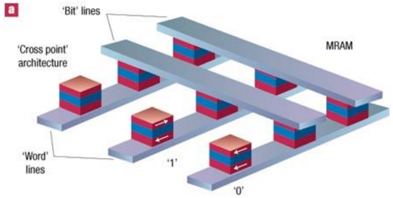


Timescales in Magnetism

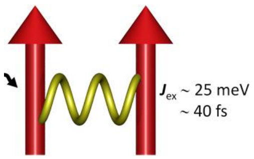


Spin-orbit coupling

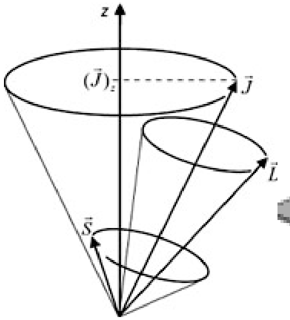




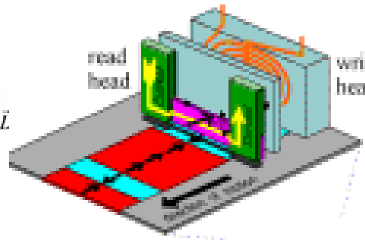
MRAM



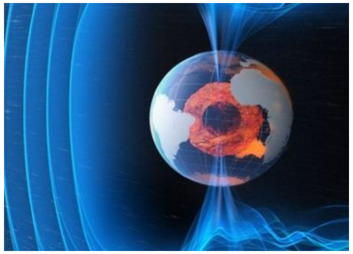
Exchange interaction



Spin precession



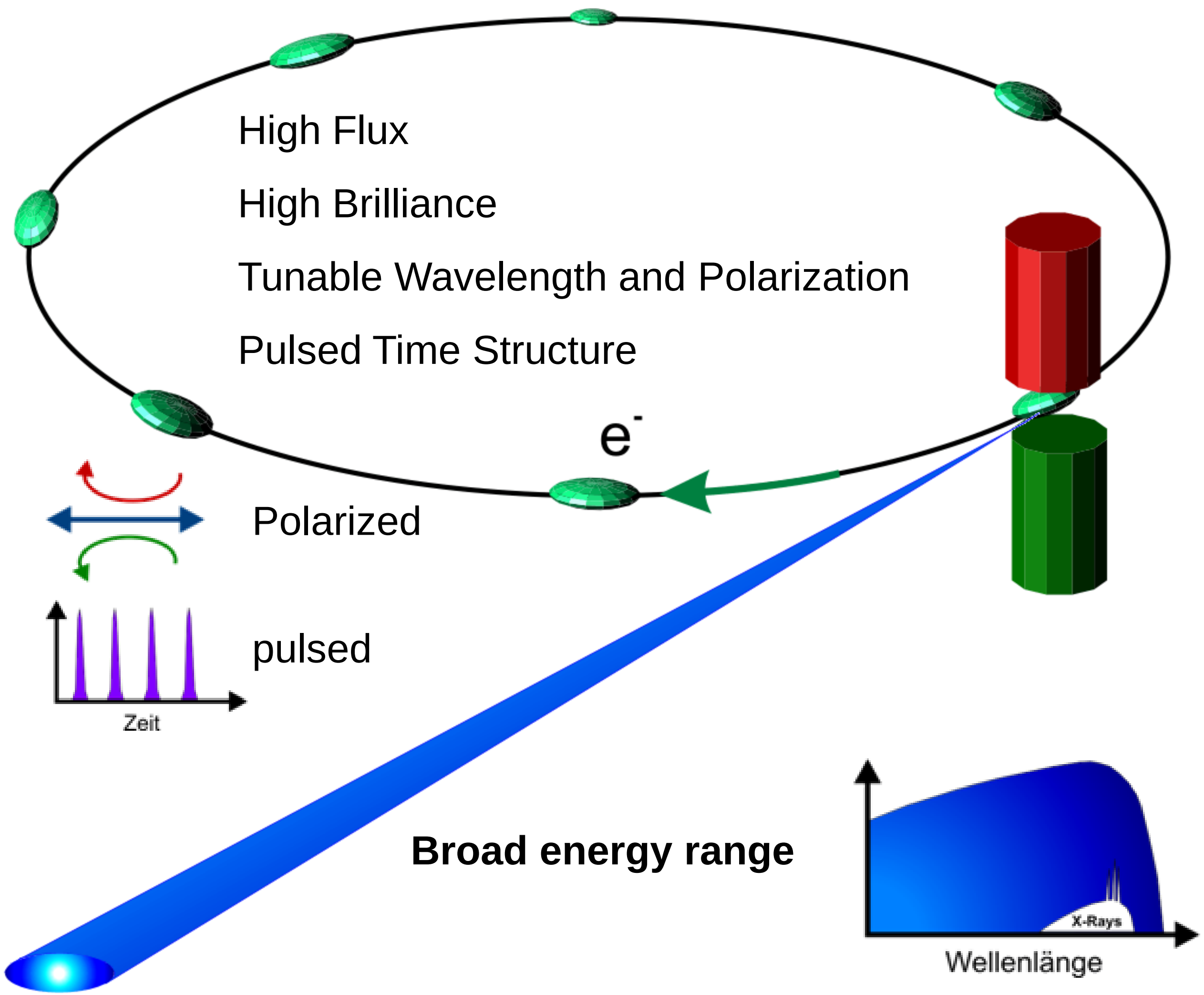
GMR heads



Earth dipolar field

Magnetic data storage
Stability requirements ~ 10 years

Synchrotron radiation



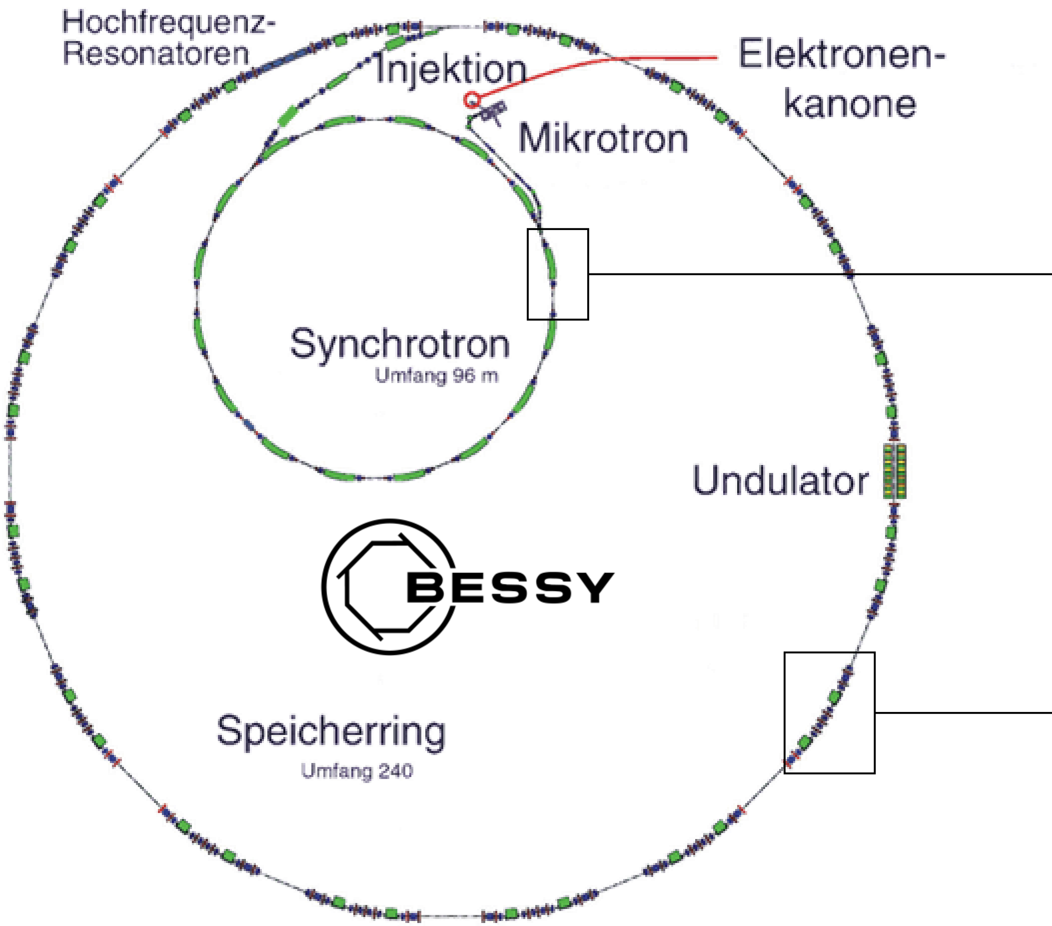
The first synchrotron light

observed at *General Electric Labs in* 1946

Elder, Gurewitsch, Langmuir and Pollock

"Radiation from Electrons in a Synchrotron“

3rd Generation Storage Ring 1.7GeV

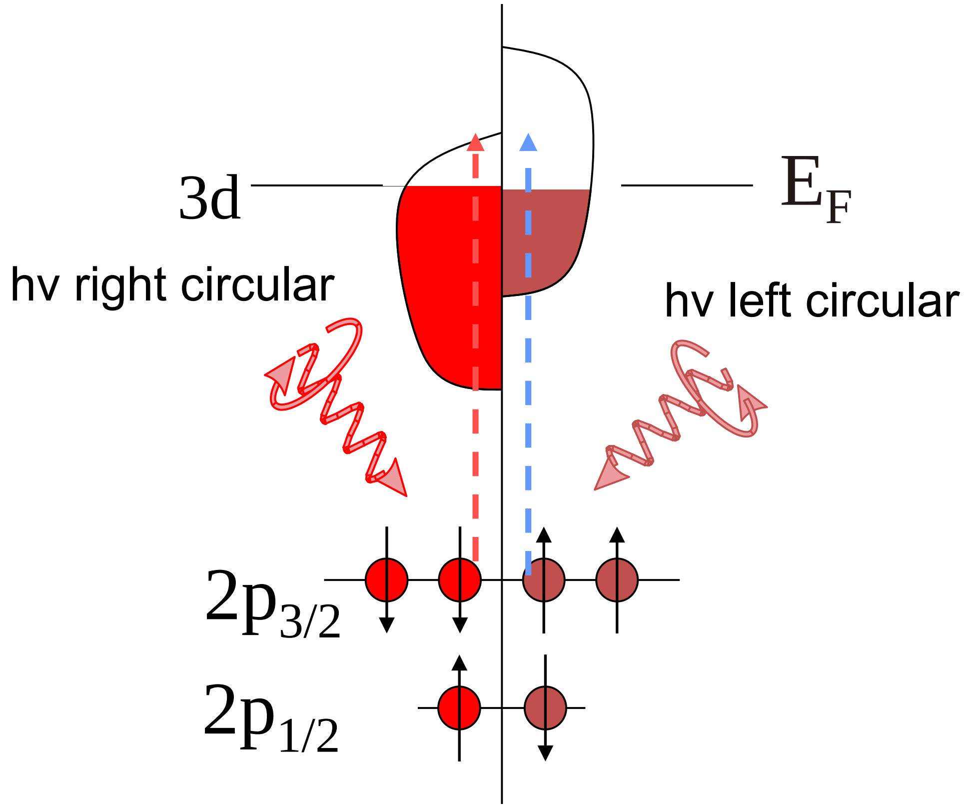


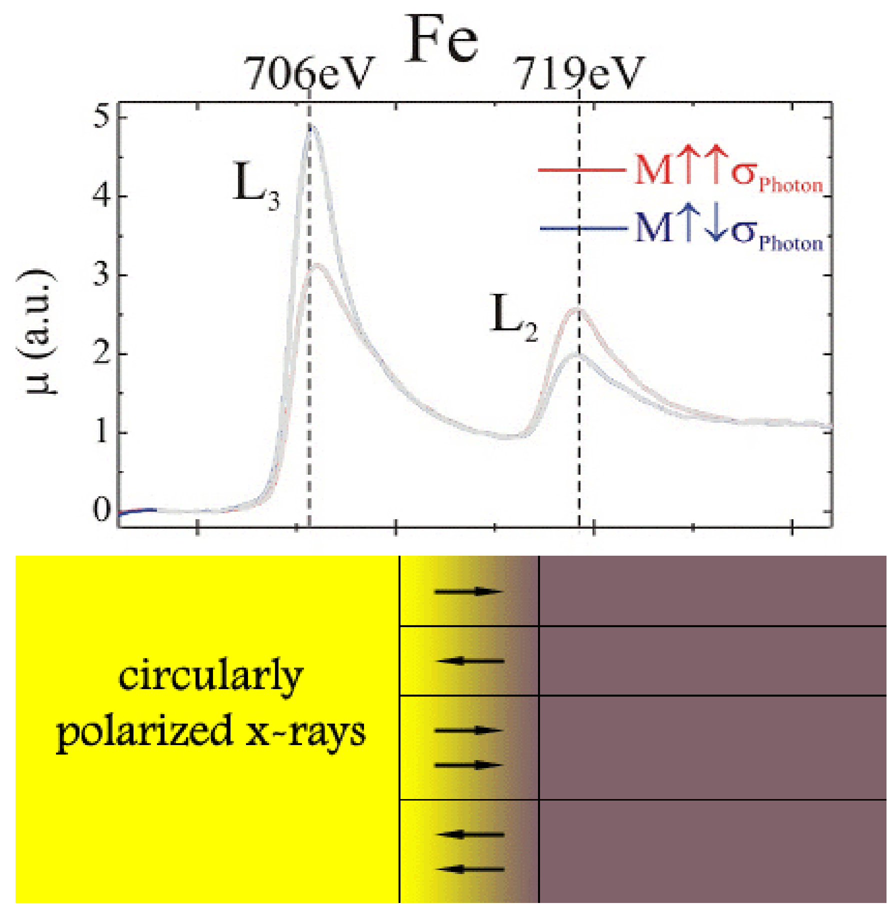
Experimental hall:
53 beamlines operating
in a broad spectral range

BESSY

X-ray magnetic circular dichroism

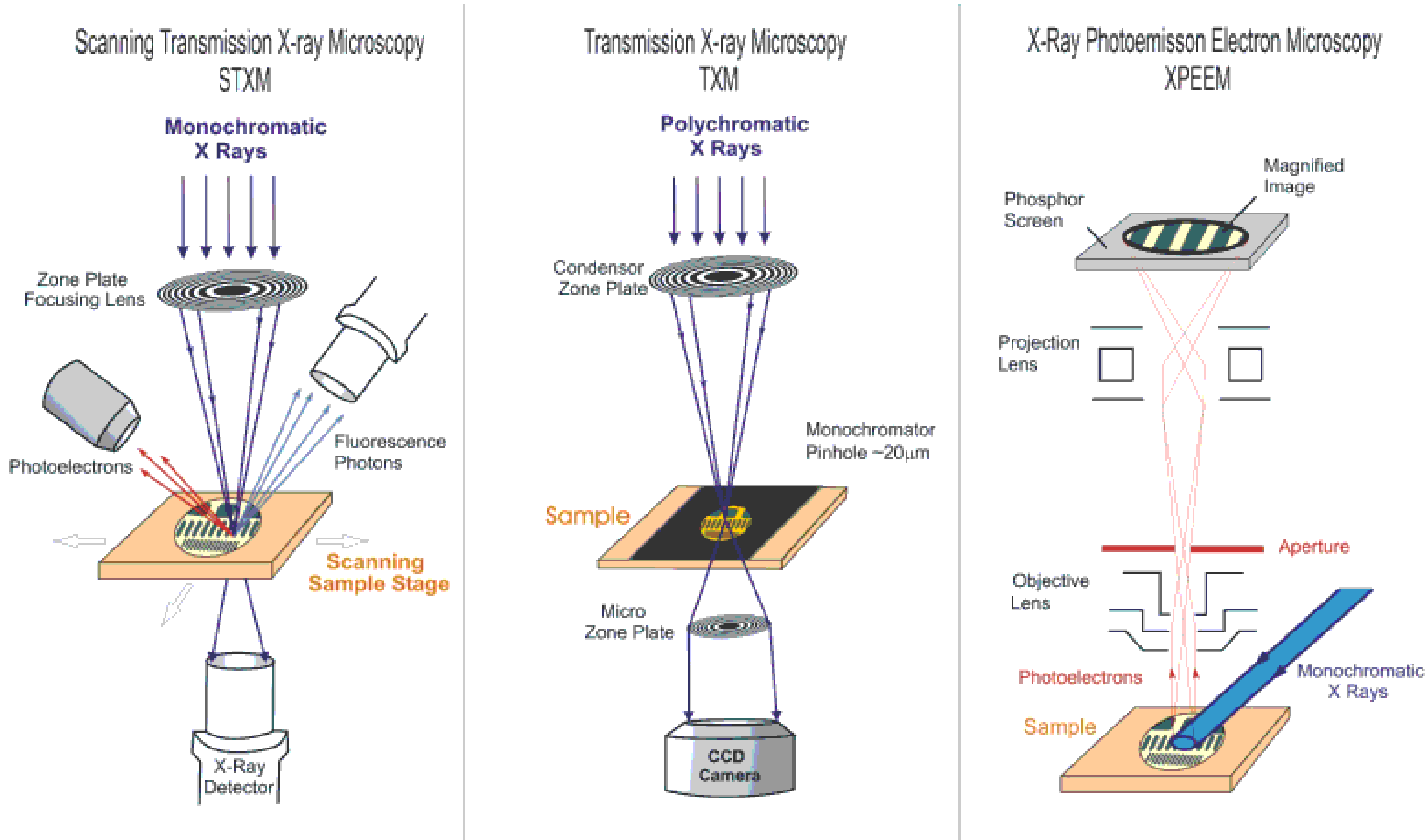
Element specific + magnetization sensitive





