Synchrotron radiation techniques for magnetism

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araid FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO

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What is a synchrotron and how does it work?

Why do we *need* SR?

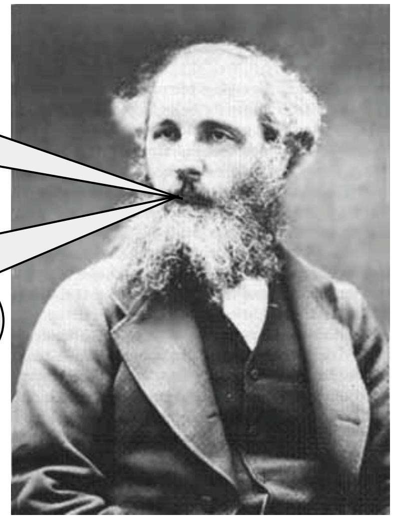
- High brightness
- Wide range tuneable energy
- Variable polarization
- Well-defined and flexible time structure
- High degree of coherence

What can we use it for in magnetism?

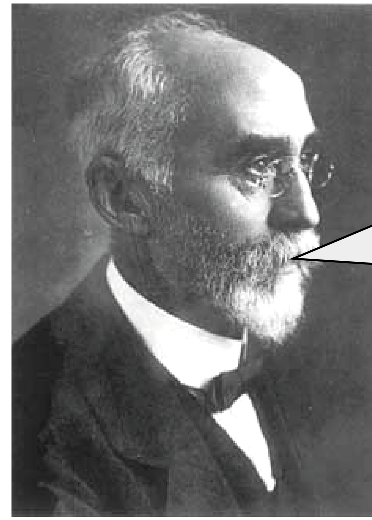
How does it work?