maximum contrast for **k || M**

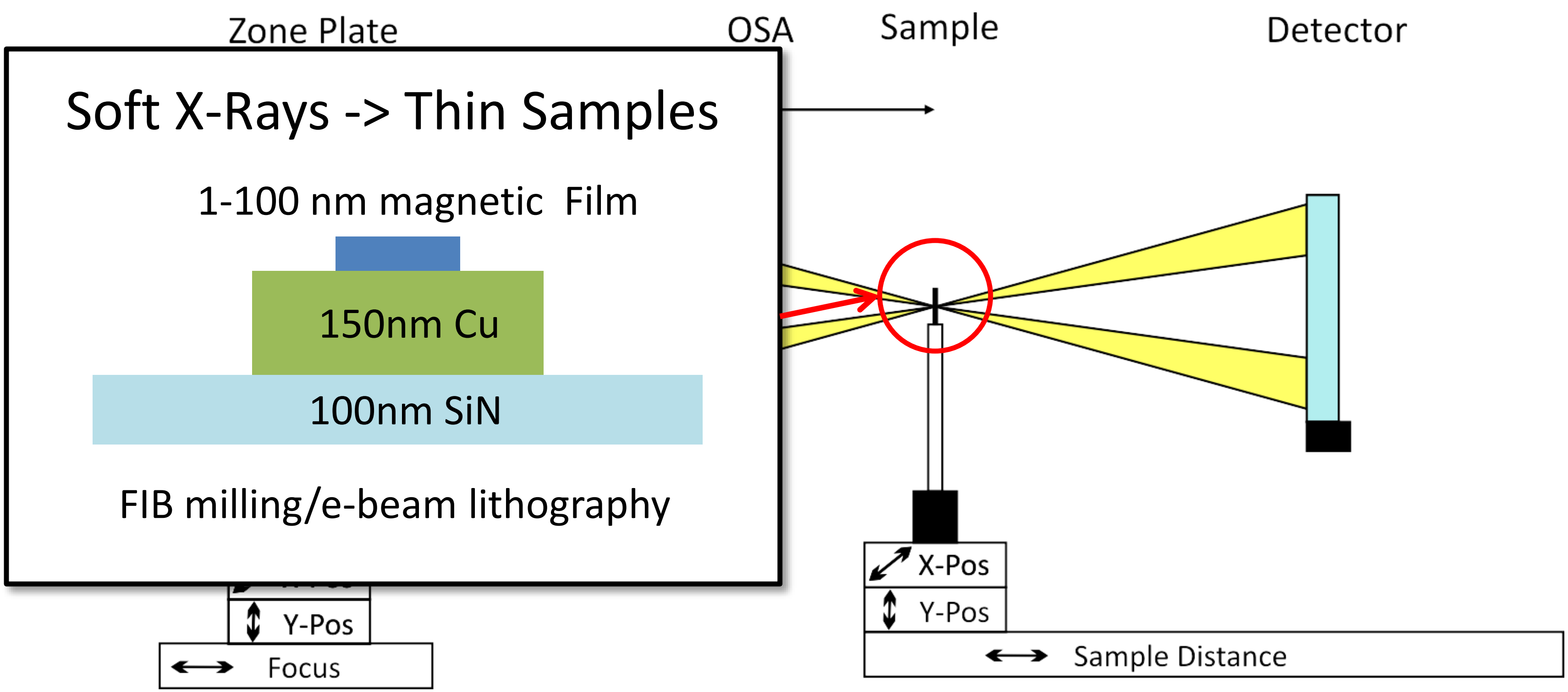
X-ray imaging in real space



Copied from ssrl.slac.stanford.edu

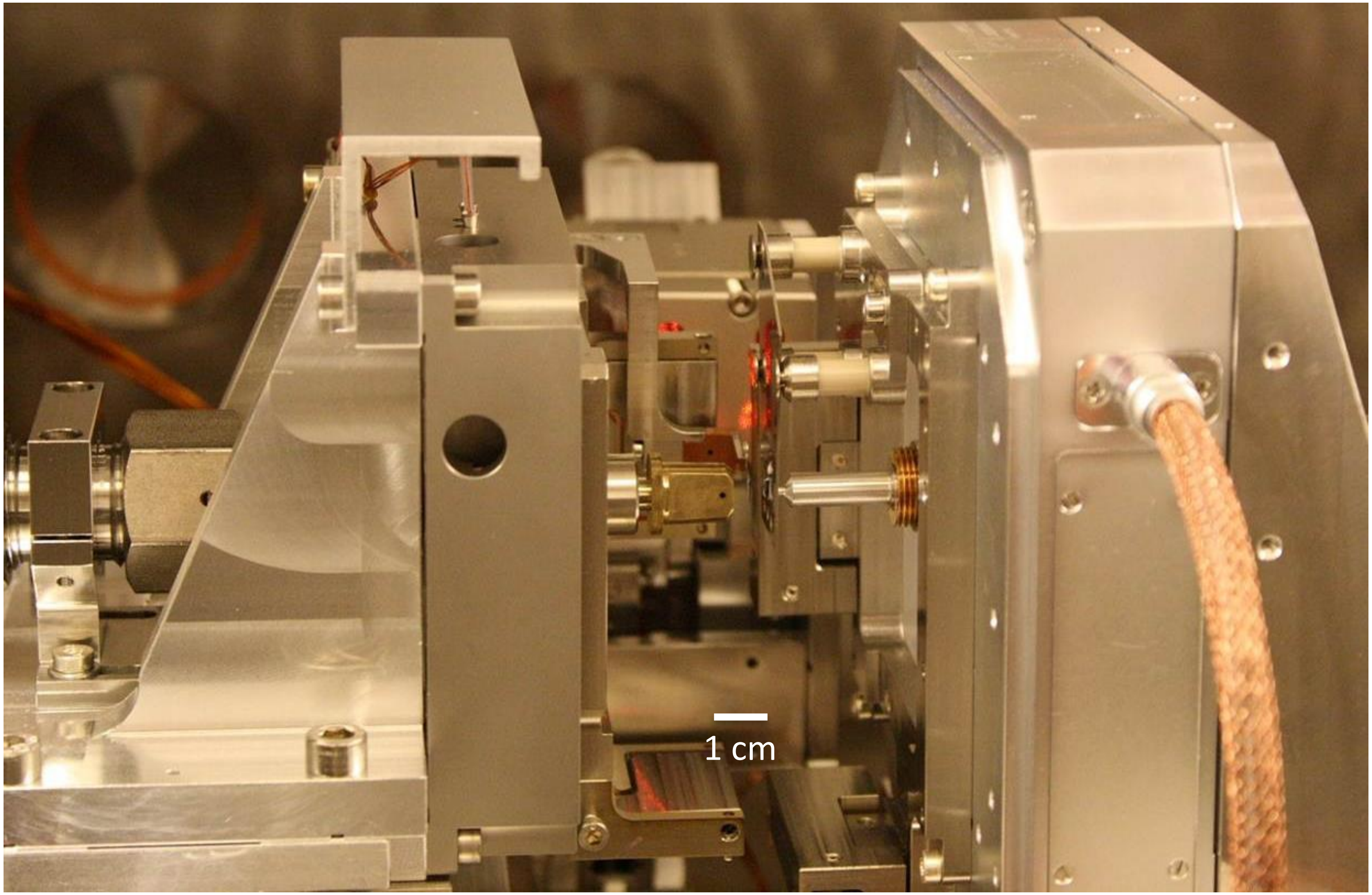
Scanning x-ray microscopy

- Contrast Mechanism: **NEXAFS | XMCD**
- Spatial Resolution: Set by Zone Plate (15nm)



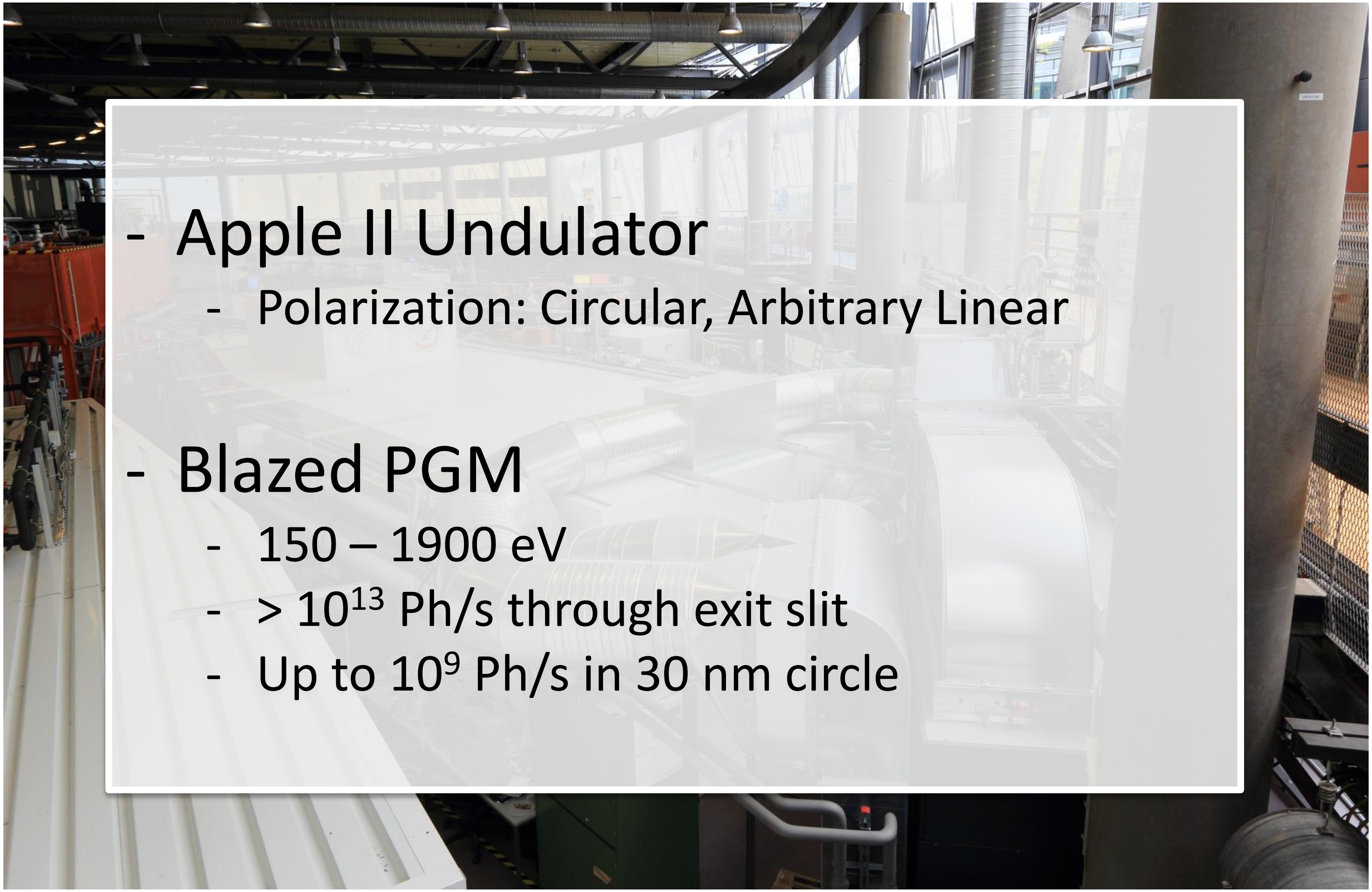
Courtesy Markus Weigand

In real life



Courtesy Markus Weigand

MAXYMUS



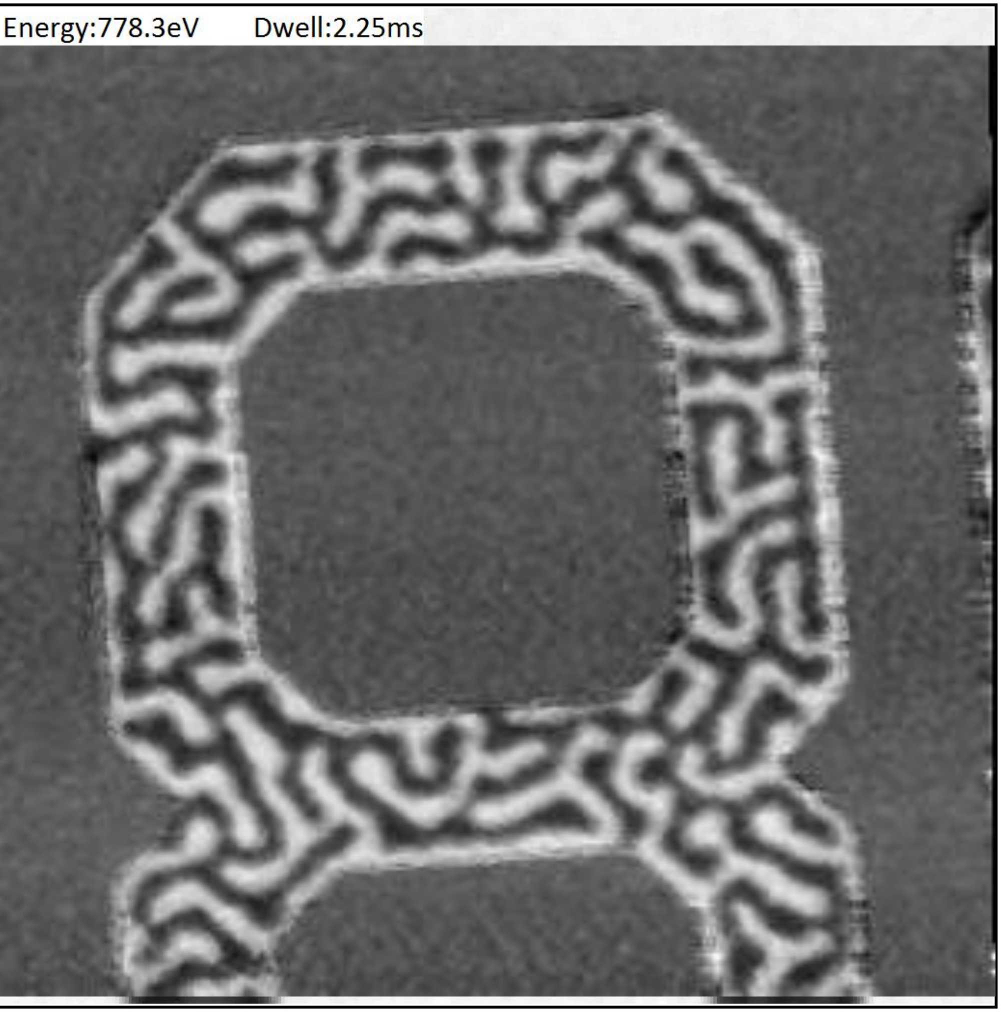
- Apple II Undulator
  - Polarization: Circular, Arbitrary Linear

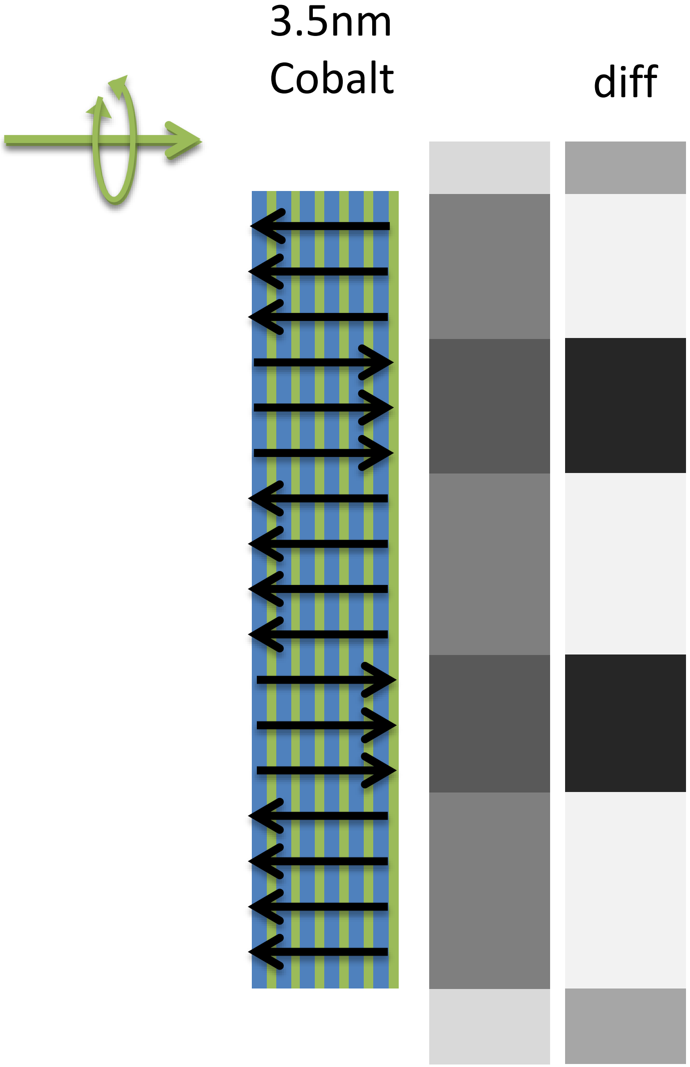
- Blazed PGM
  - 150 – 1900 eV
  - > 10^{13} Ph/s through exit slit
  - Up to 10^{9} Ph/s in 30 nm circle

Courtesy Markus Weigand

XMCD imaging

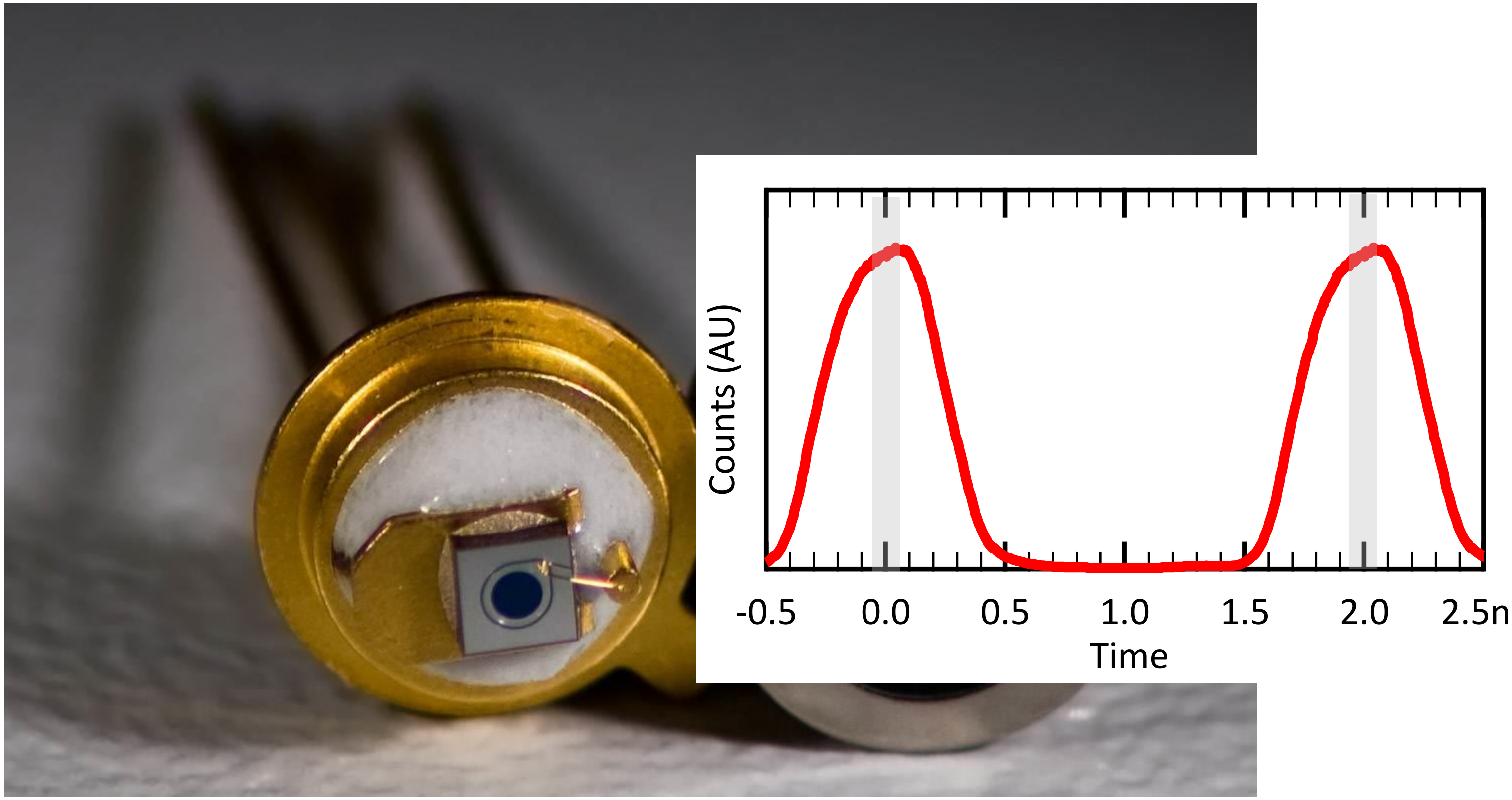
- Strong Magnetic Contrast
- Differential contrast





Courtesy Markus Weigand

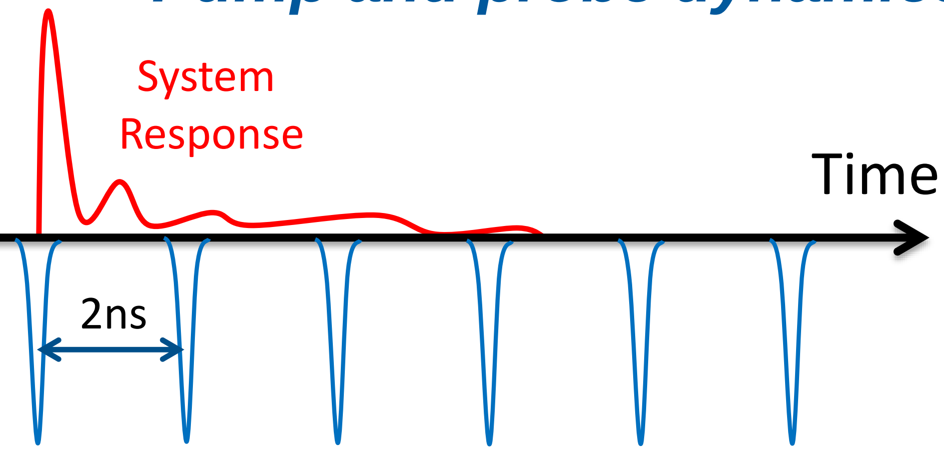
Fast single photon detection

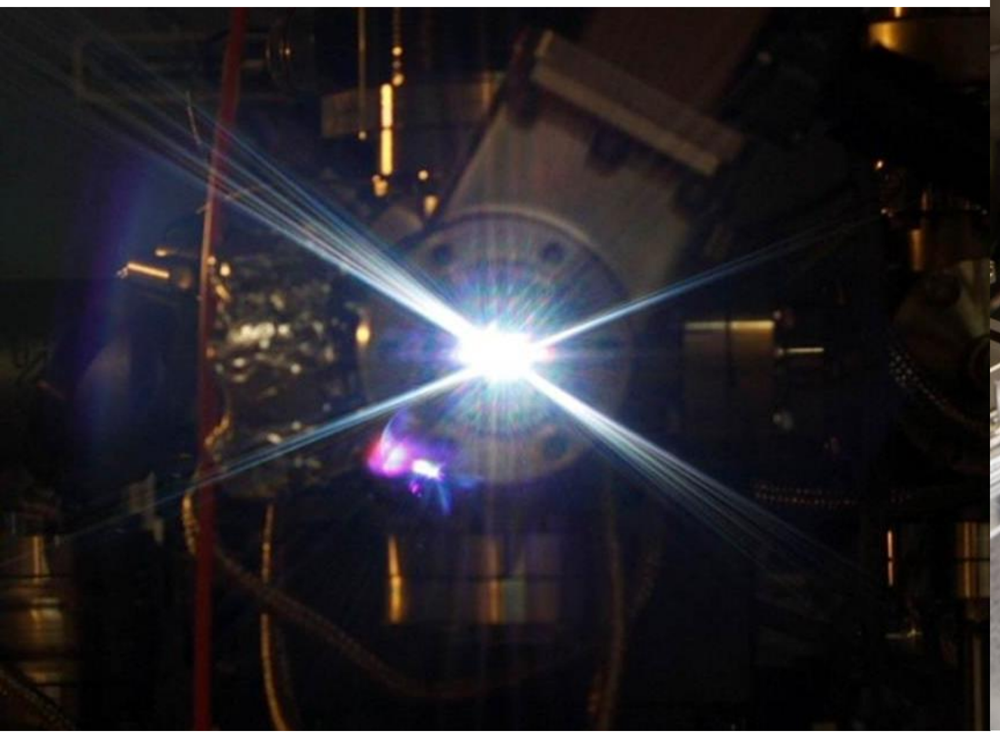


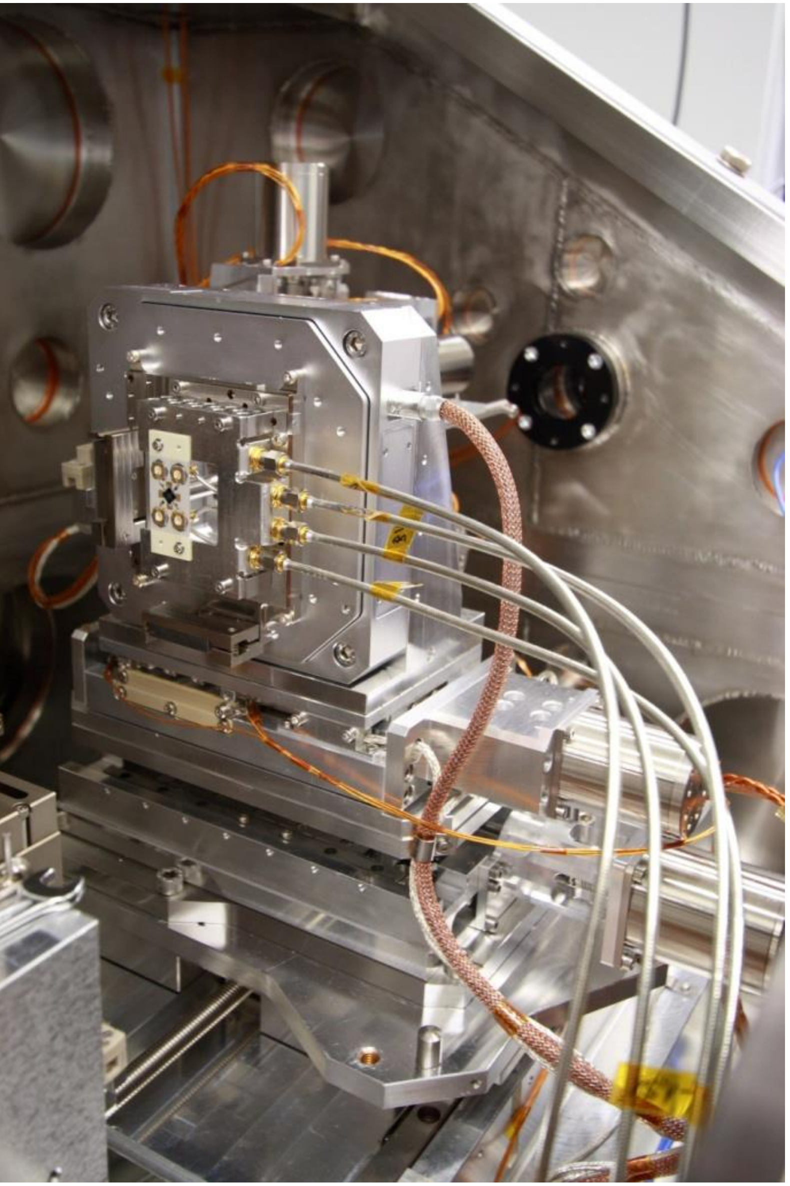
- Avalanche Photodiodes with internal gain
- Single Photon QE>60% at Fe,Co,Ni L-edges
- Recovery time << 2ns
- SNR $>10^6$ @ $>10^8$ events/s !

Courtesy Markus Weigand

Pump and probe dynamics

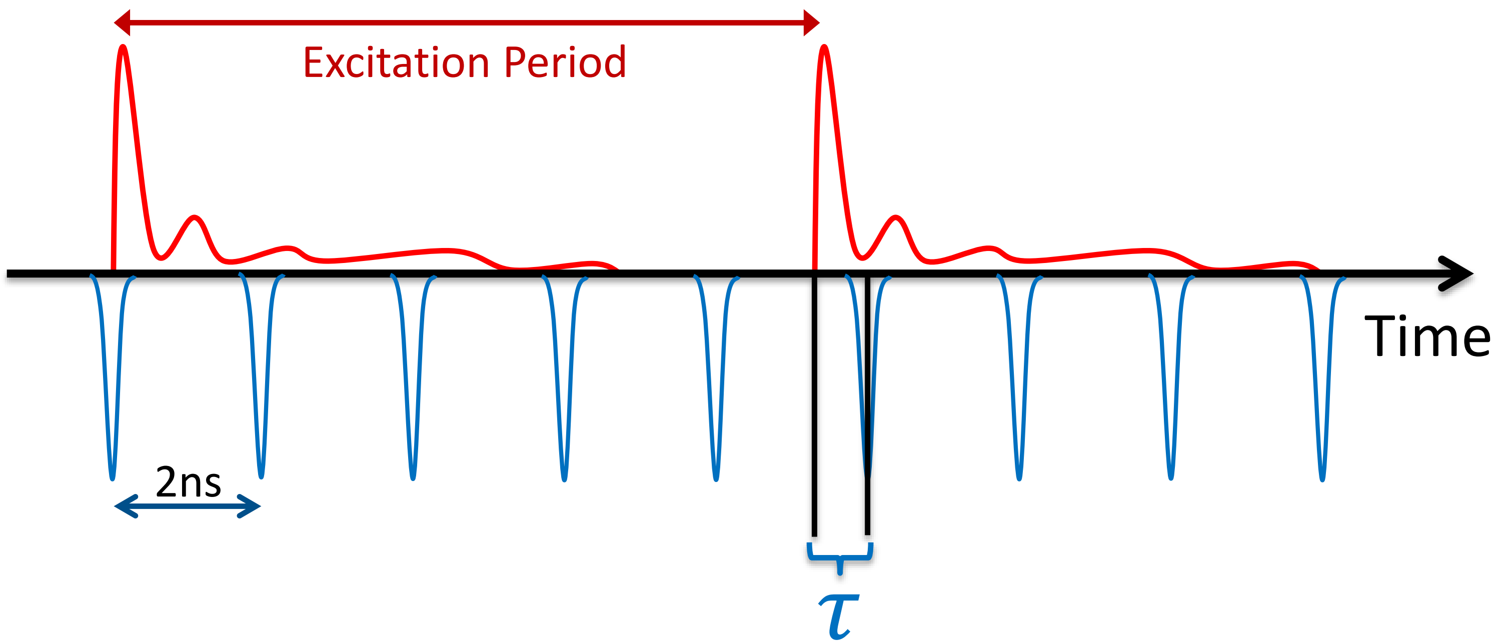






Courtesy Markus Weigand

Asynchroneous excitation possible



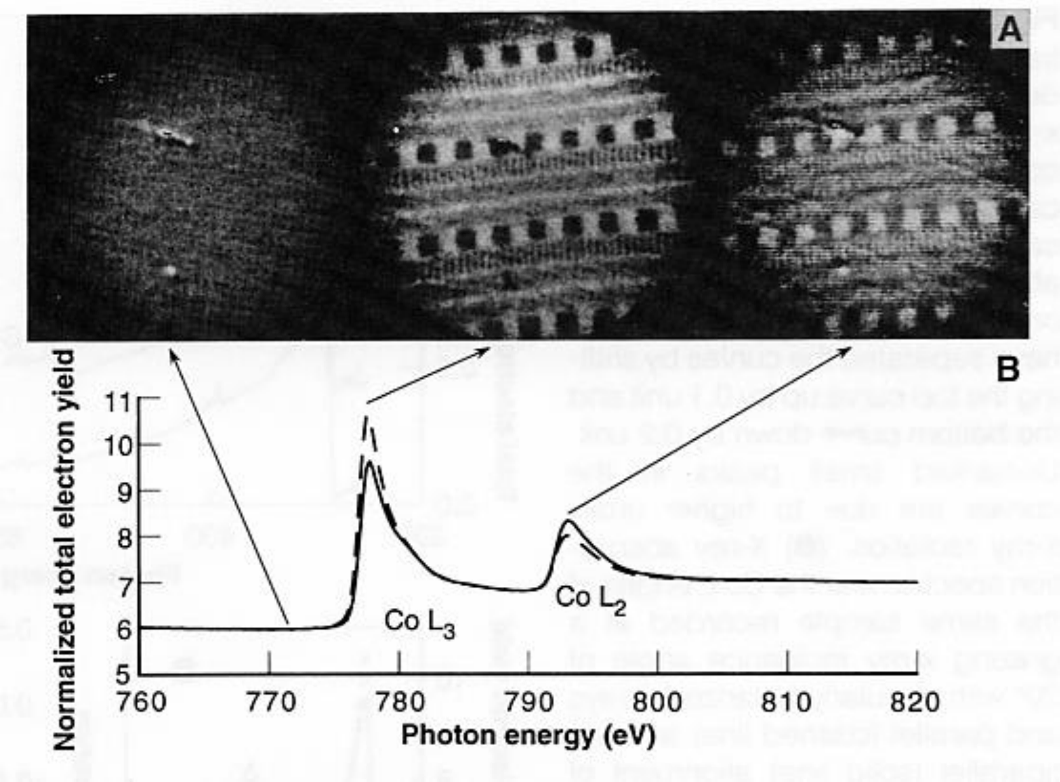
- Simultaneous acquisition of all time channels!
- All buckets contribute to all time channels (if $\gcd(N_{Buckets}, N_{Channels}) = 1$)

Photon sorting at 500MHz using FPGA Courtesy Markus Weigand

Photoemission electron microscopy

1993 Element-Specific Magnetic Microscopy with Circularly Polarized X-rays

J. Stöhr, Y. Wu, B. D. Hermsmeier, M. G. Samant, G. R. Harp, S. Koranda, D. Dunham, B. P. Tonner



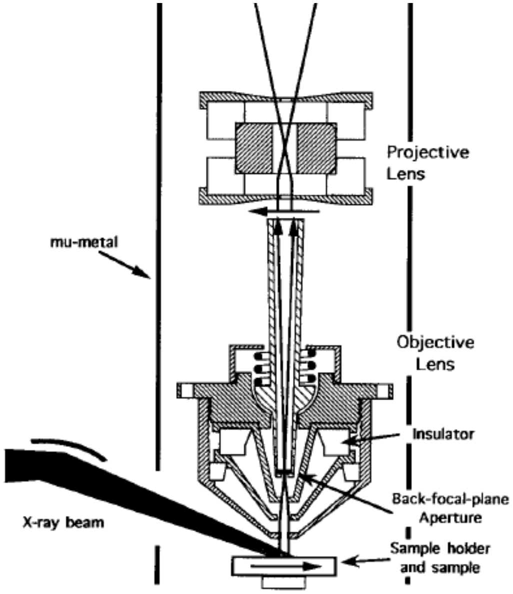
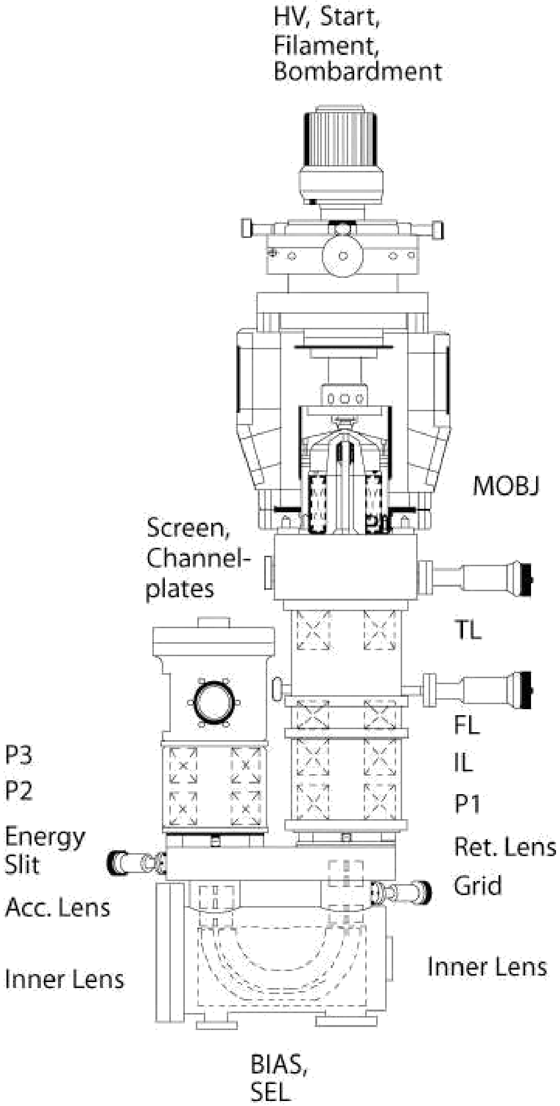
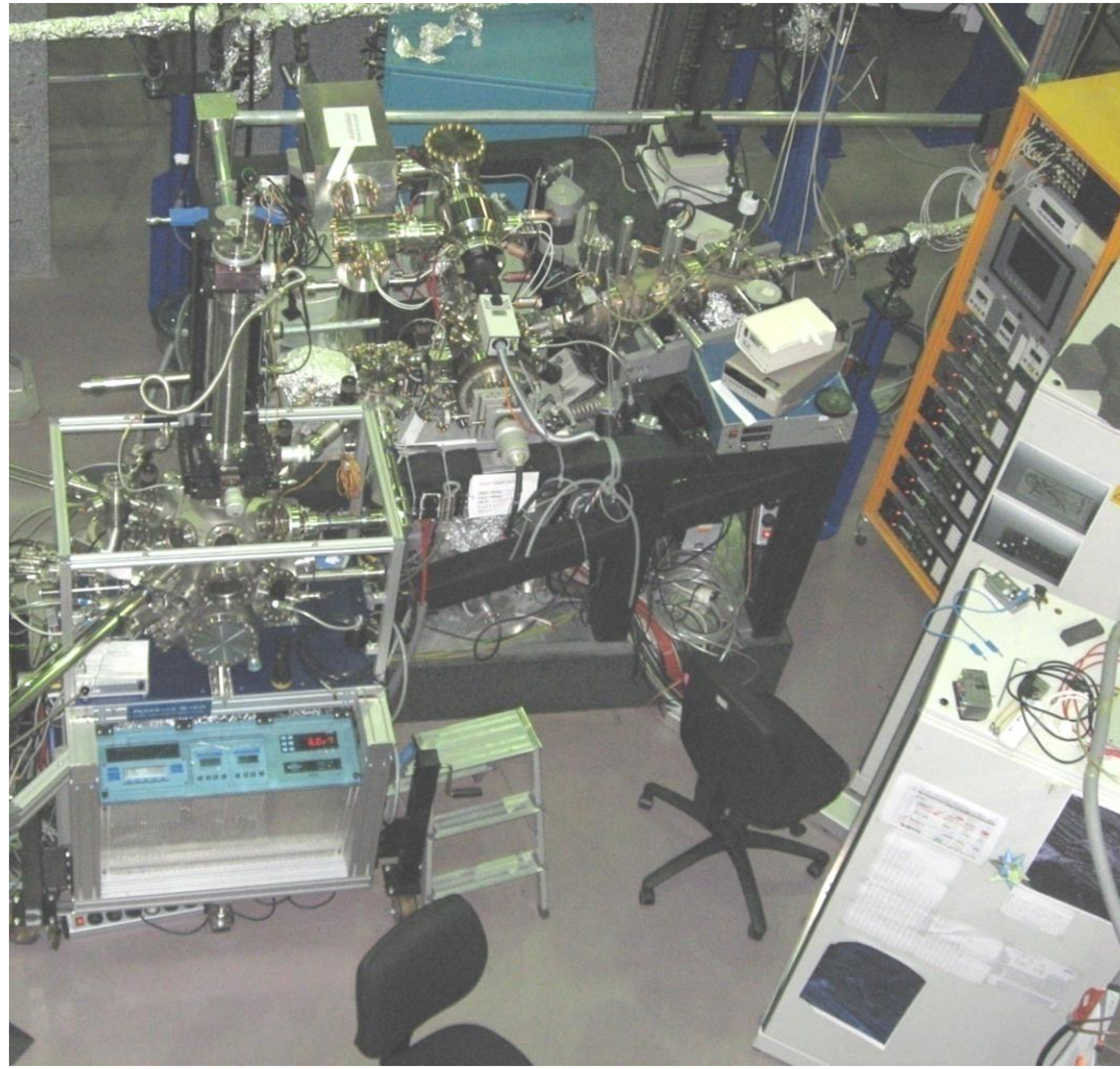


Fig. 2. Schematic diagram of the magnetic X-ray dichroism apparatus. Circularly polarized X-rays illuminate the field-of-view on the sample, which emits secondary electrons in proportion to the absorption of X-rays. The secondary electrons are focussed with electrostatic lenses to form a magnified image of the sample surface on the microchannel-plate intensifier.

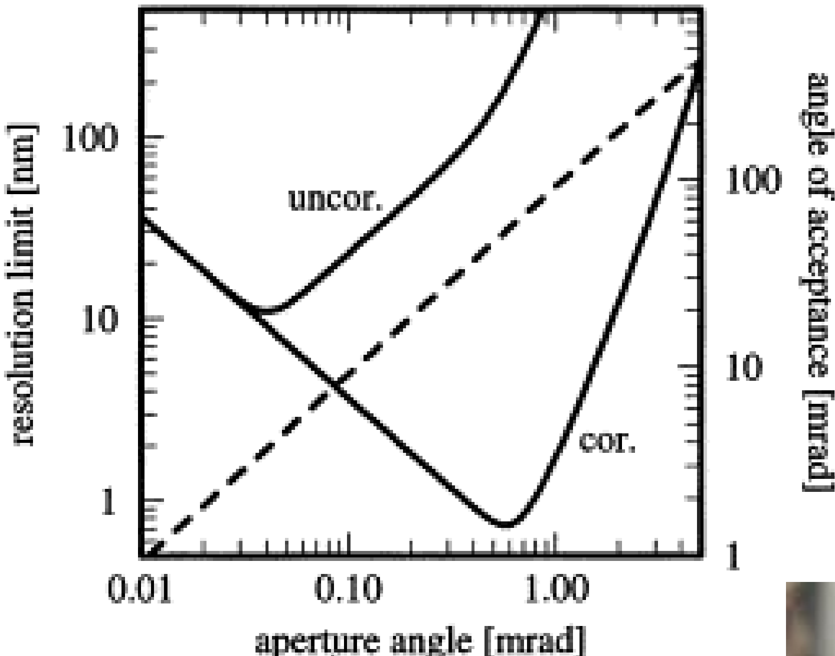
J. Stöhr et al. Science 259, 658 (1993)

Microscopy & magnetic imaging on the nanometer scale



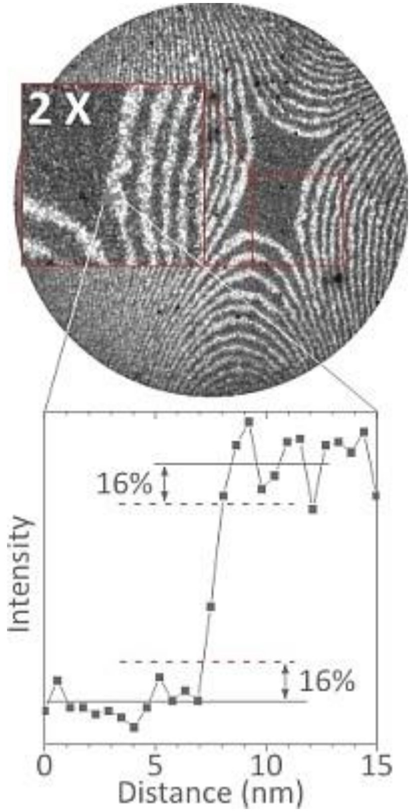


Aberration correction using an electron mirror



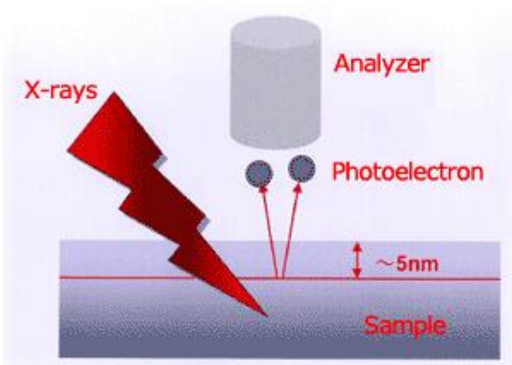
Journal of Electron Spectroscopy and Related Phenomena
Volume 84, Issues 1–3, 1 March 1997, Pages 231–250