Light is an electromagnetic wave

Any accelerated electric charge emits light

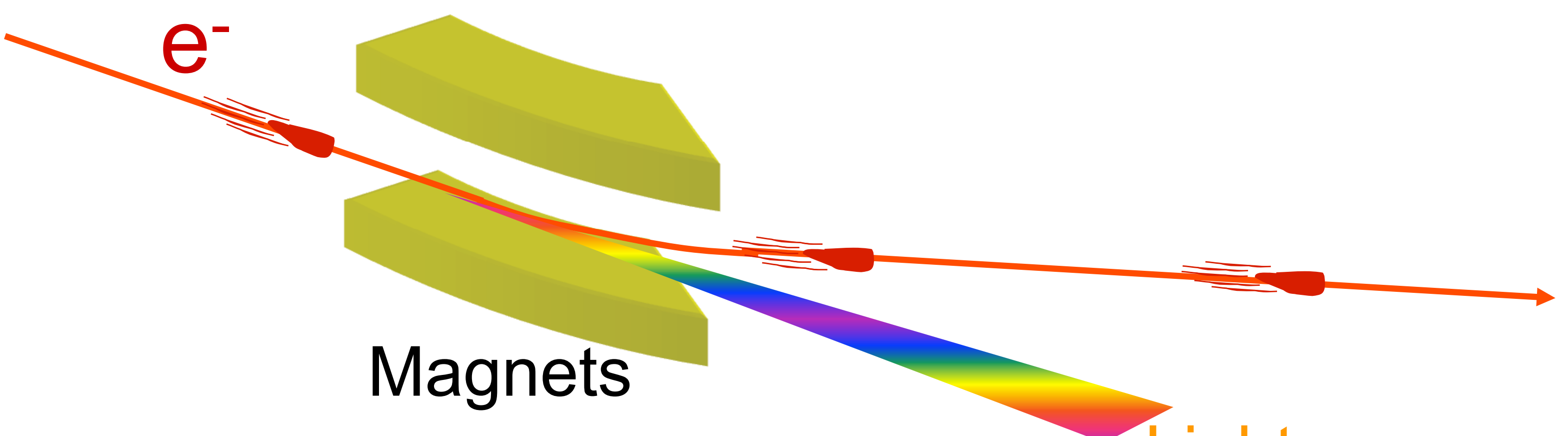


James Clerk ***Maxwell***
1831 -1879



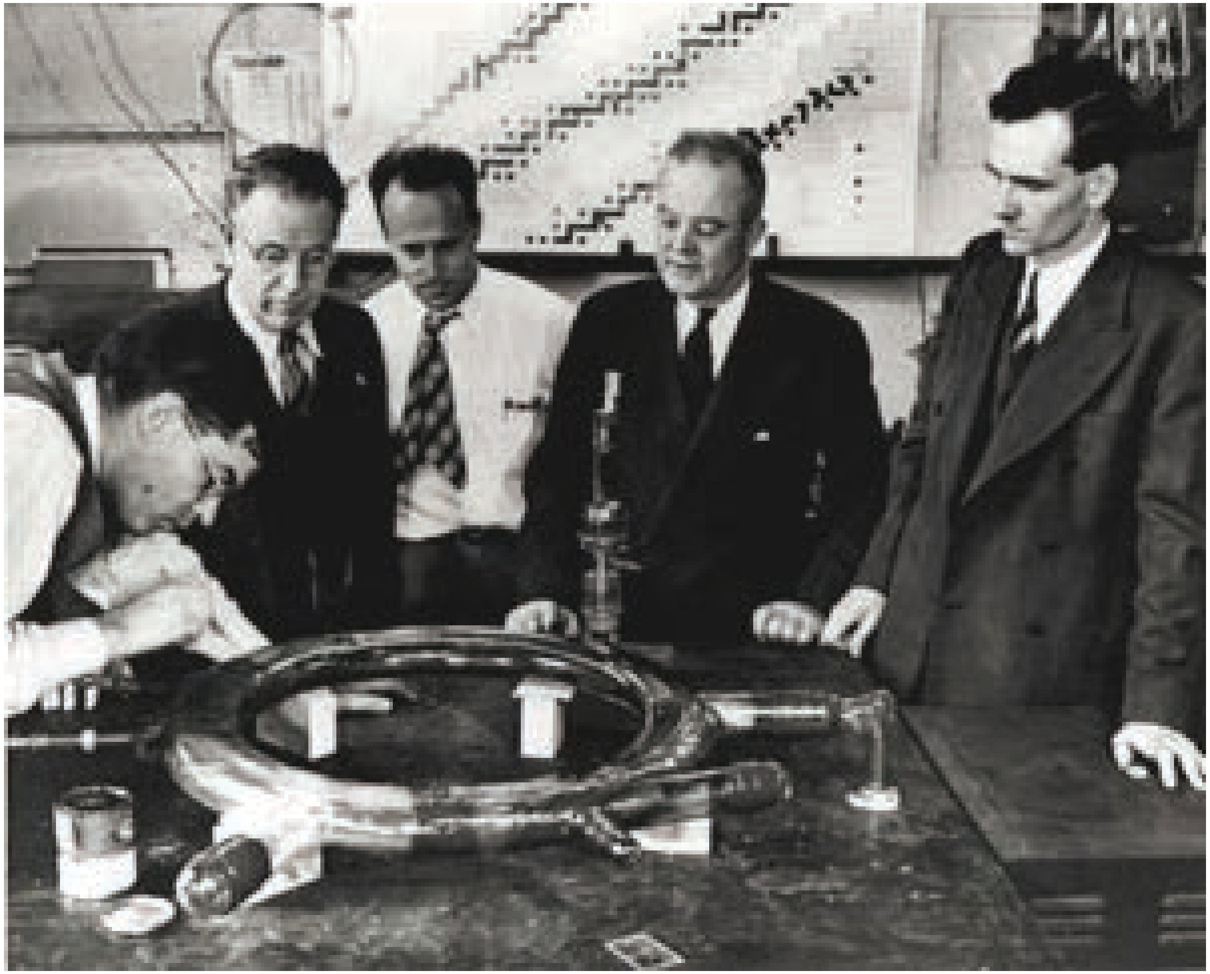
Hendrik Antoon ***Lorentz***
1853 -1928

The force *F* on a particle with charge *q* and velocity *v* in a magnetic field *B* is given by : $\vec{F} = q\left(\vec{\mathrm{v}} \times \vec{B}\right)$



The first synchrotron light…

The first synchrotron light was observed at *General Electric Labs in* 1946



Elder, Gurewitsch, Langmuir and Pollock

"Radiation from Electrons in a Synchrotron“

Modern synchrotrons around the world

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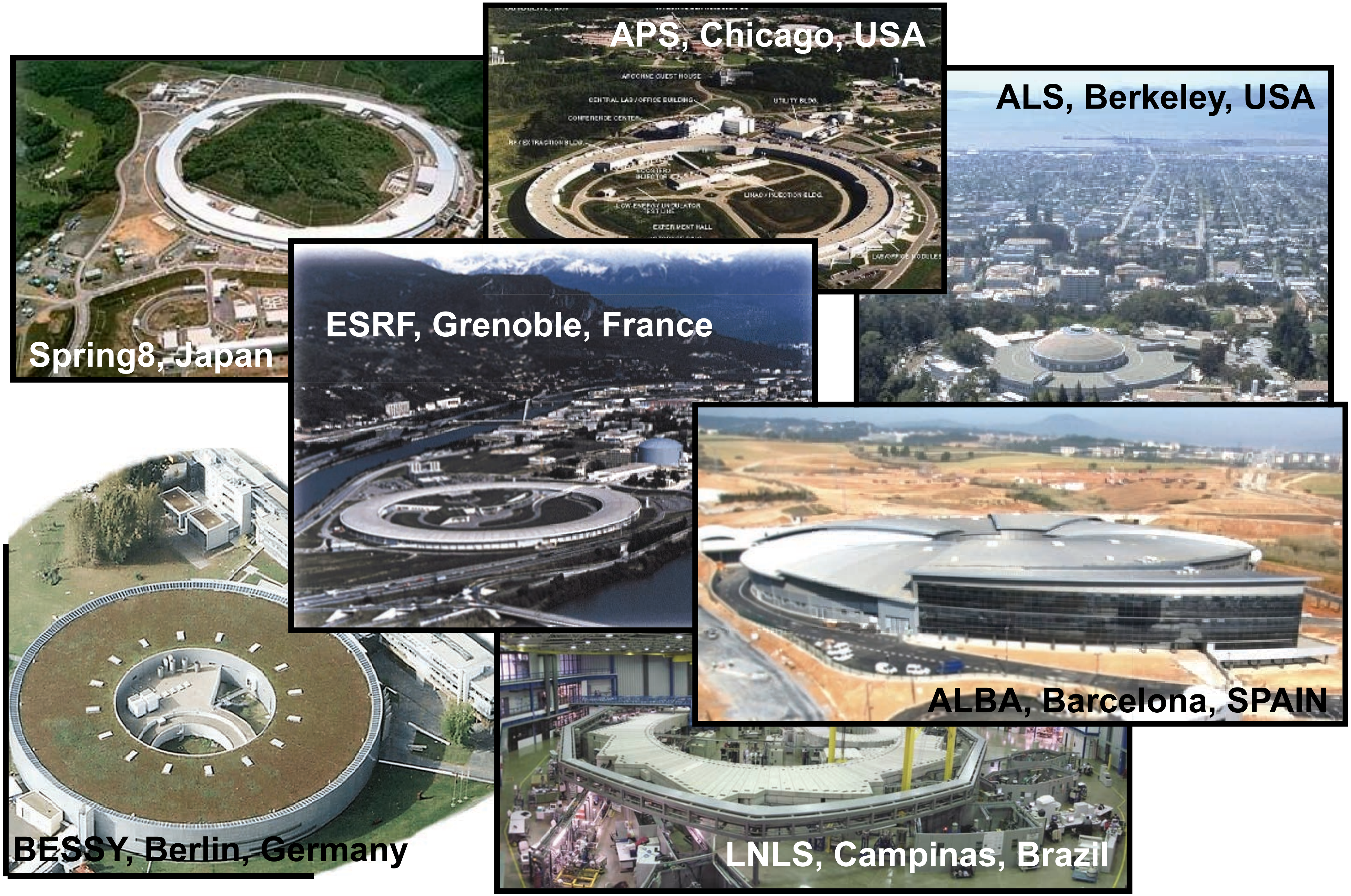

And inside…

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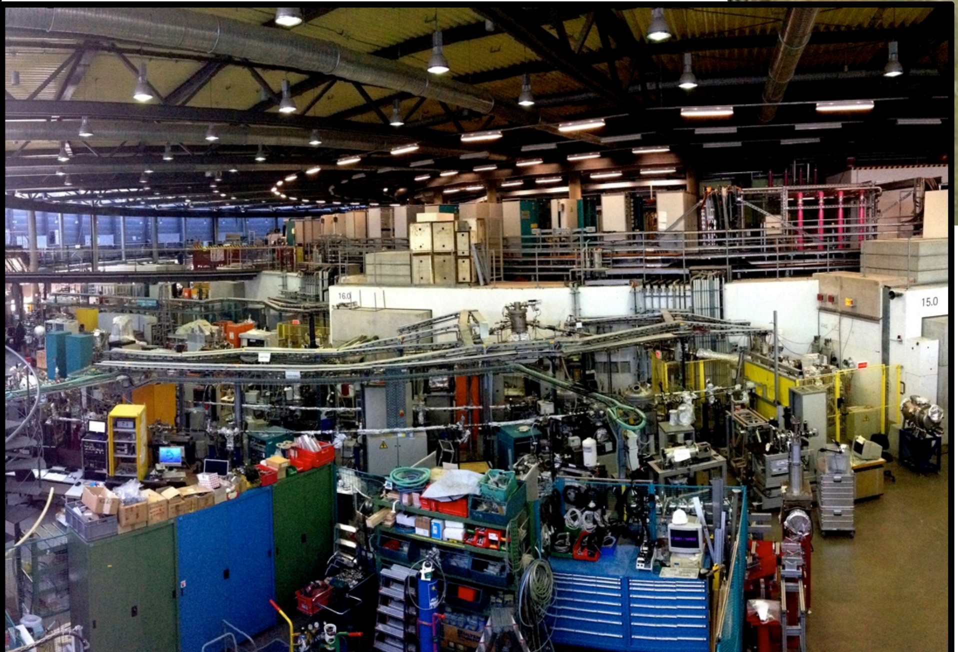
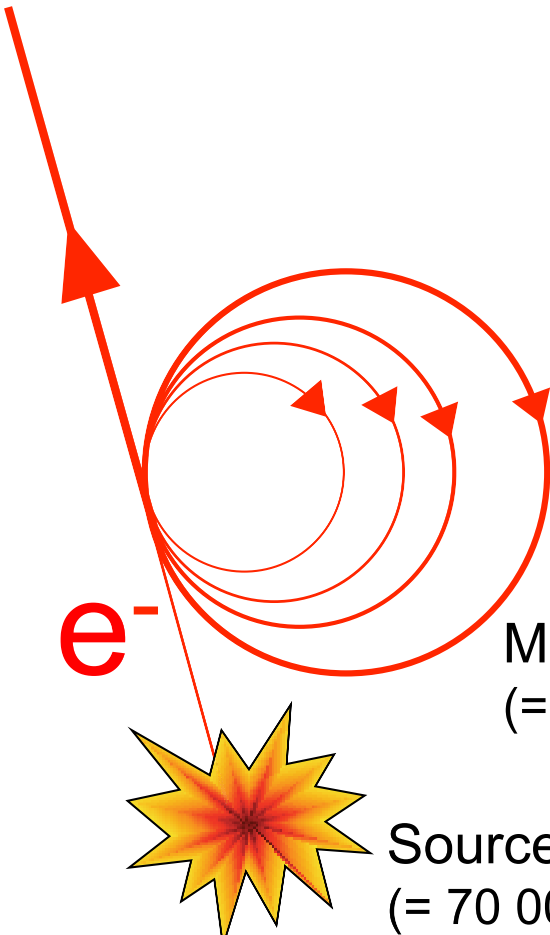
Experimental hall