2nm spatial resolution



Elmitec GmbH

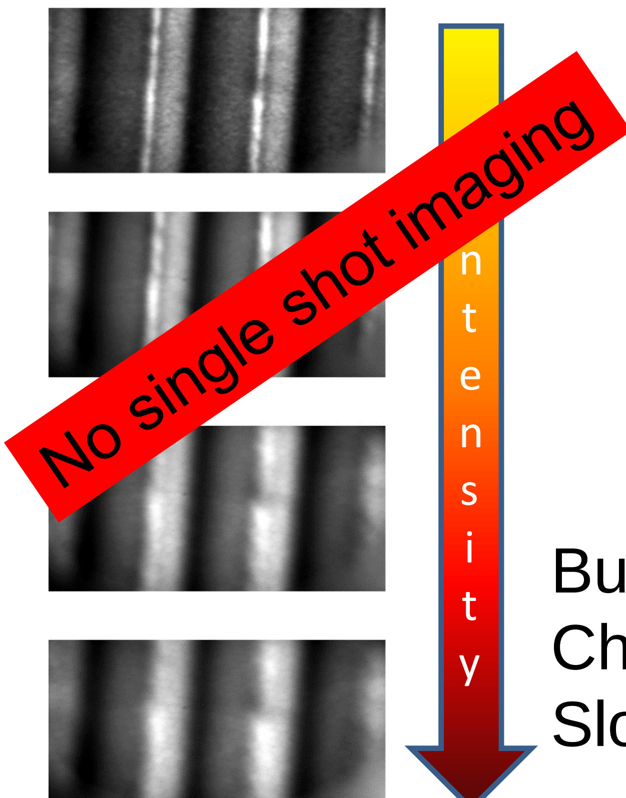
Photoemission electron microscopy



PEEM is surface / interface sensitive
(electron escale depth 3-5nm)

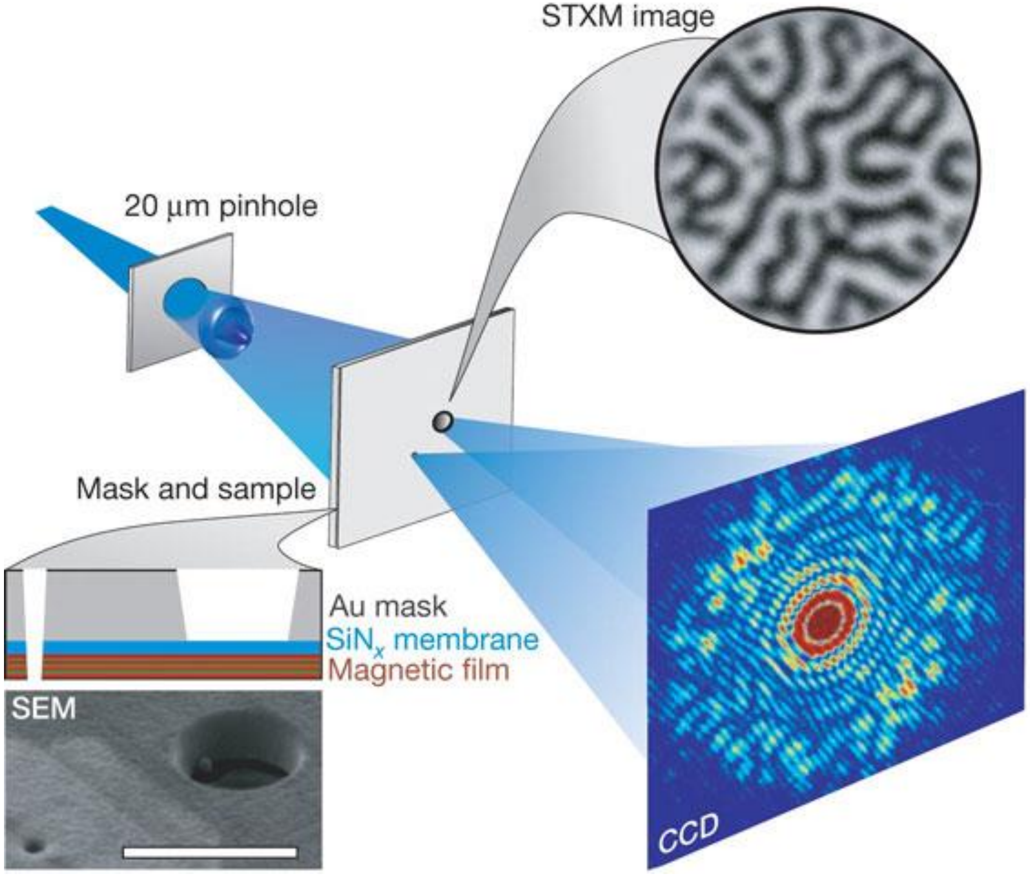
requires conductive sample

Information on
- elemental composition
- chemistry
- structural parameters
- electronic structure
- magnetic properties
- topography



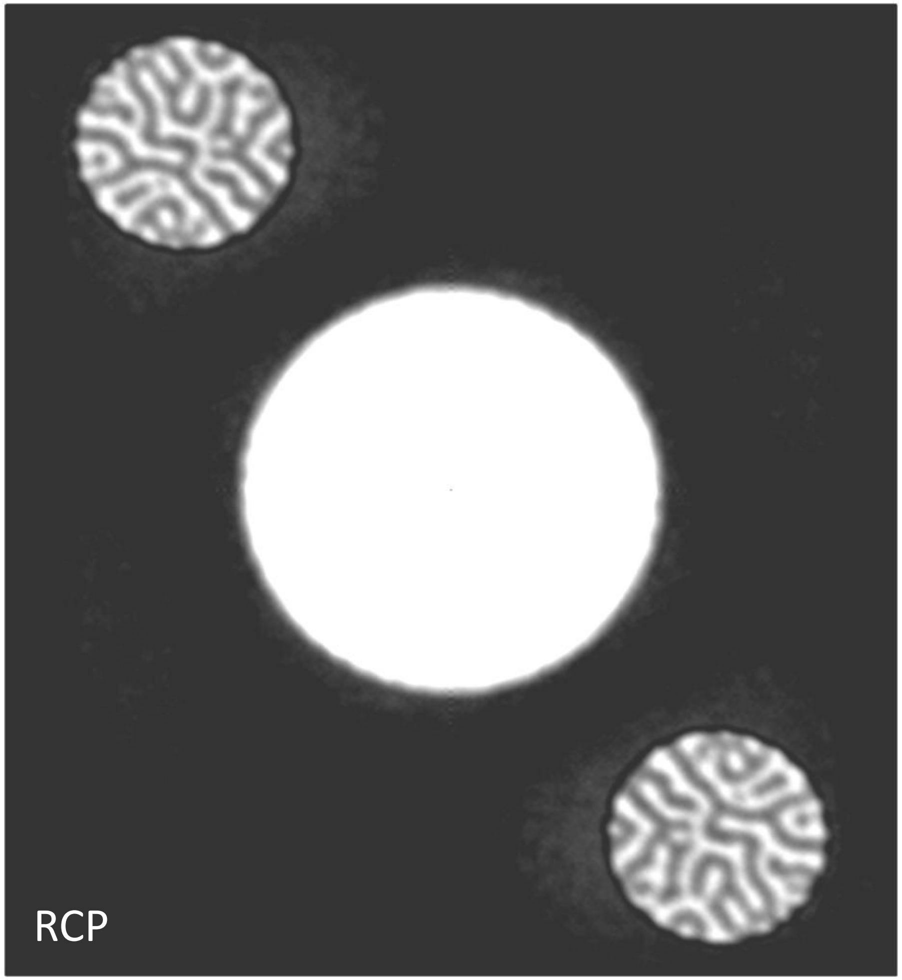
But:
Charging effects at higher pulse intensity
Slow 2d detector

X-ray imaging in reciprocal space: holography



S. Eisebitt, et al. *Nature* **432**, 885 (2004)

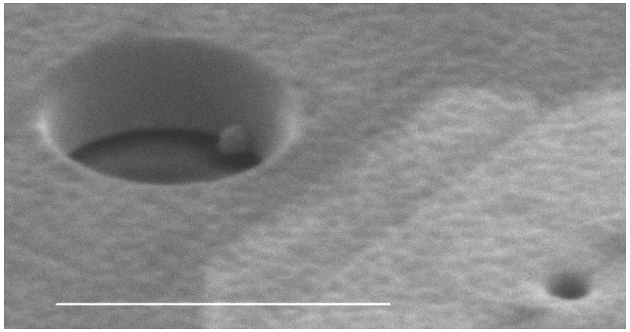
Digital image reconstruction



Convolution theorem applied to diffraction:
FT(diffraction) = Autocorrelation (Object)

FT (a ⊗ b) = FT(a) · FT(b)

(a ⊗ a) = FT^{-1} {FT(a) · FT(a)}

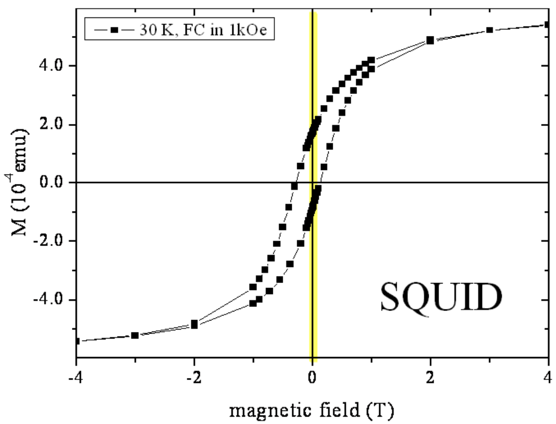


a real space object
FT(a) · FT(a) diffraction intensity

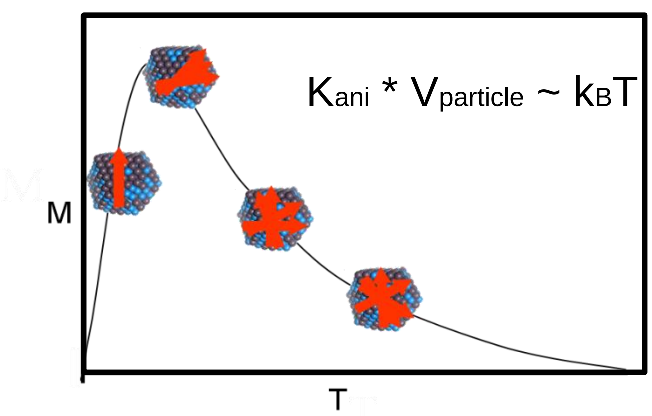
S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt, J. Stöhr, ***Nature* 432**, 885 (2004)

Time for some examples

1. Magnetic nanoparticles



Superparamagnetism



Magnetic properties depending on

-composition

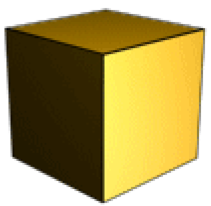
-size

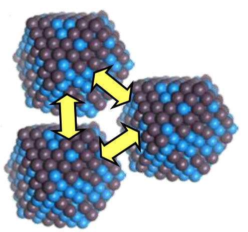
-shape

-orientation

-configuration

- particle interactions

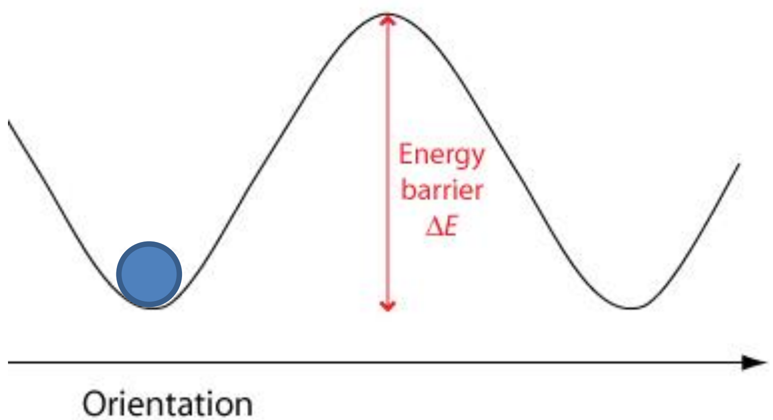




Thermally activated dynamics in nanoparticles

Thermally activated magnetization dynamics
Stoner Wohlfarth model : macrospin, energy barrier KV

Neel relaxation time given by the Neel Arrhenius equation $t_N = t_0 \, e^{KV/kT}$



t_0 = 10^{-9}
t_m = measurement time
K = anisotropy energy density (4.8 10^4 J/m^3)
V = Volume
k = Boltzmann constant
T = temperature

Fe particle at room temperature

100x100x100nm^3 t_N = infinity

20x20x20nm^3 t_N = 1.76 x 10^{32} s

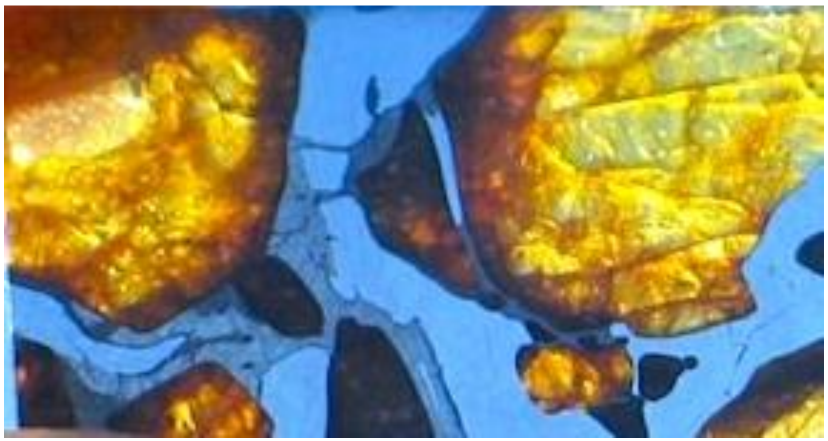
15x15x15nm^3 t_N = 2.51 x 10^8 s

13x13x13nm^3 t_N = 212 s

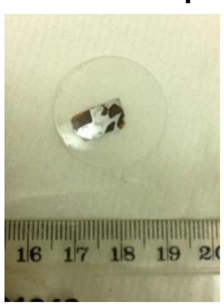
10x10x10nm^3 t_N = 0.00014 s

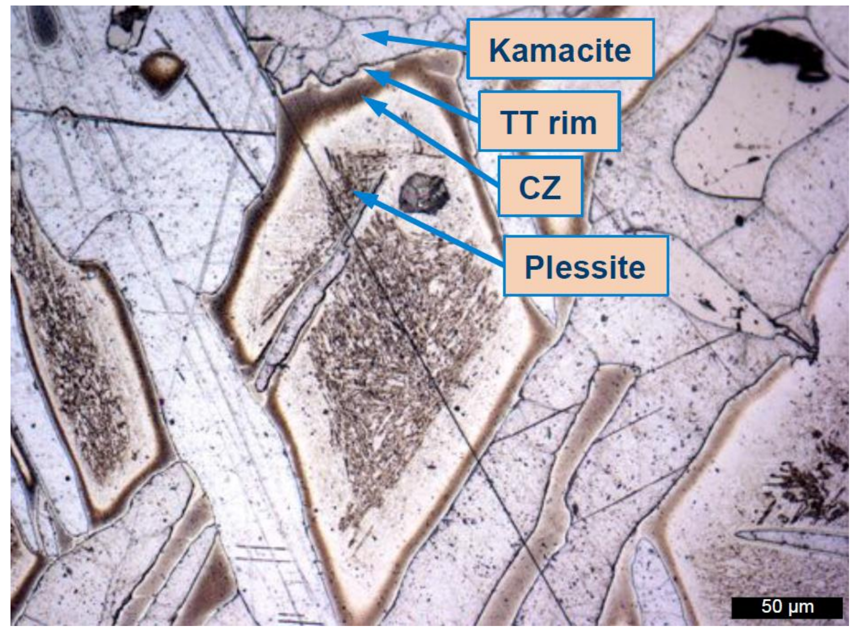
1 year= 3 x 10^7 s

Magnetic nanostructures within meteoritic Fe-Ni can provide a dynamo field record of its parent body



Piece of imilac pallasite

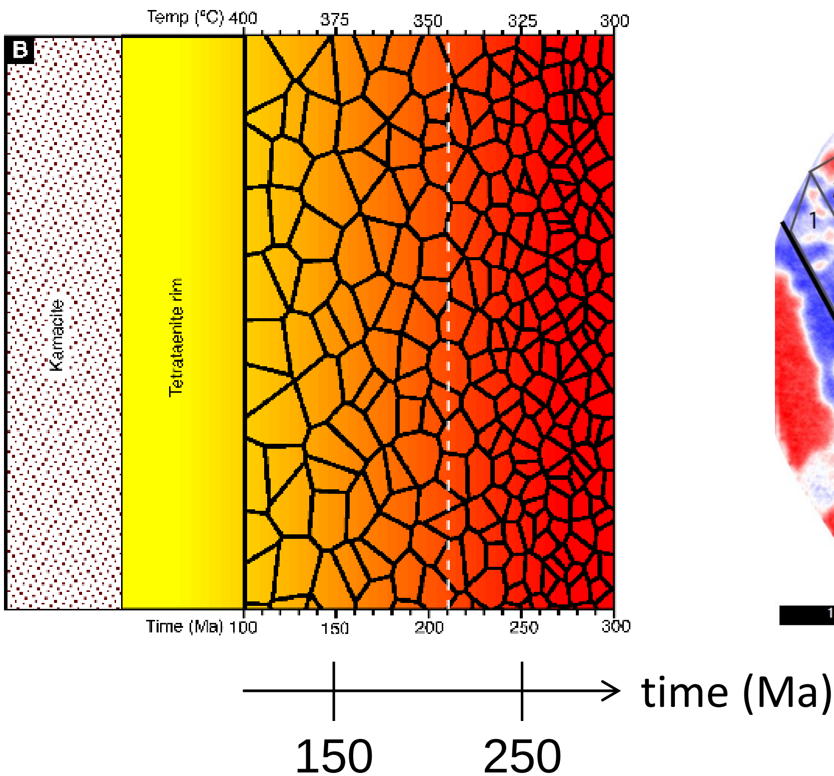


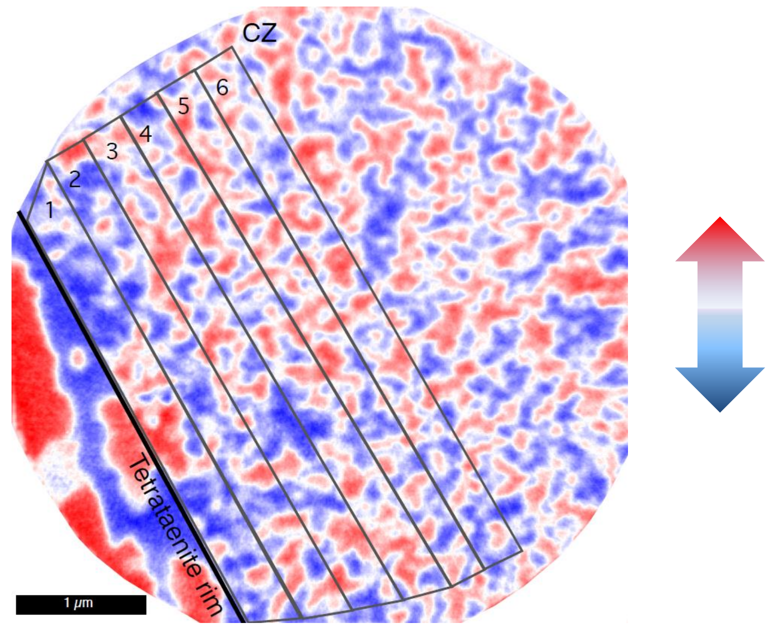


time-resolved asteroid dynamo field record

Nanostructures forming with time

Magnetic domain image
(Fe XMCD / PEEM)

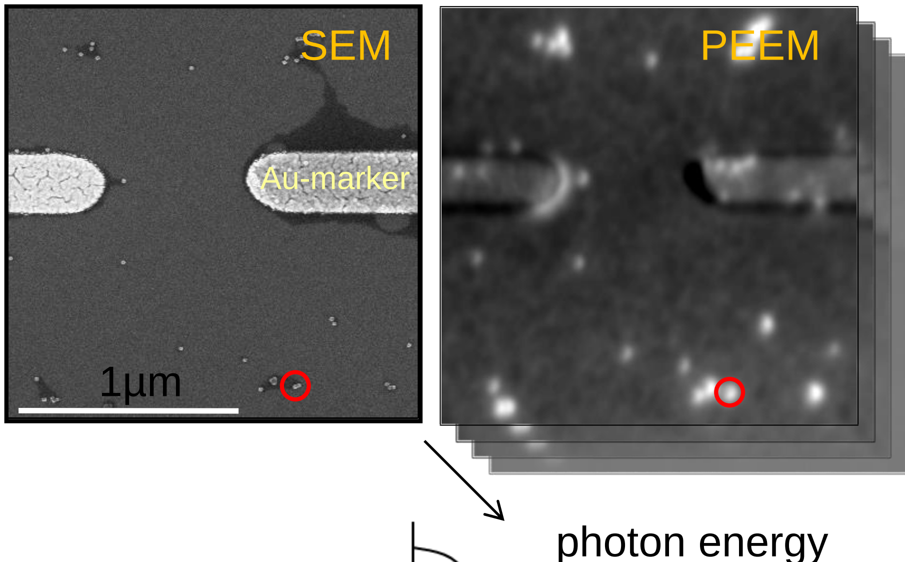


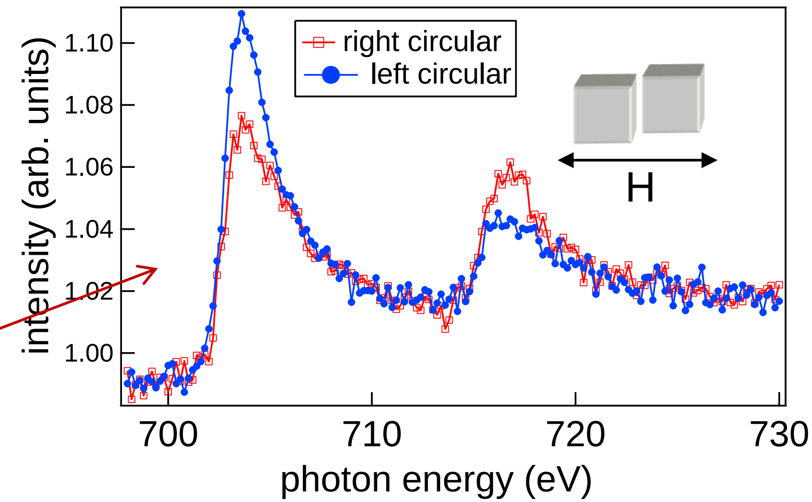


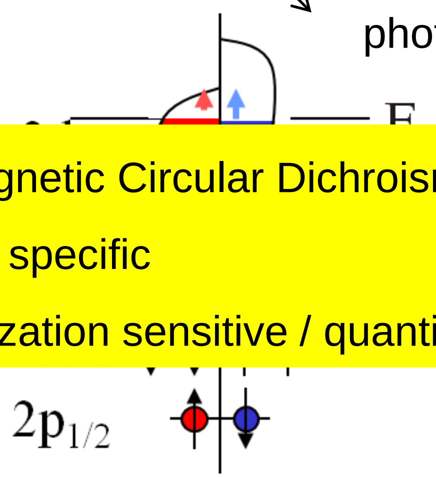
Structure sizes 40 -100nm Magnetic fields can be recorded over 100 million years

Earth and Planetary Science Letters 396 (2014) 125–133

Magnetic response of individual nanoparticles



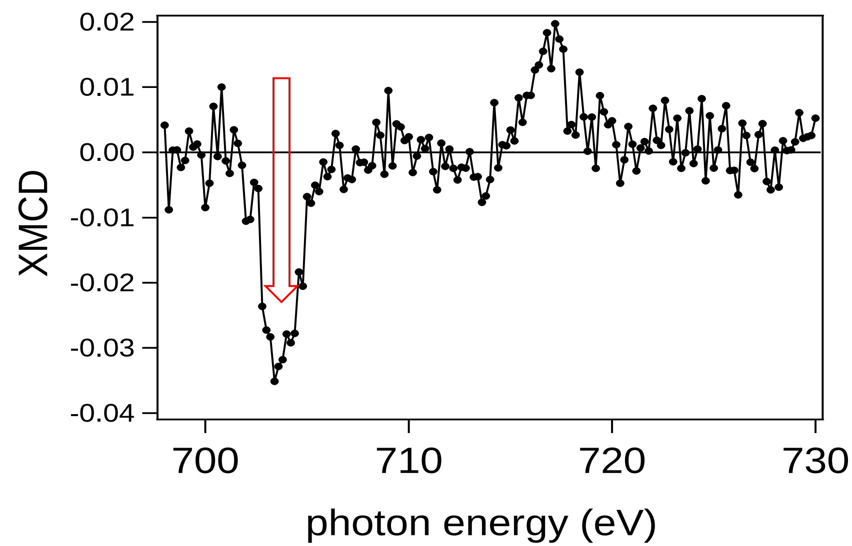




maximum contrast for **k** || **M**

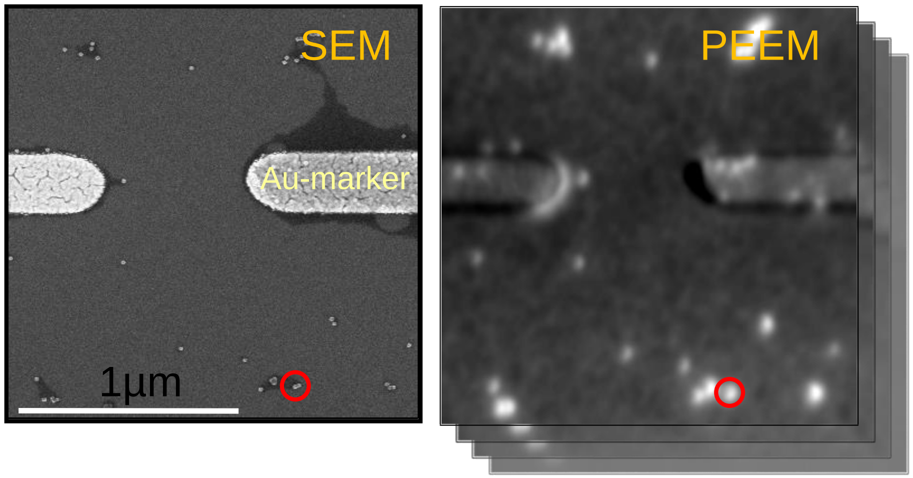
X-ray Magnetic Circular Dichroism (XMCD)

- element specific
- magnetization sensitive / quantitative



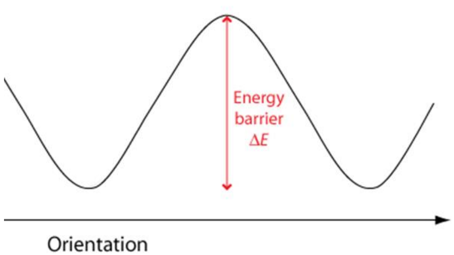
F.Kronast et al.,Nano Lett. 2011, 11, 1710–1715

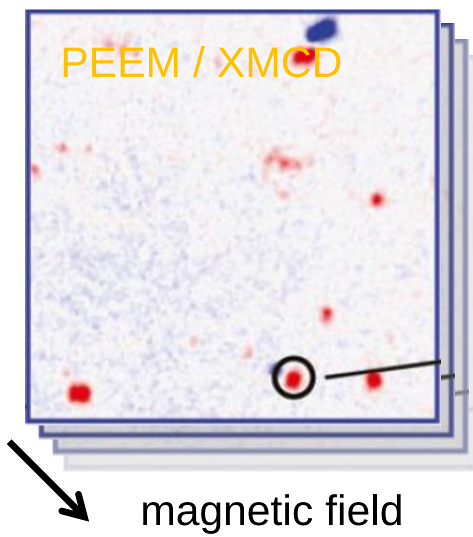
direct access to magnetic anisotropy energy

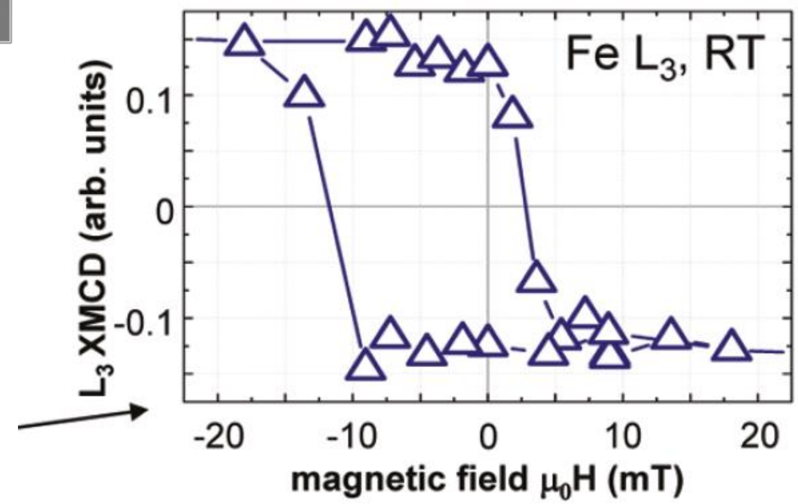


•PEEM fov 3-5µm

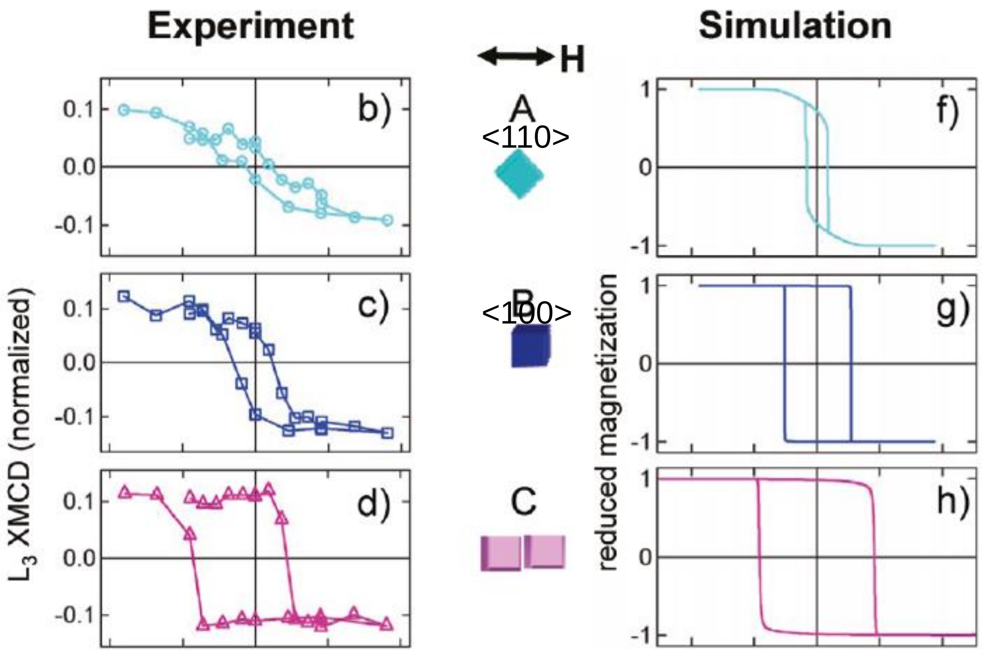
•simultaneous recording of several 100 hystersis







F.Kronast et al.,Nano Lett. 2011, 11, 1710–1715



strongly reduced coercitive field close to the blocking temperature

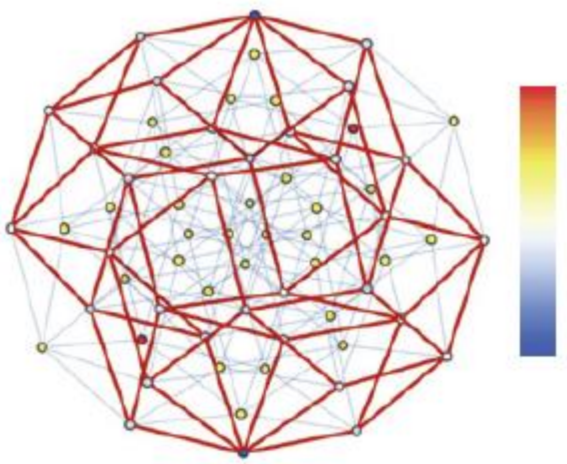
evidence for magnetocrystalline anisotropy

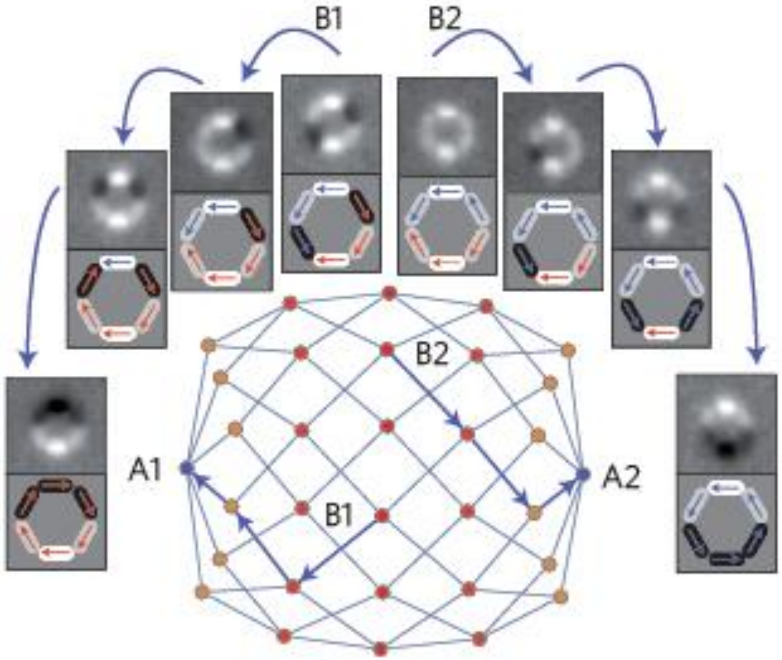
dipolar coupling enhances
shape anisotropy and increases blocking temperature

material parameters for (bcc) Fe :
A = 21 pJ/m (exchange constant)
$\mu_0 M_s$ = 2.15 T (M_s: saturation magnetization).

F.Kronast et al.,Nano Lett. 2011, 11, 1710–1715

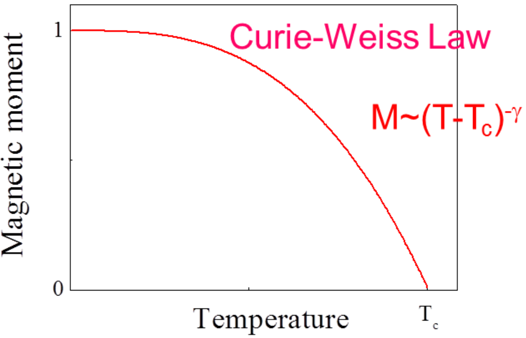
Real time observation of magnetic fluctuations in structures with tailored thickness

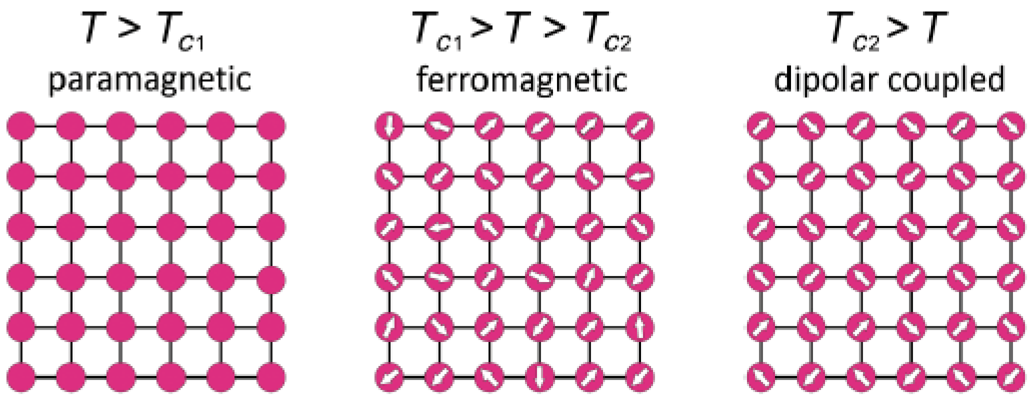


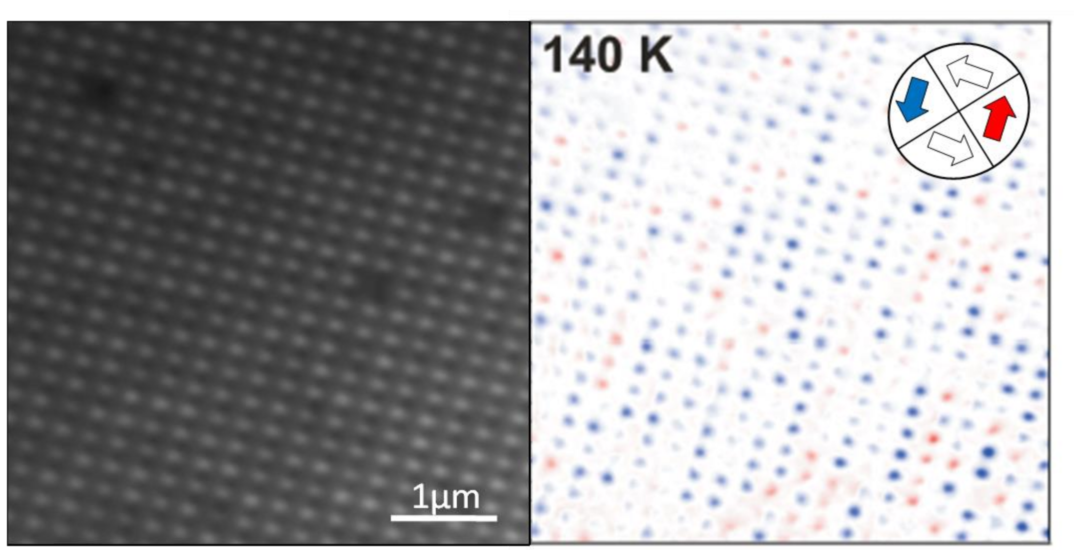


A. Farhan NATURE PHYSICS j VOL 9 j JUNE 2013

2. Magnetic phase transitions: magnetic ordering in 2d macrospin arrays

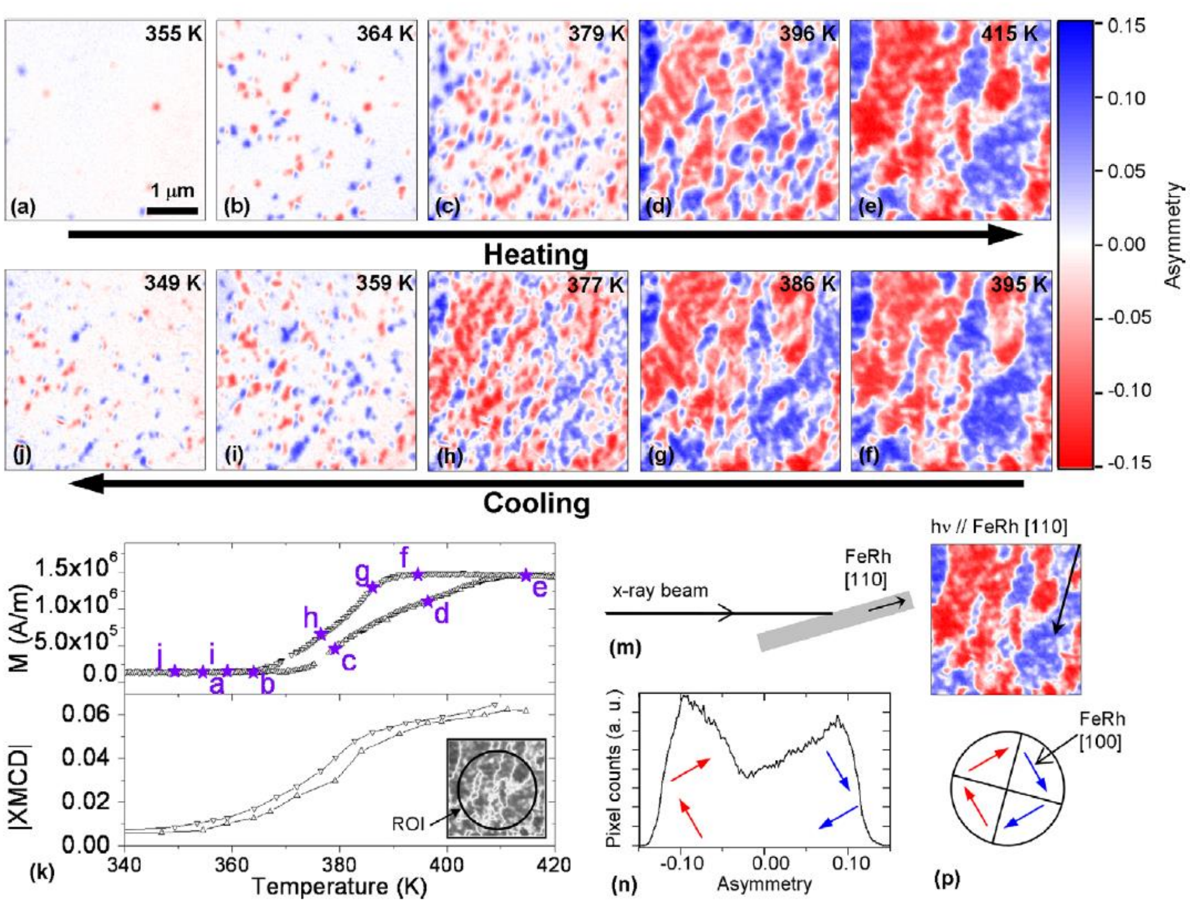






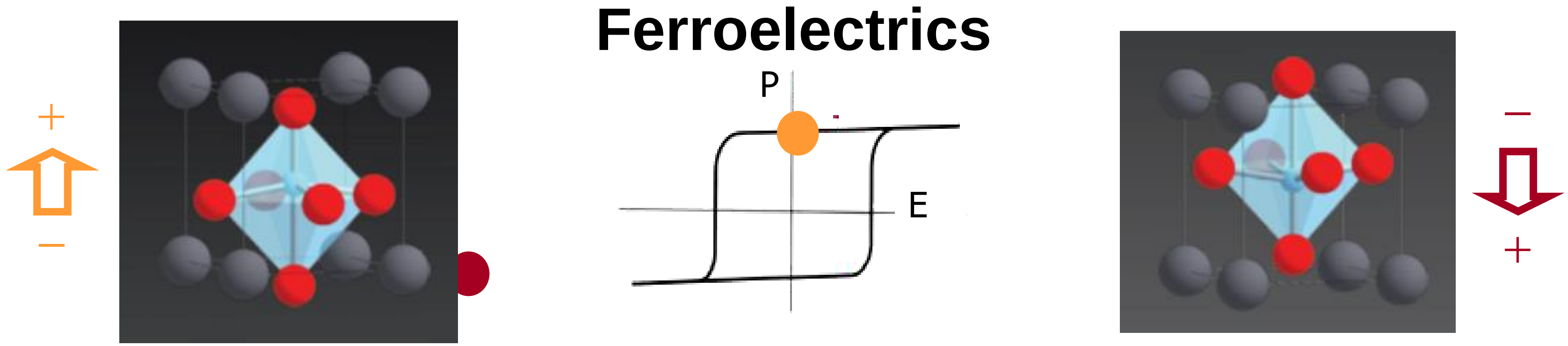
Ewerlin et al. PRL 110, 177209 (2013)