And a small journey through the interior…

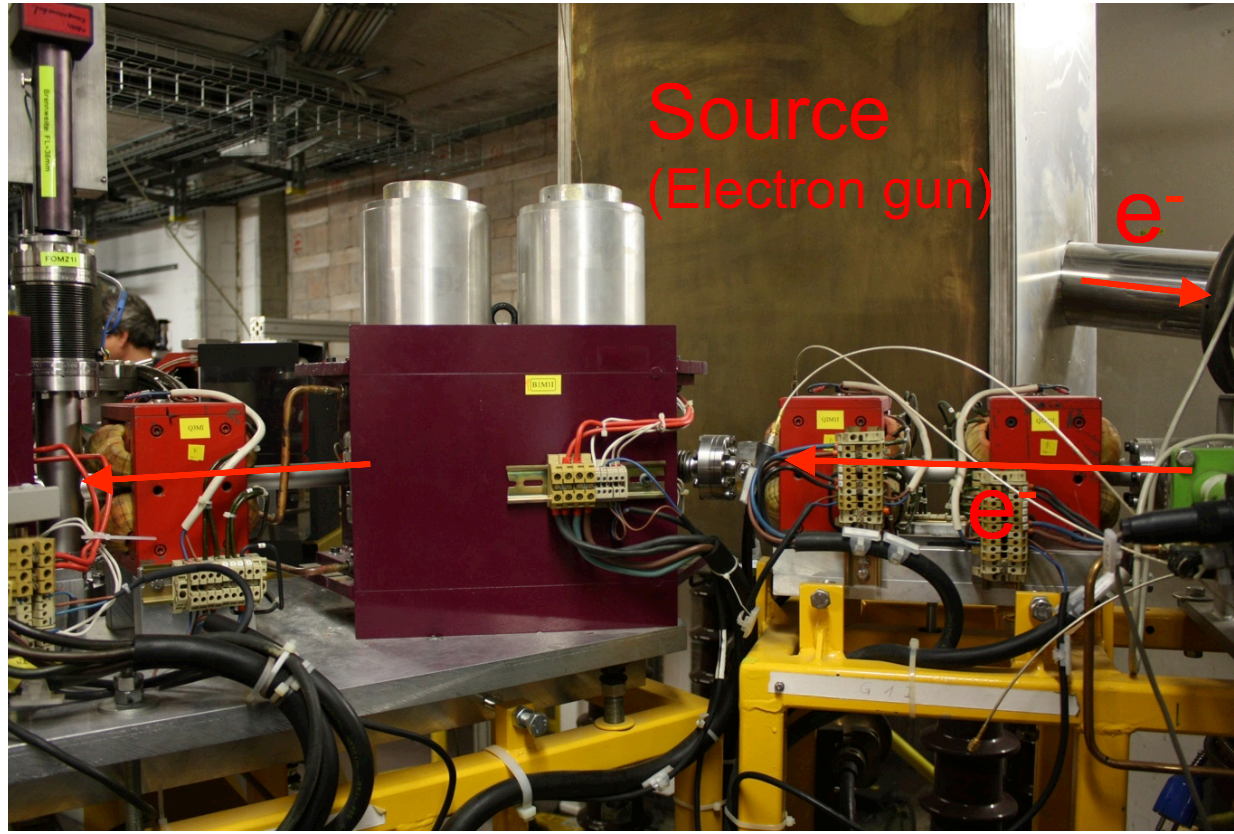
- **Source and microtron**
- **Synchrotron**
- **Storage ring**

Source and Microtron



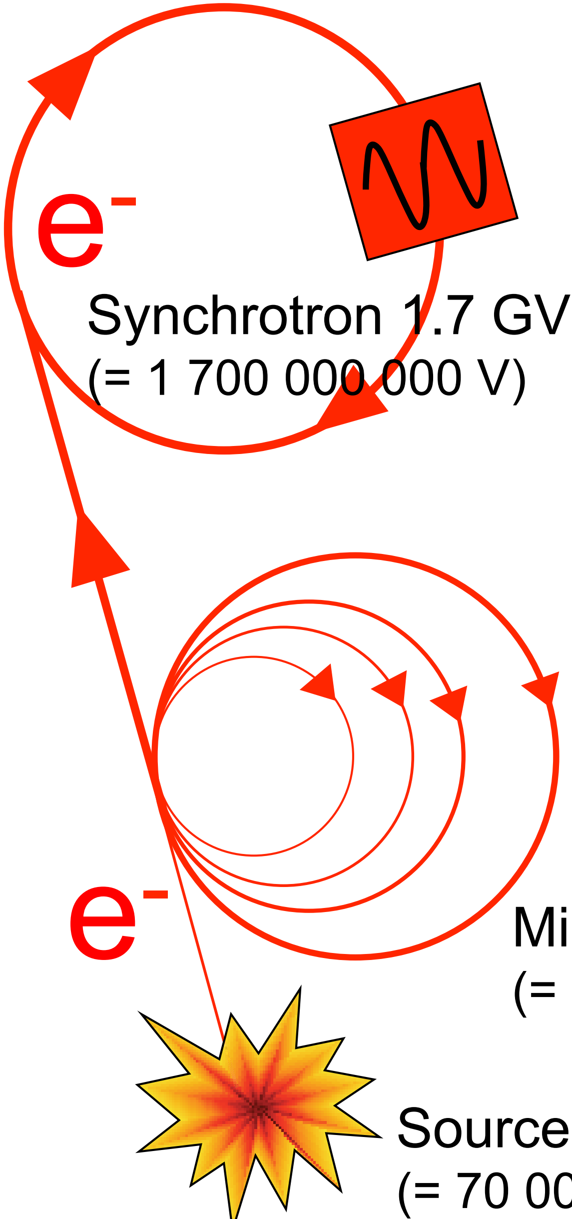
Microtron 50 MV
(= 50 000 000 V)