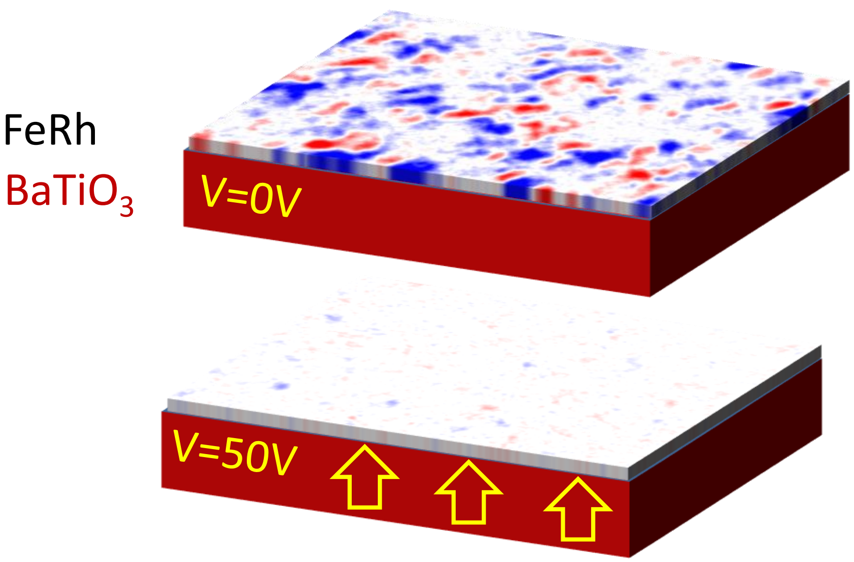
temperature-driven AF- FM phase transition in FeRh thin films



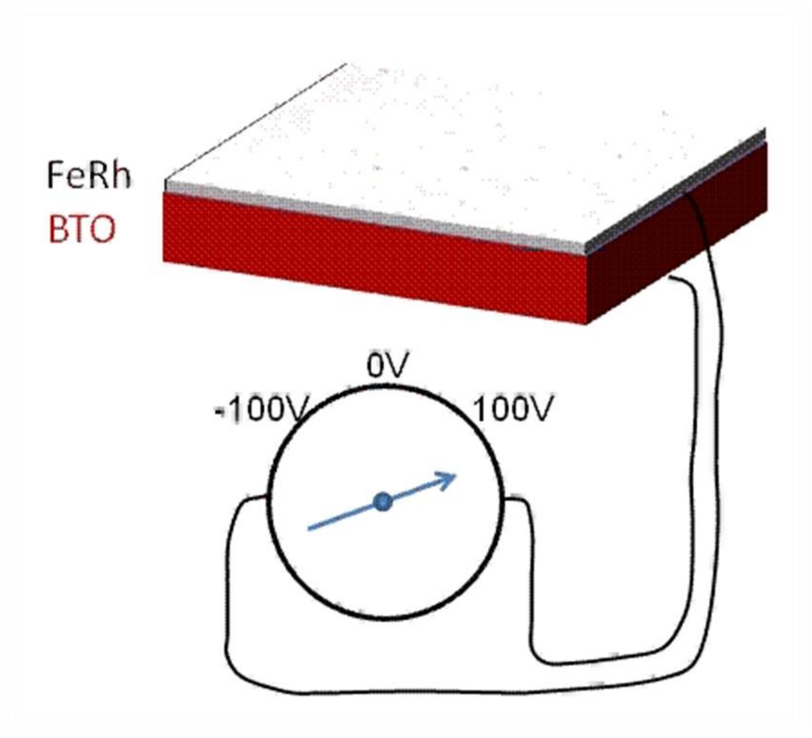
Baldasseroni et al. APL 100, 262401 (2012)

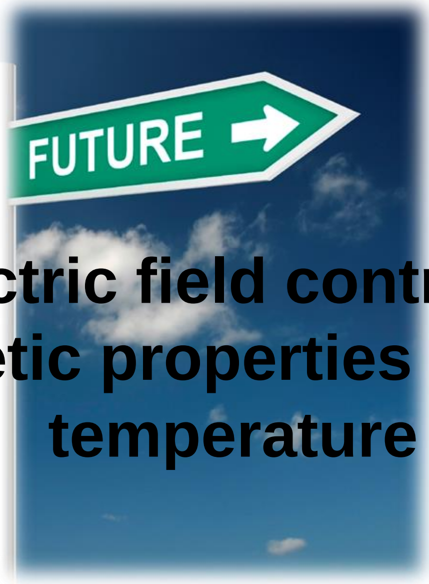
Electric field / strain induced AF/FM phase transition on FeRh





Electric field / strain induced AF/FM phase transition on FeRh

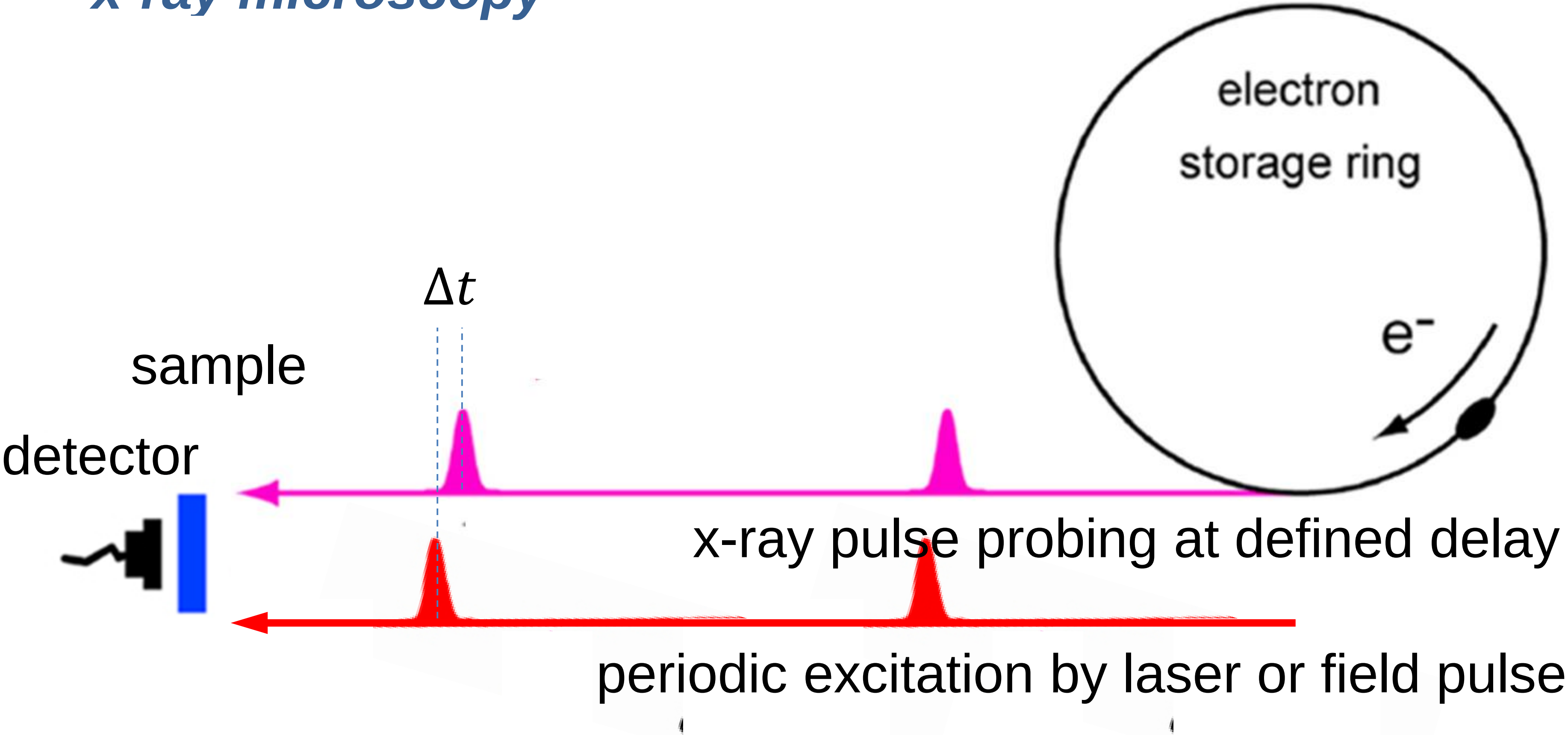




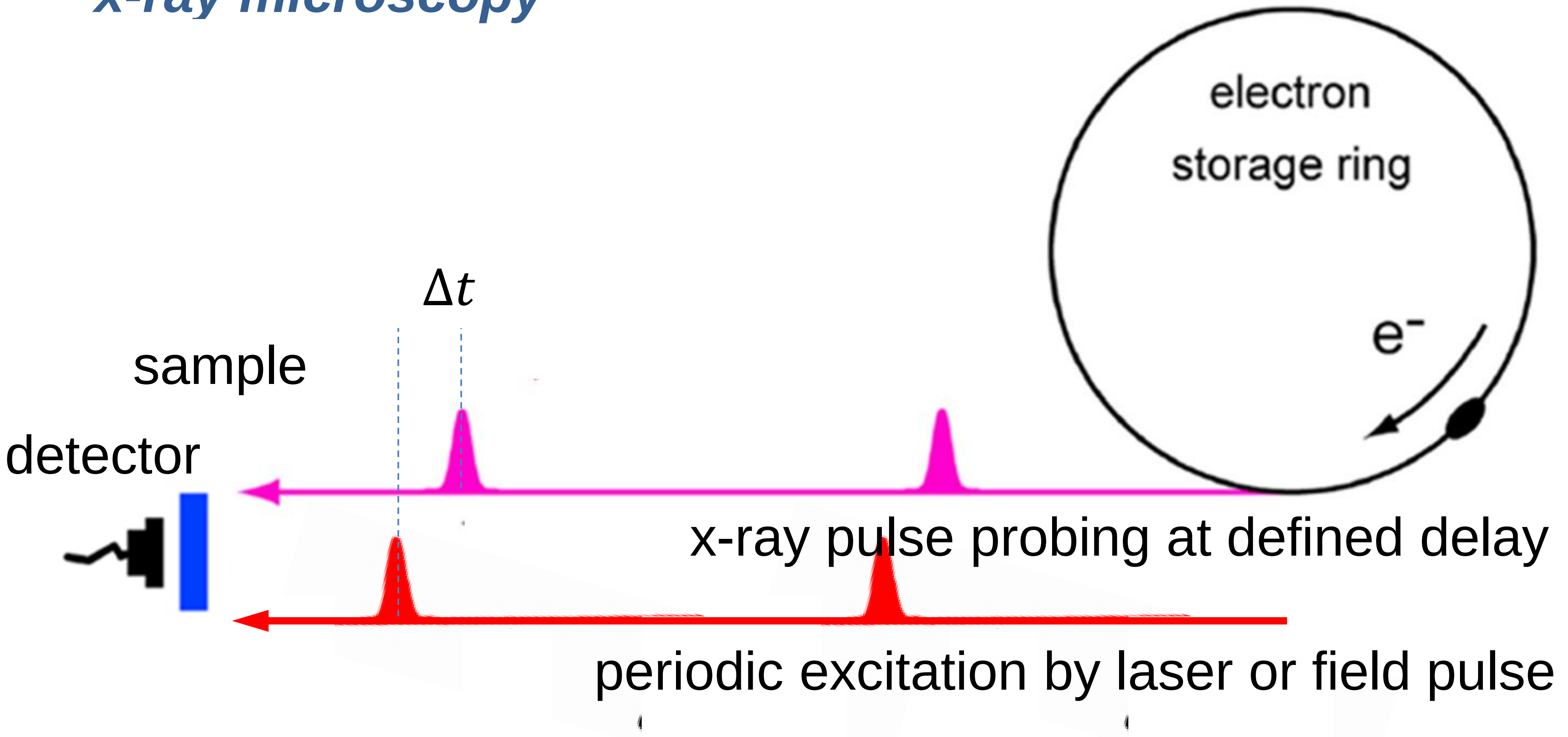
Electric field control of magnetic properties at room temperature

- **Electric-field controlled spintronics**
- **Multi-state data storage**
- **Low power dissipation**

3. Stroboscopic pump-probe setup for time-resolved x-ray microscopy

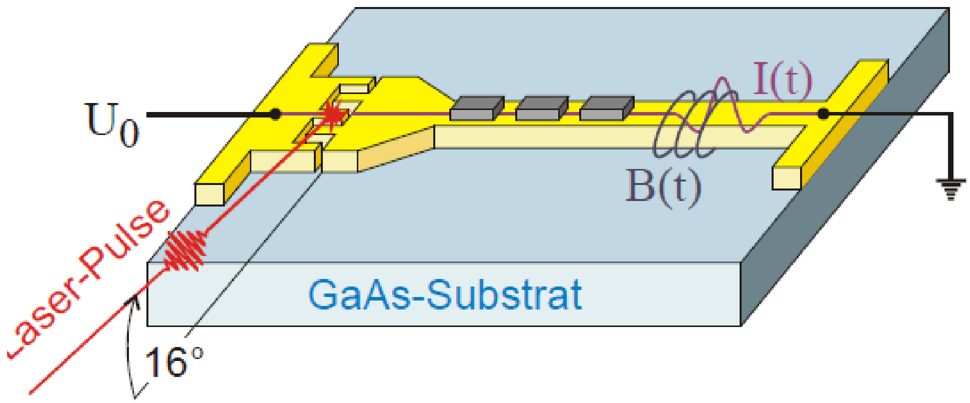


Stroboscopic pump-probe setup for time-resolved x-ray microscopy



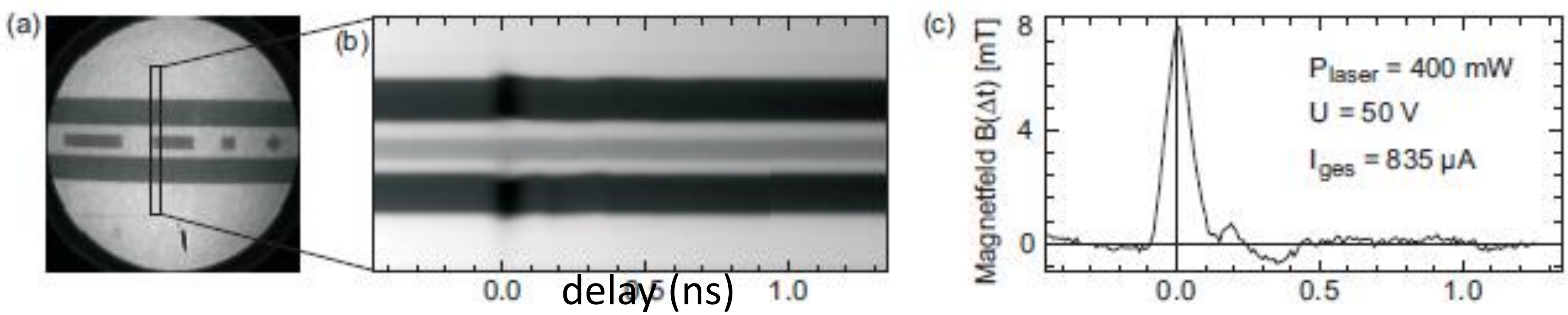
Accumulation of large number of independent events necessary
Only reversible processes can be imaged
No acces to irreversible, stochastic processes e.g. fluctuations

Excitation by a field pulse generated by a photoconductive switch (Auston switch)



$$\mu_0 I = \oint_C B \, \mathrm{d}s \approx B \, 2b$$

$$\Leftrightarrow B \approx \frac{\mu_0 I}{2b},$$

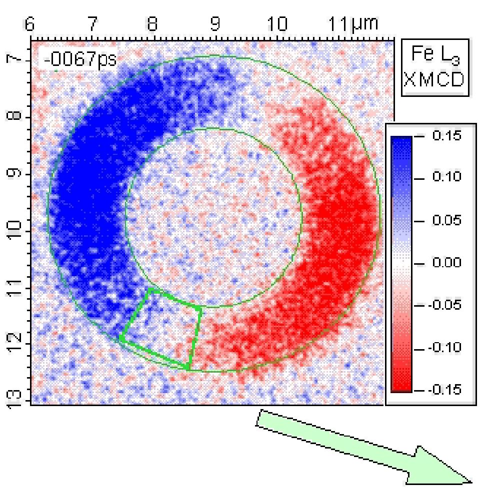


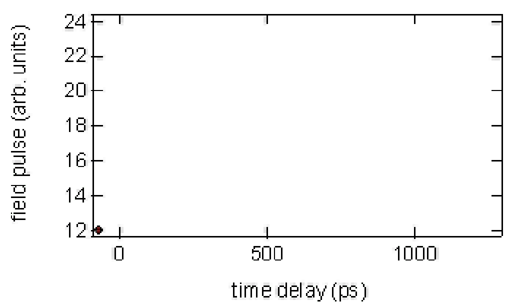
$$I(\Delta t) = \alpha \, p(\Delta t) \quad \text{mit} \quad \frac{1}{\alpha} = \frac{f_{\text{Laser}}}{I_{\text{ges}}} \int_{T_{\text{Puls}}} p(\Delta t) \, \mathrm{d}(\Delta t).$$

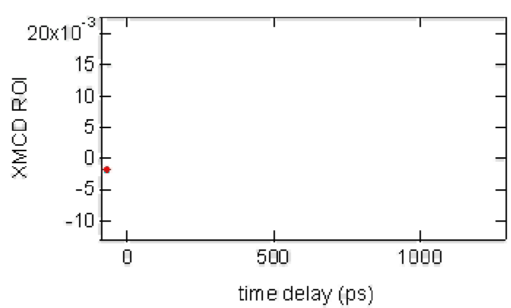
Excitation in a permalloy ring
Magnetic precession and damping

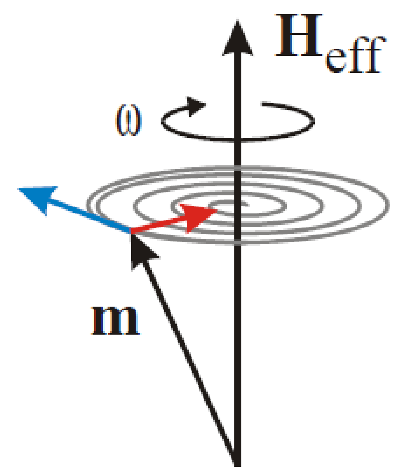
Landau-Lifshitz-equation

$$\frac{d\mathbf{m}}{dt} = \underbrace{-\gamma\,(\mathbf{m}\times\mathbf{H}_{\text{eff}})}_{\text{precession}} \underbrace{-\,\gamma\alpha\,[\mathbf{m}\times(\mathbf{m}\times\mathbf{H}_{\text{eff}})]}_{\text{damping}}$$

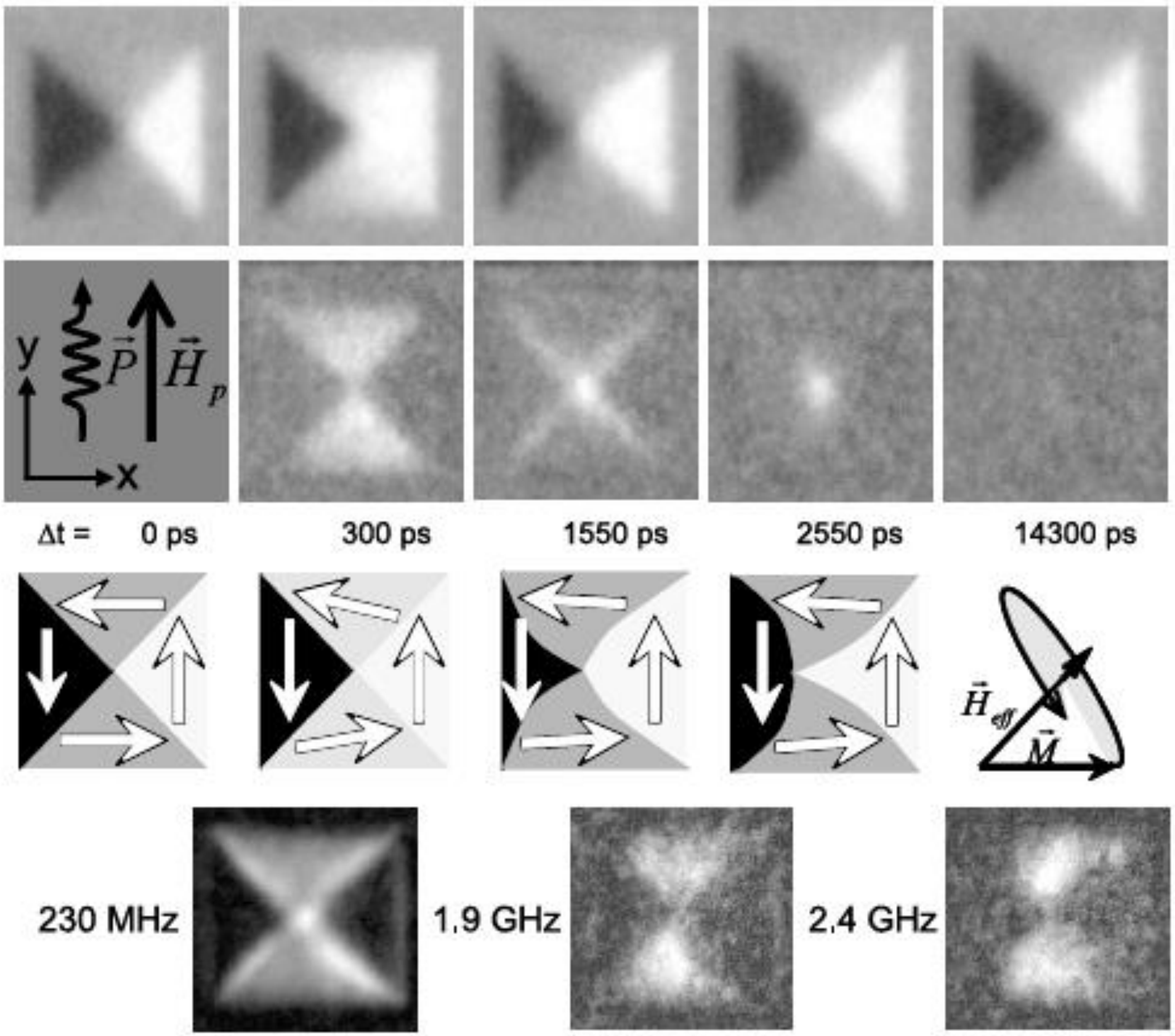








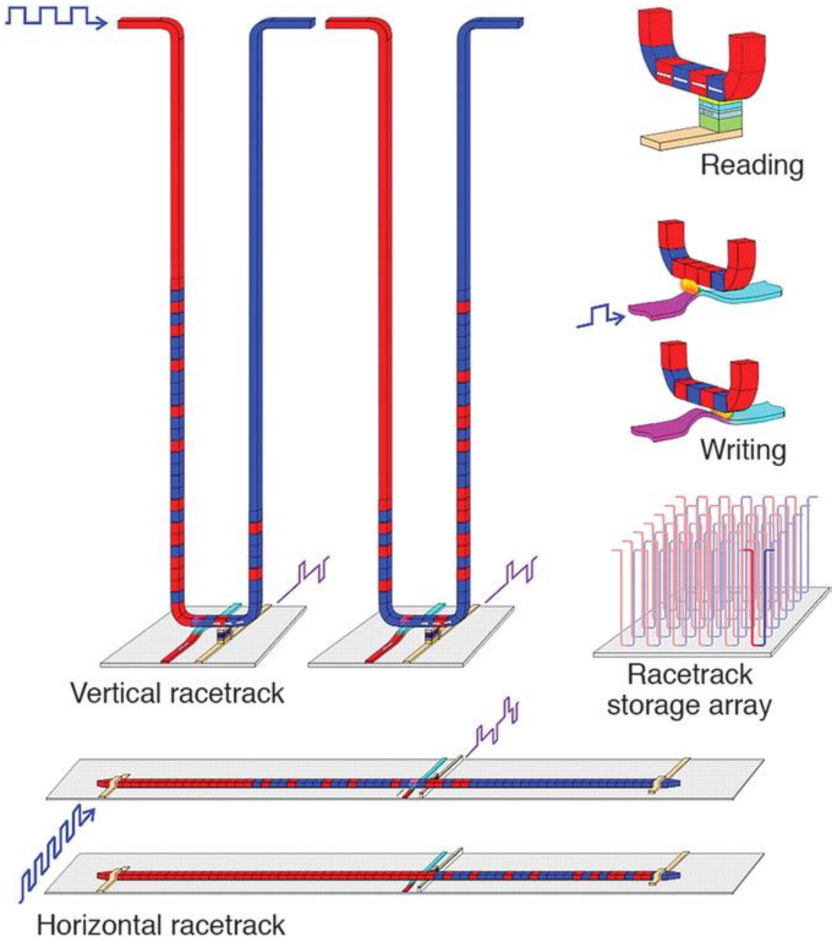
Magnetic excitation in a permalloy square

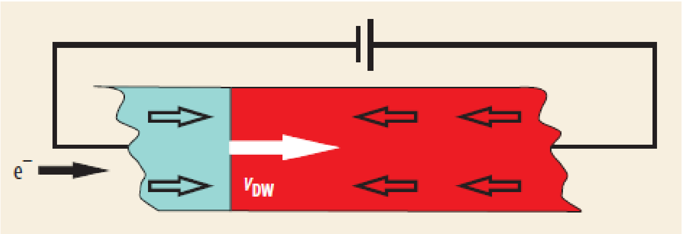


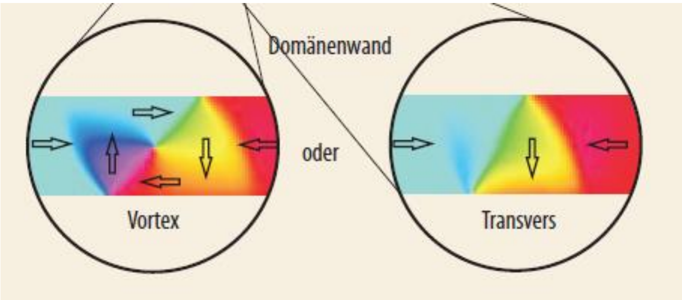
Permalloy $Ni_{81}Fe_{19}$

J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

Domain wall memories

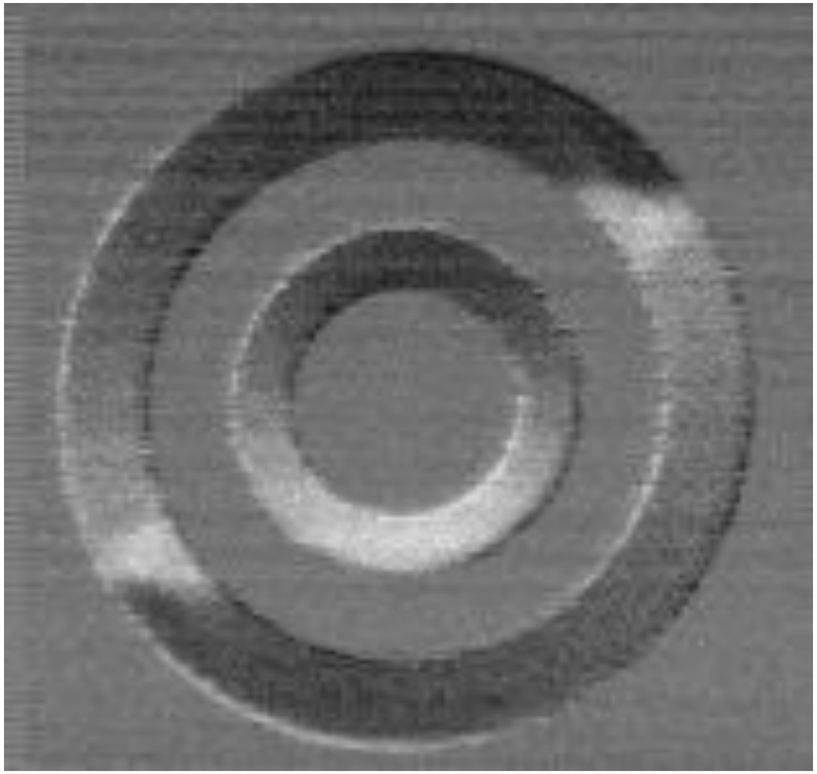


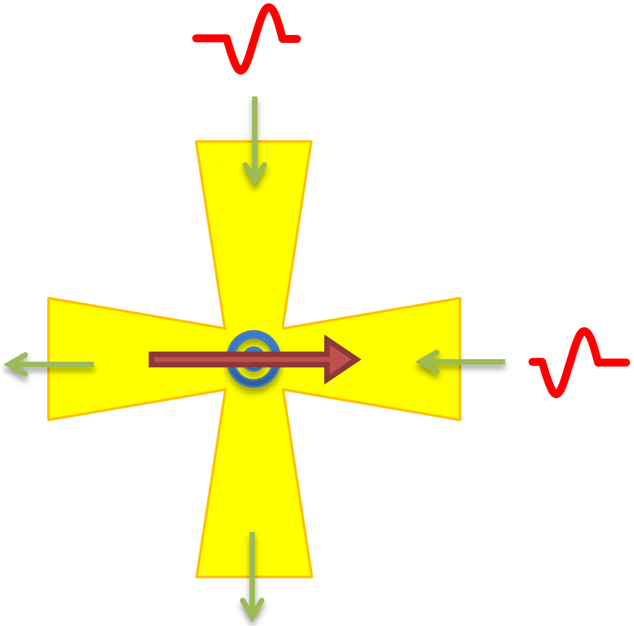




S.S.P. Parkin IBM patent

Field driven domain wall motion





A.Bisig, et. al. Nature Commu 4-2328

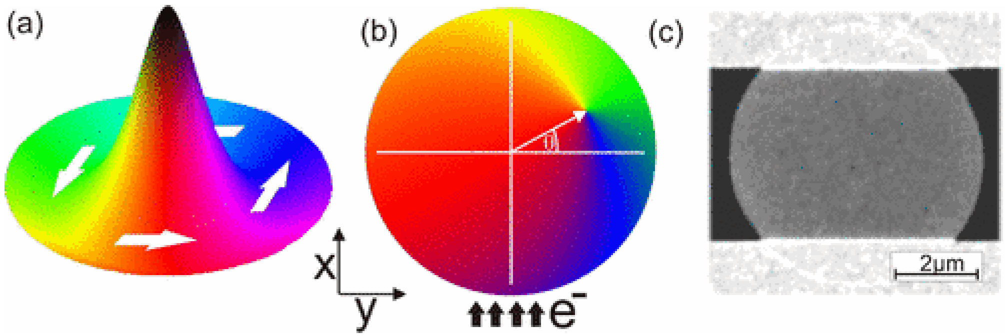
7*7um^2 2ns/frame

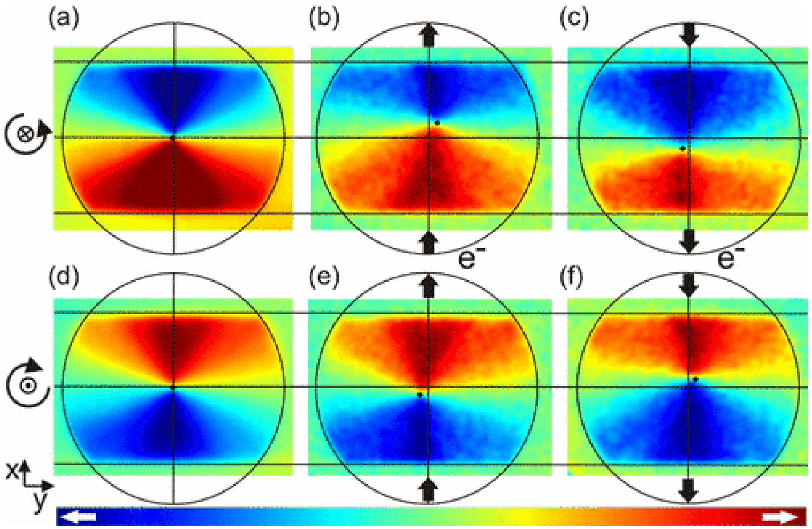
Photon rate through sample > 150MHz

Ring: 30nm Permalloy, 6um diameter, 750nm wide

1173 channels, 80ms/Pixel

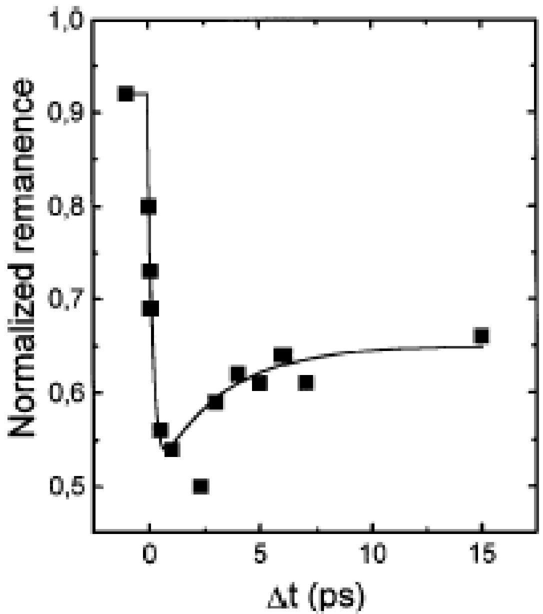
Current driven displacement of a vortex



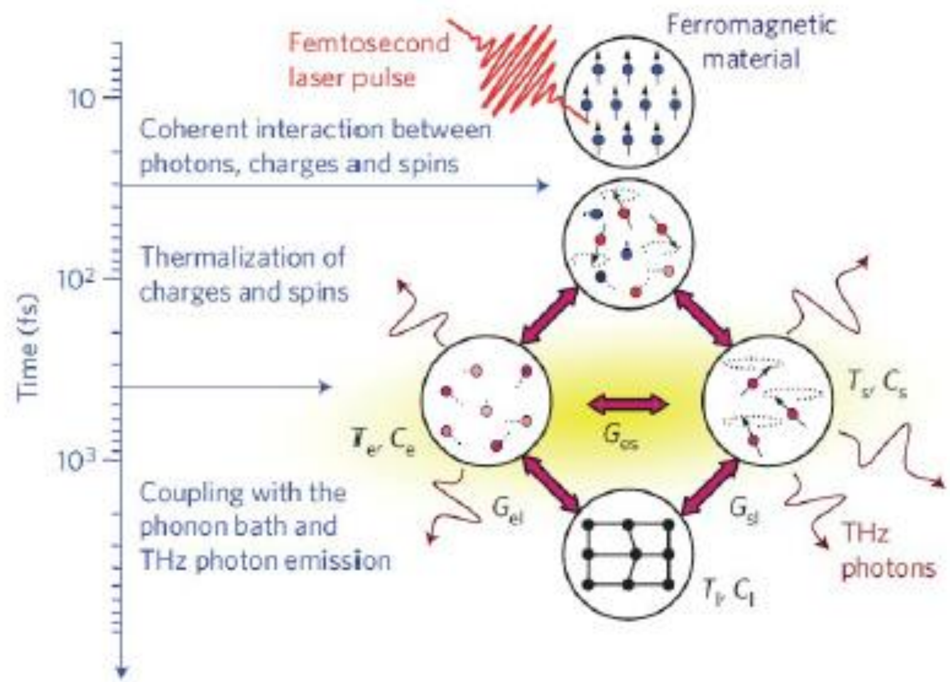


L. Heyne et al., Phys. Rev. Lett. 105, 187203 (2010)

4. Ultra-fast magnetization dynamics

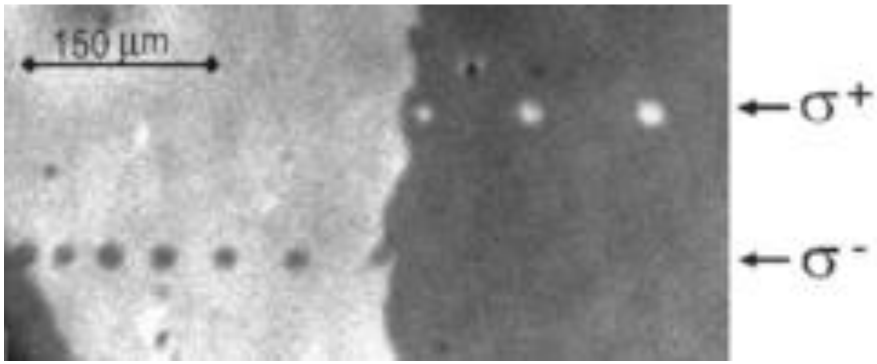


Beaurepaire et al.,
Phys. Rev. Lett. 76, 4250 (1996).

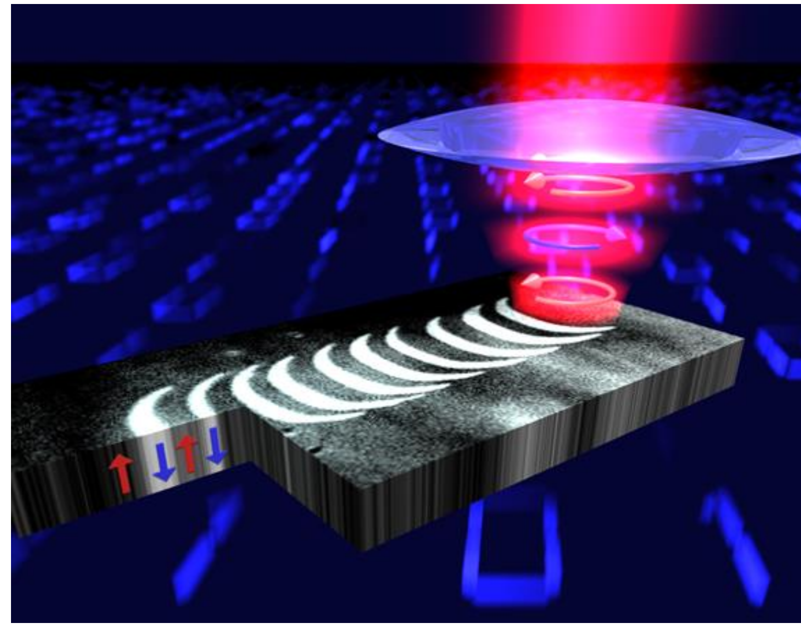


Bigot et al., Nature Phys. 5, 515 (2009)

All-optical switching



Magnetization reversal with one circularly polarized laser pulse. (40fs duration)



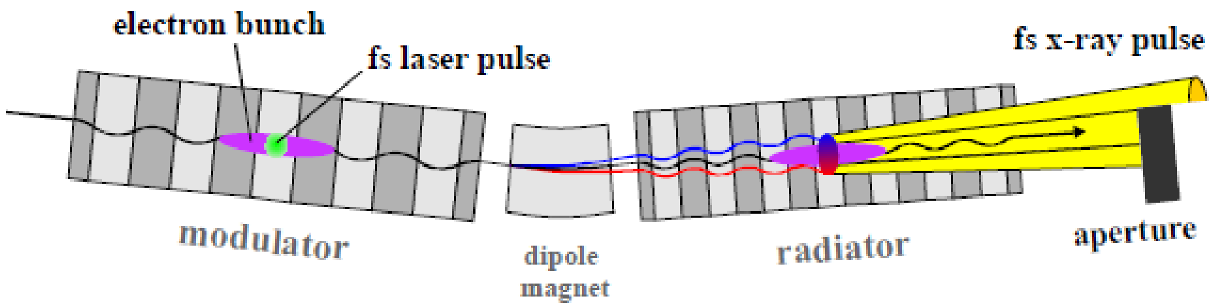
C.D. Stanciu et al., Phys Rev Lett 99 047601 (2007)

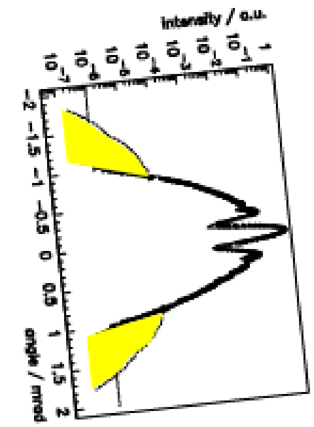
- **What is the ultimate fast … nipulate and control the … ation?**
- **Understand the … pic processes involved**
- **Develop nov… erials and approaches to control magnetism**

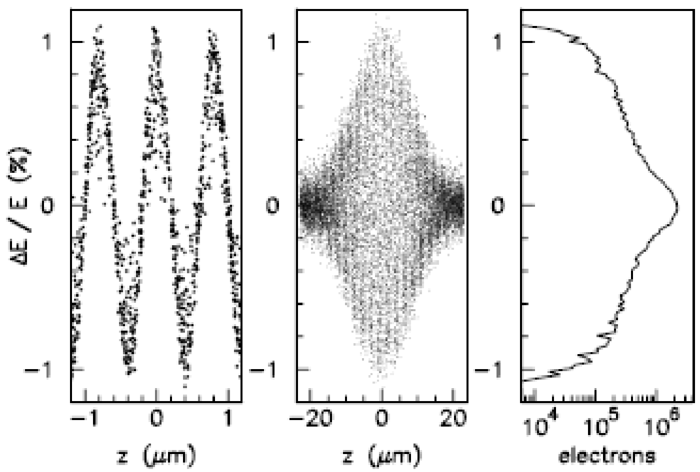
Time-resolved measurements require x-ray pulses < 100fs