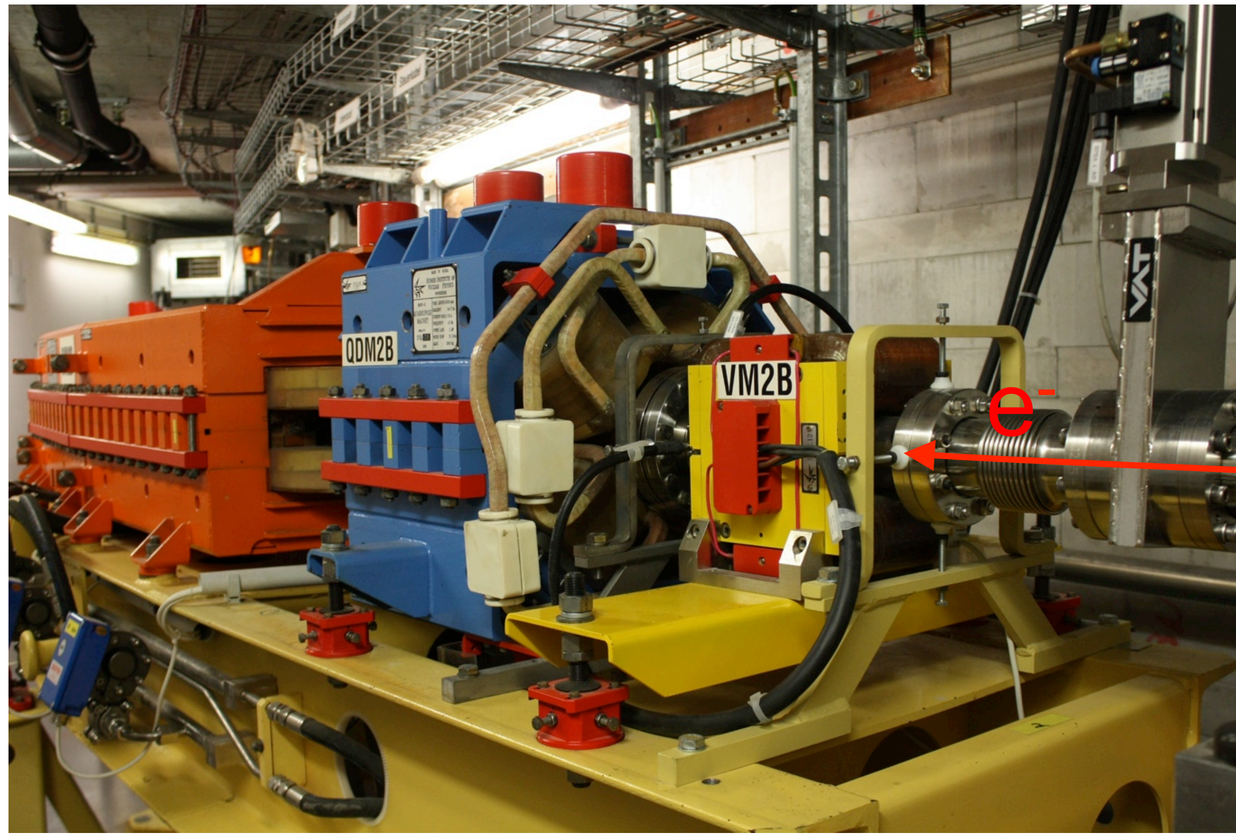
Source 70 kV
(= 70 000 V)



(TV: 20kV)

Synchrotron



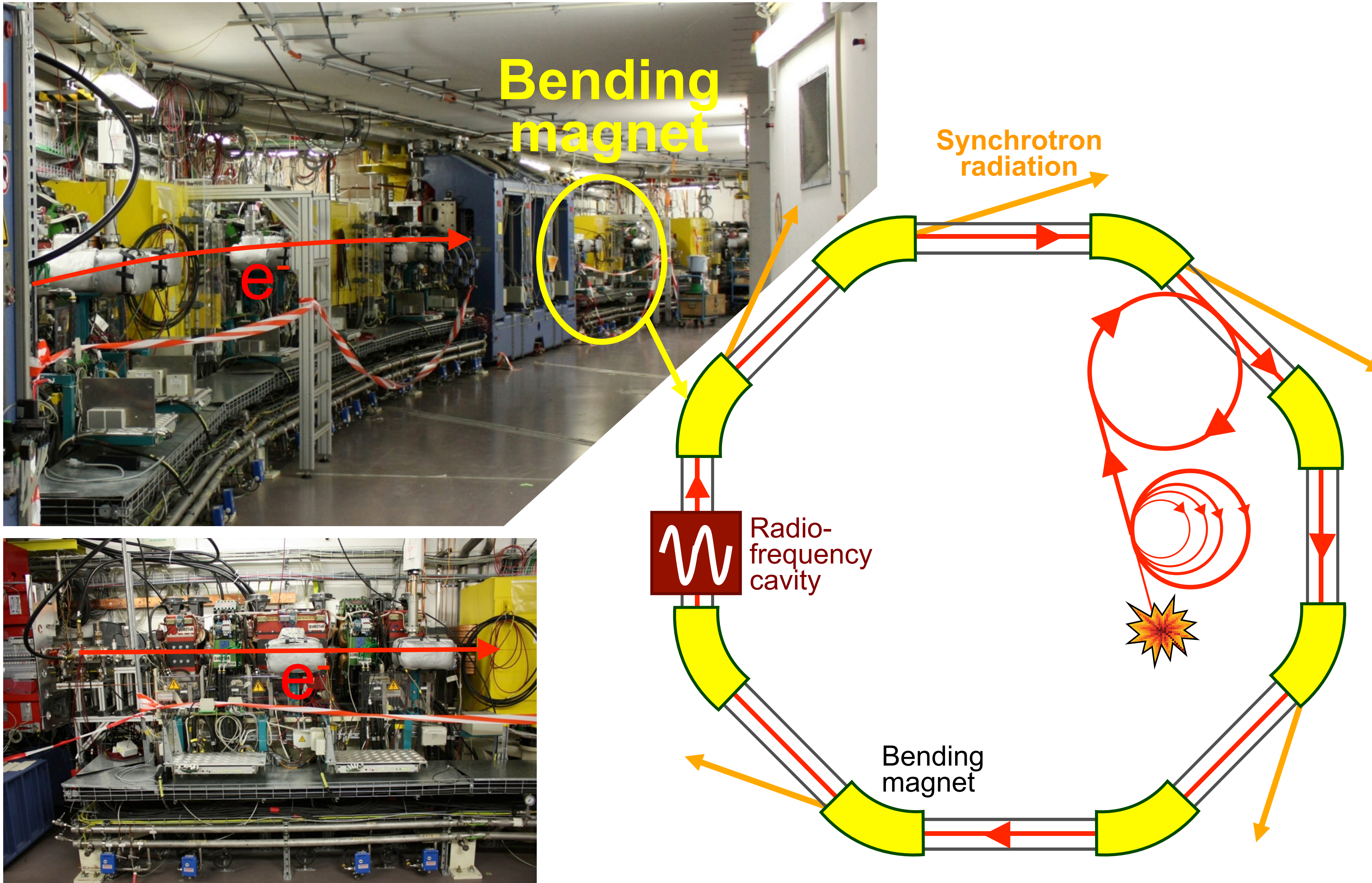


Microtron 50 MV
(= 50 000 000 V)