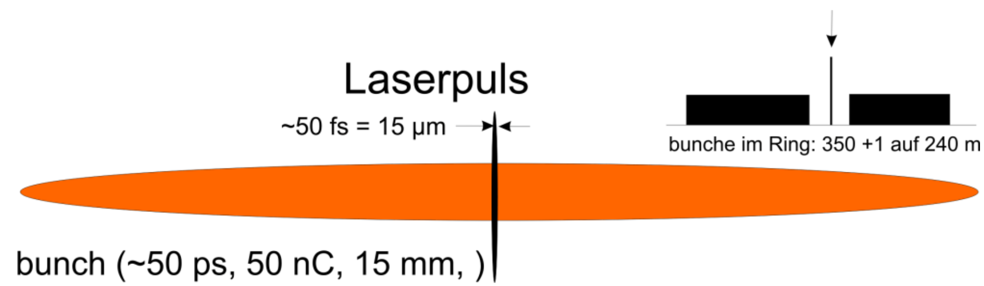
Slicing principle

modulation of the electron bunch energy





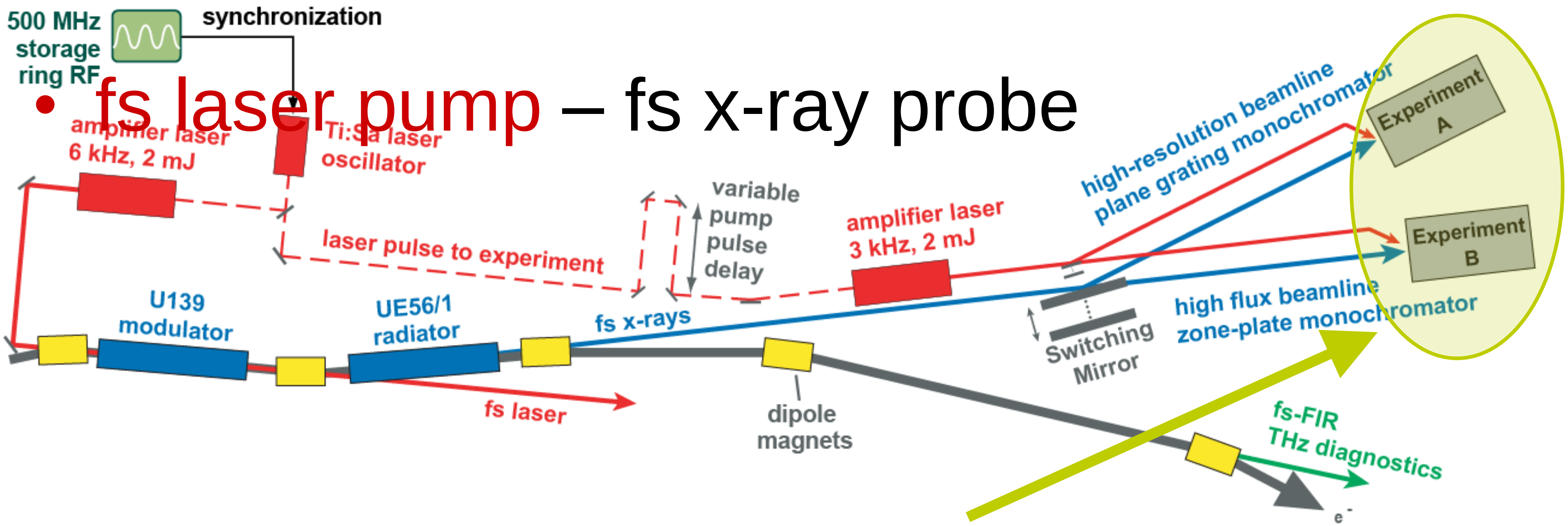




[1] A. A. Zholents, M. S. Zoloterev, PRL 76 (1996), 912.

BESSY II femtoslicing source

- fs laser pump – fs x-ray probe

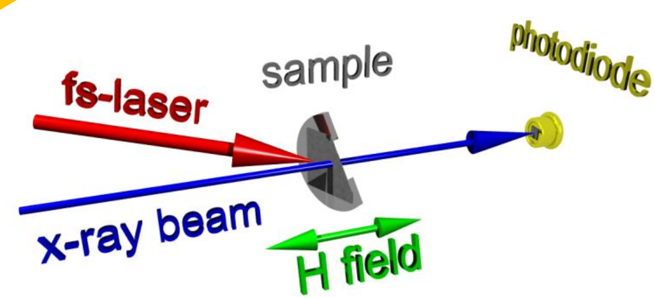


pump with 3 kHz laser pulses
probe with 6 kHz x-ray pulses

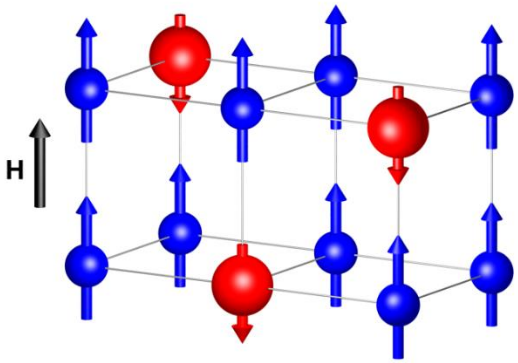
- **pump-probe delay**
- **x-ray photon en**
- **x-ray polarizat**
- **magnetic field**

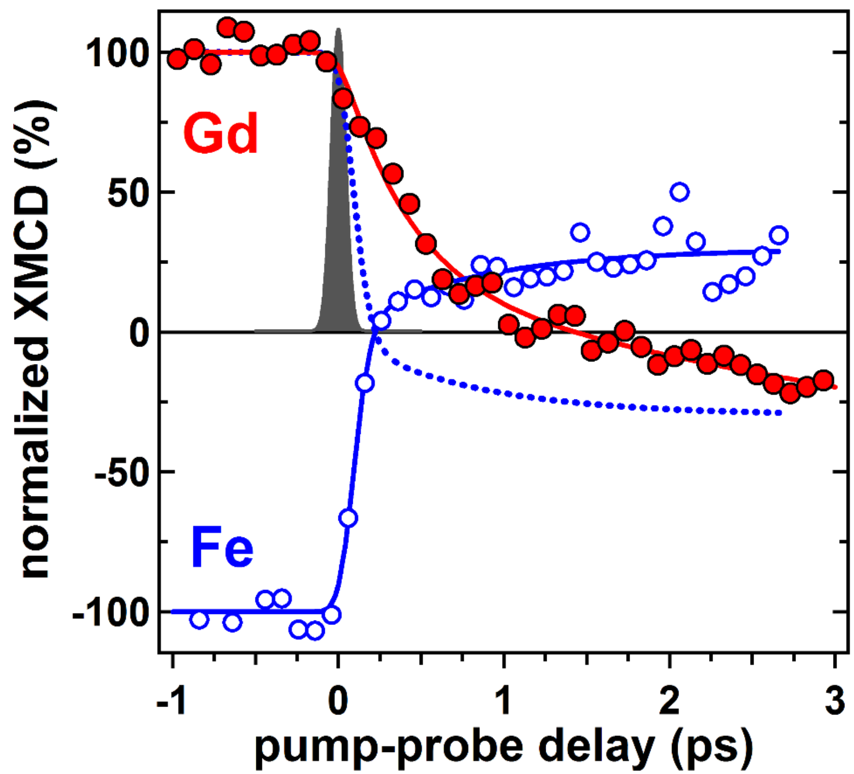
Pulse width < 100fs
Not enough intensity for imaging

x-ray transmission setup



Ultra-fast magnetic reversal in GdFeCo

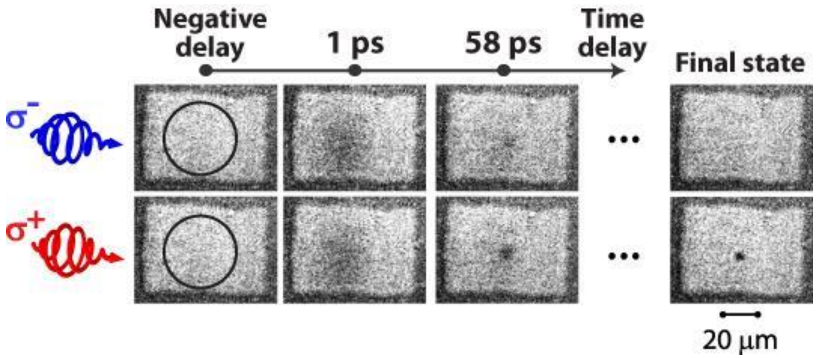


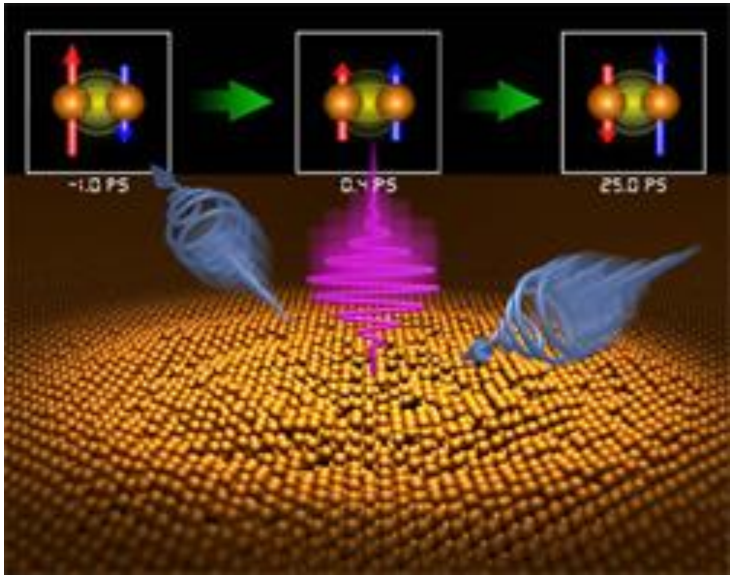


I. Radu et al., *Nature* 472, 205 (2011)

- Different dynamics of the magnetic moments
- Ultrafast Magnetization Switching
- Transient Ferromagnetic State

Ultra-fast magnetic reversal in GdFeCo



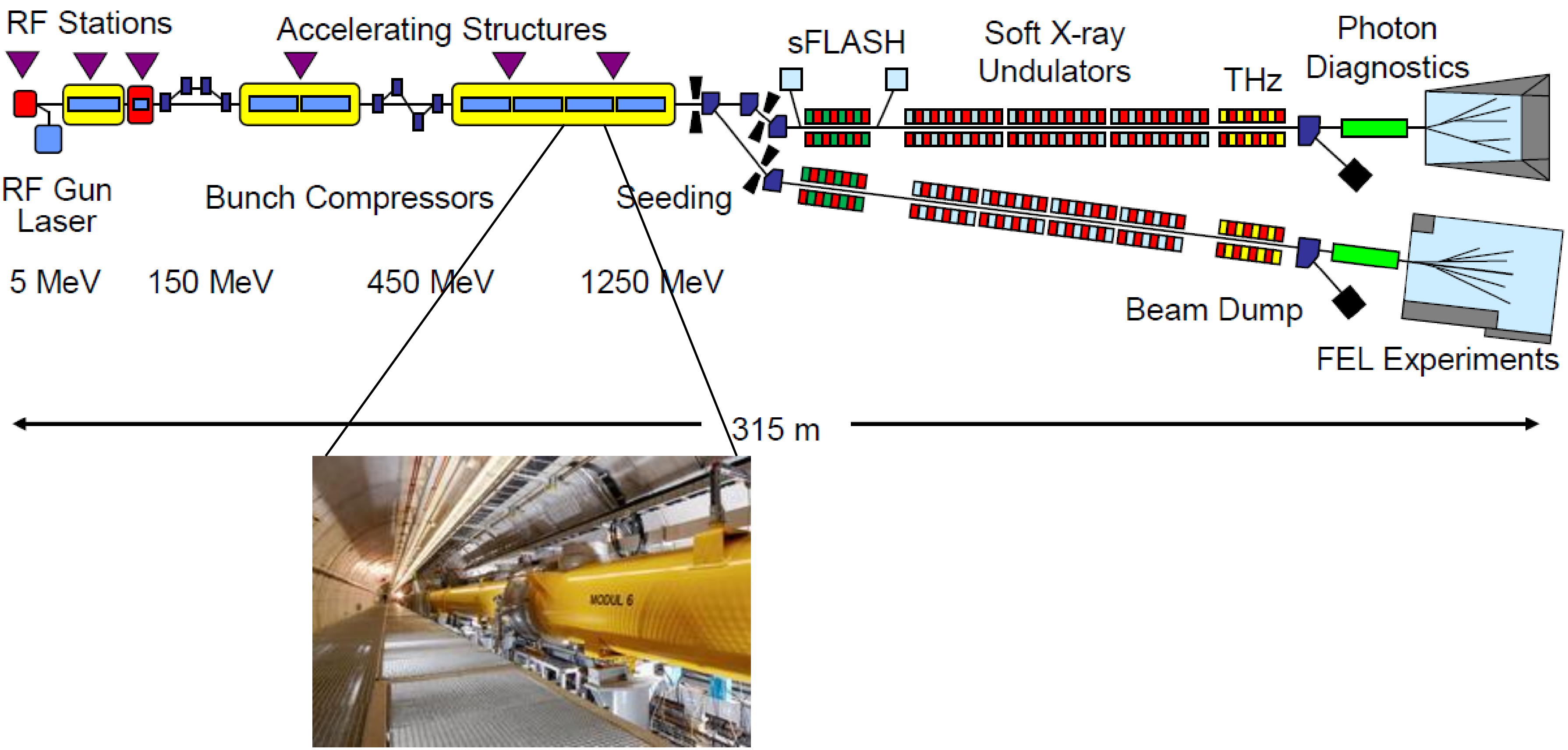


Helicity dependent switching in GdFeCo
Observed by MOKE (pulse width 100fs)

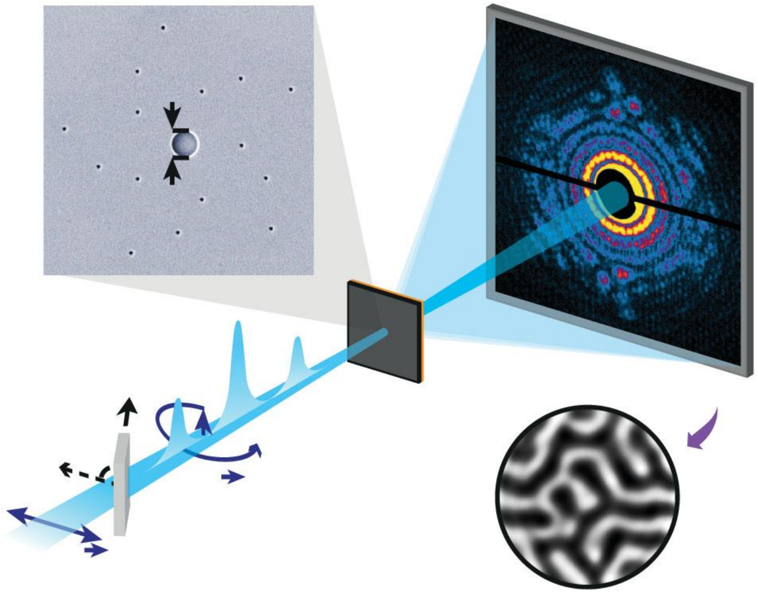
What are the fundamental interactions between spin, conduction electrons and the laser light?
What is the origin of the laser-induced “optomagnetic” field?
What is the relevance of the specific spin ordering (ferro, ferri, antiferro - magnetic)
in the materials of interest?

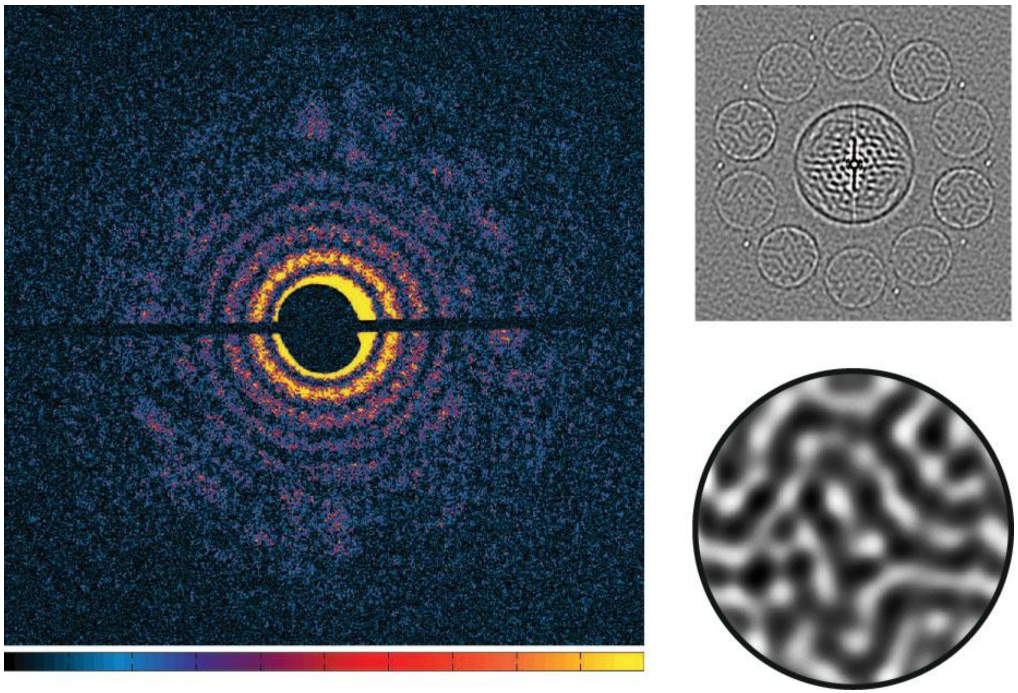
Free electron laser : short pulses + huge intensity

FLASH in Hamburg



Single shot magnetic imaging at a free electron laser





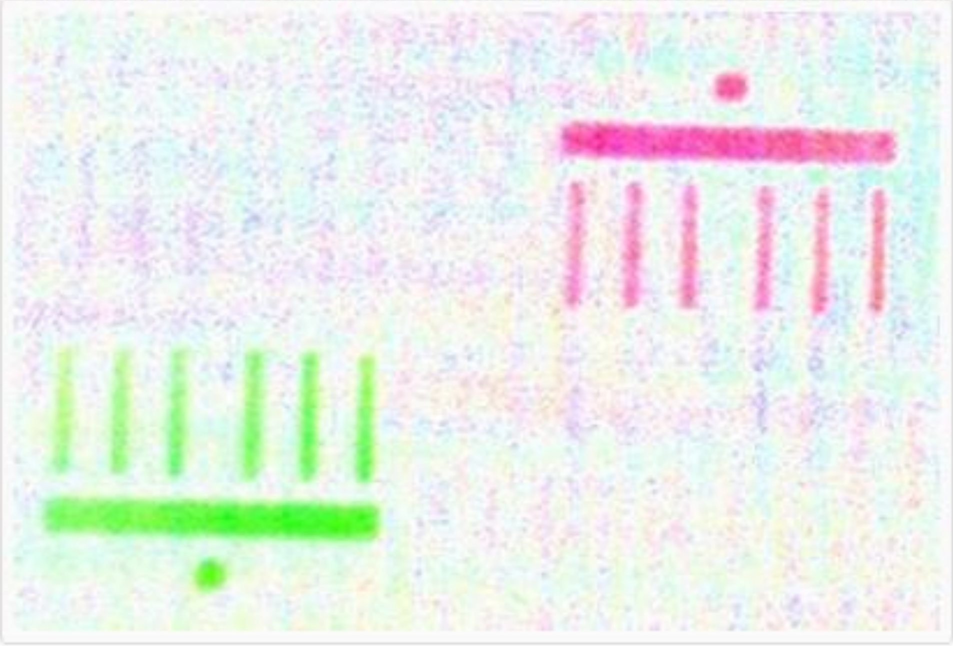
Single shot image 80fs pulse duration

T. Wang et al., PRL 108, 267403 (2012)

World record: Two frames within 50fs

World's fastest movie shot by DESY's X-ray laser FLASH in Hamburg

World's fastest movie shot by DESY's X-ray laser FLASH in Hamburg
The world's fastest movie was shot by DESY's X-ray laser FLASH in Hamburg. In its 2012 edition, the famous Guinness Book of World Records lists an interval of a mere 50 femtoseconds between two frames for FLASH. A femtosecond is a quadrillionth of a second, meaning that the two images are separated by just 0.000 000 000 000 05 seconds – this is 800 billion times faster than a feature film.



S. Eisebitt

The end

Thank you!