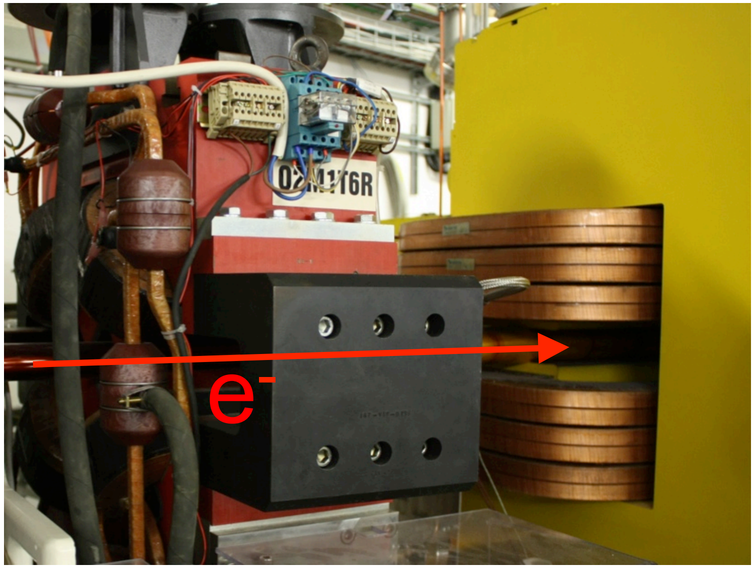
Source 70 kV
(= 70 000 V)

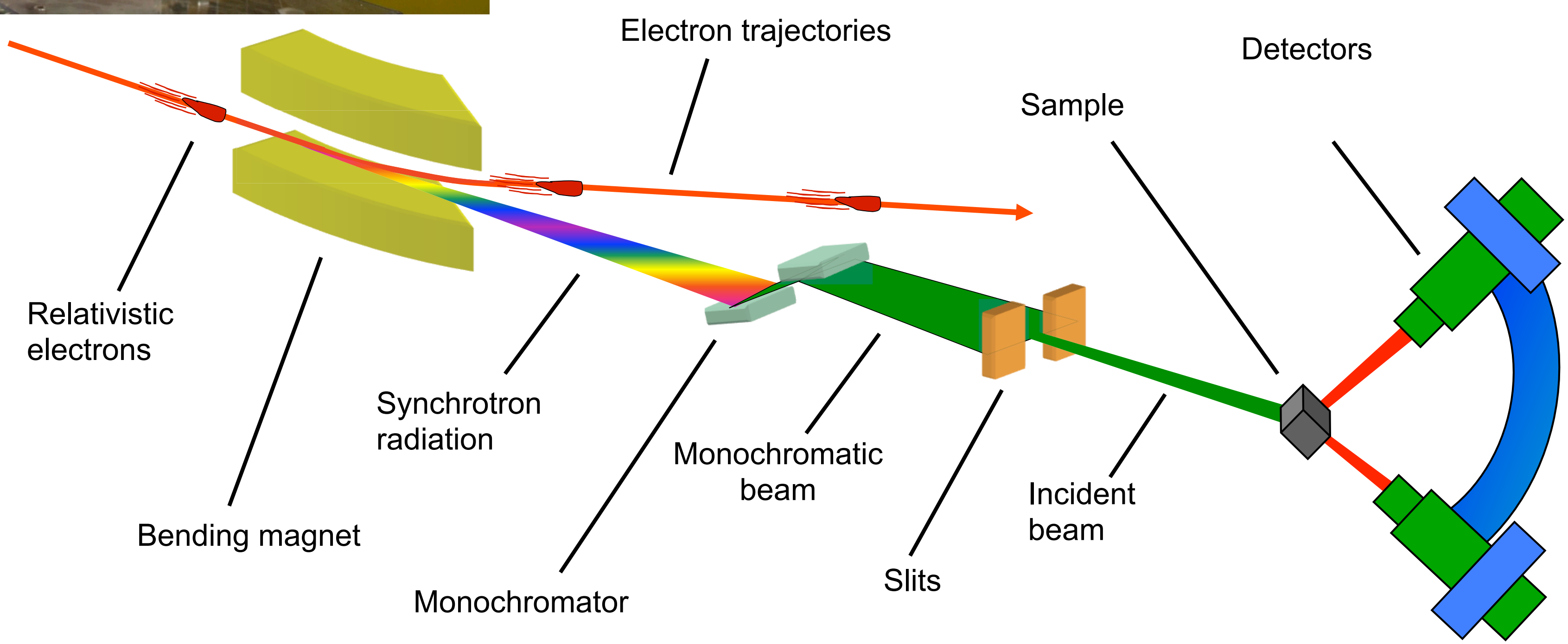
(TV: 20kV)

Storage ring

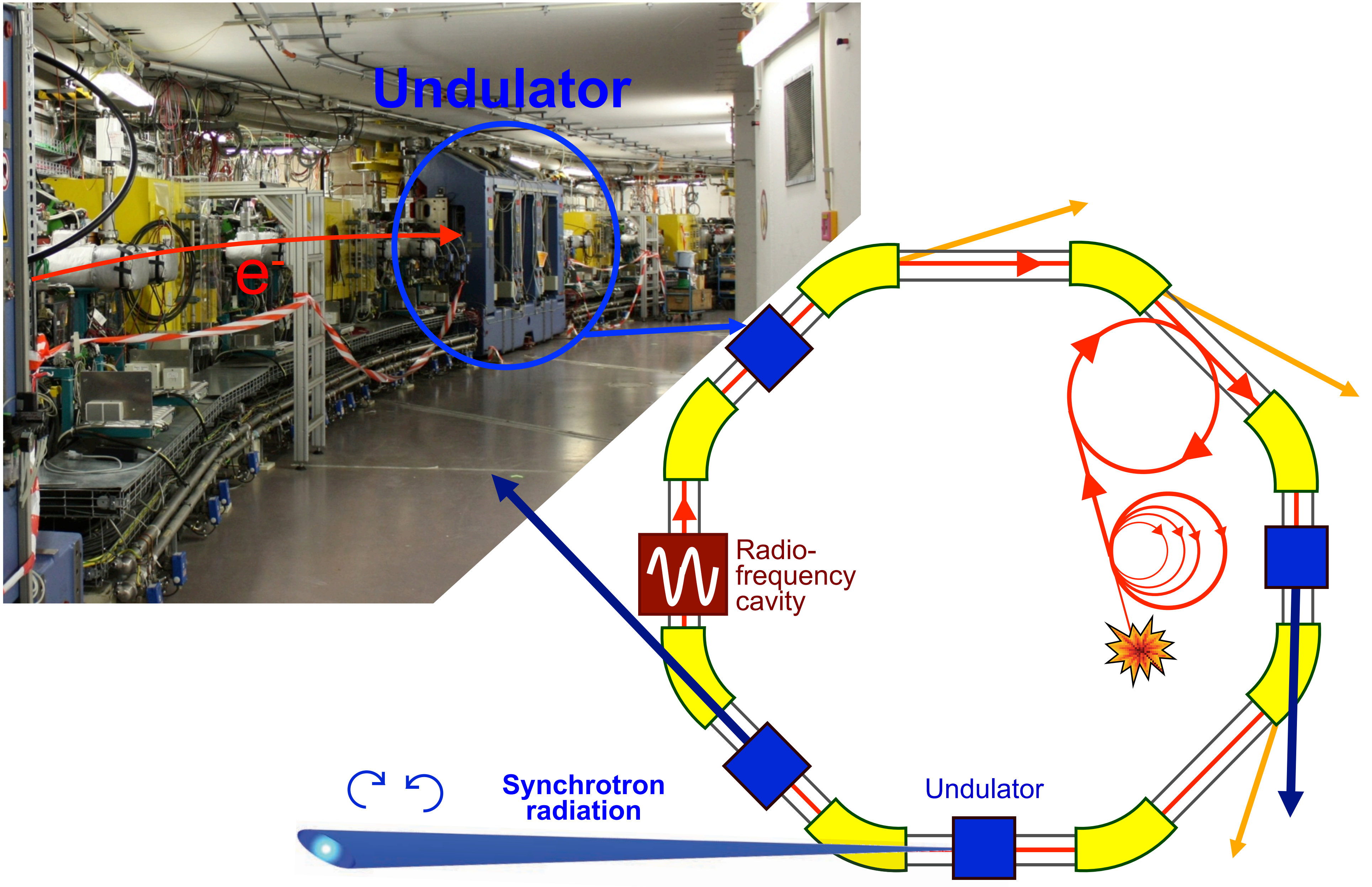


Beamline layout (Bending magnet)





Storage ring



Beamline layout (Undulator)

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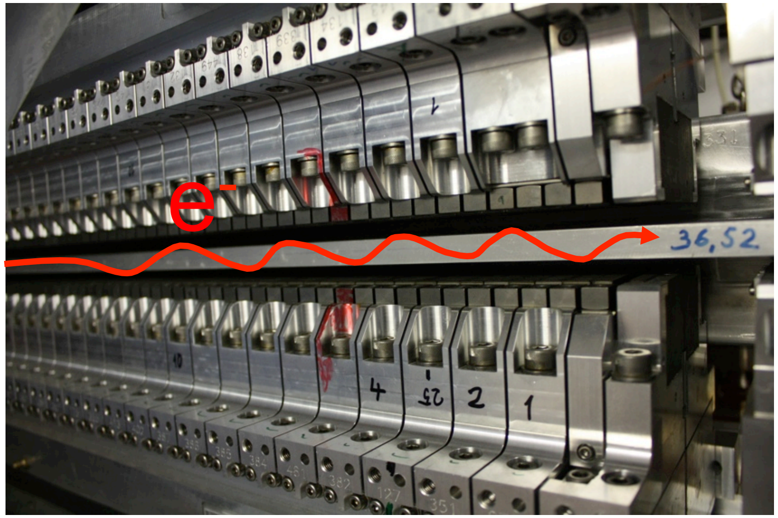
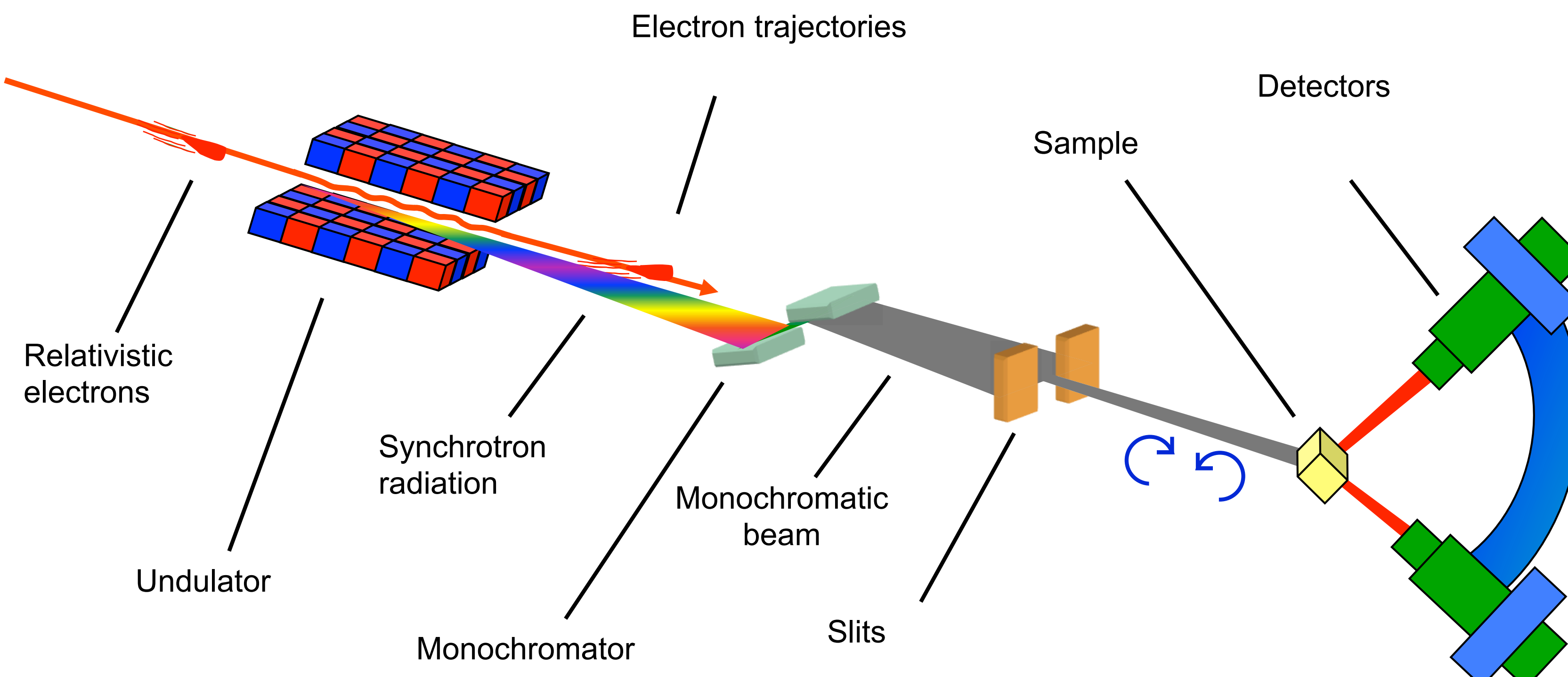
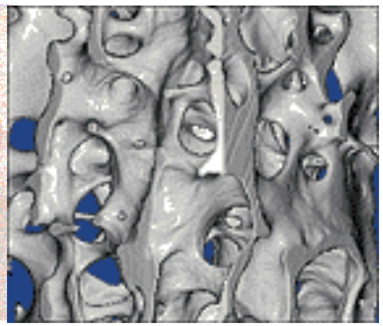
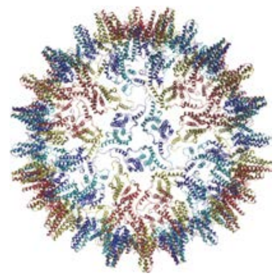




What can we use it for?

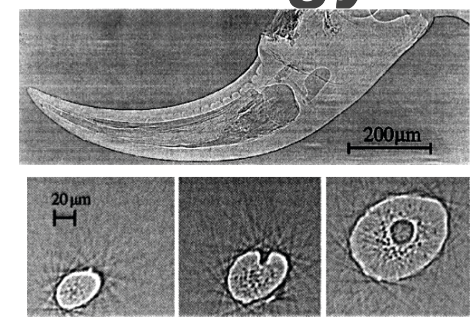
Medicine





Hepatitis B virus

Biology

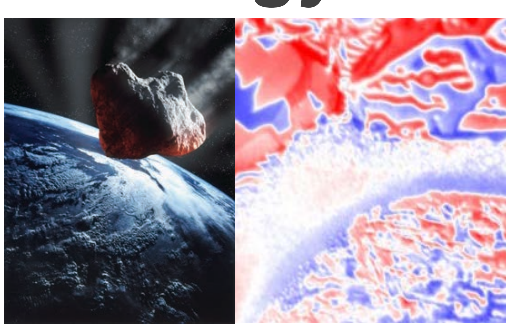


Physics

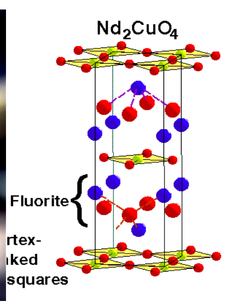
Magnetism

Chemistry

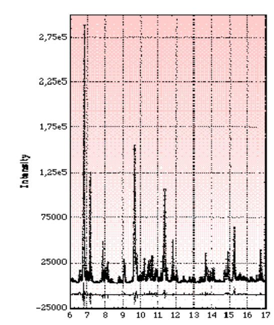
Geology

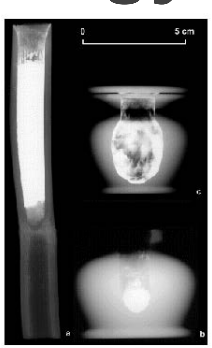


Material Science



Archeology





Synchrotron radiation techniques for magnetism

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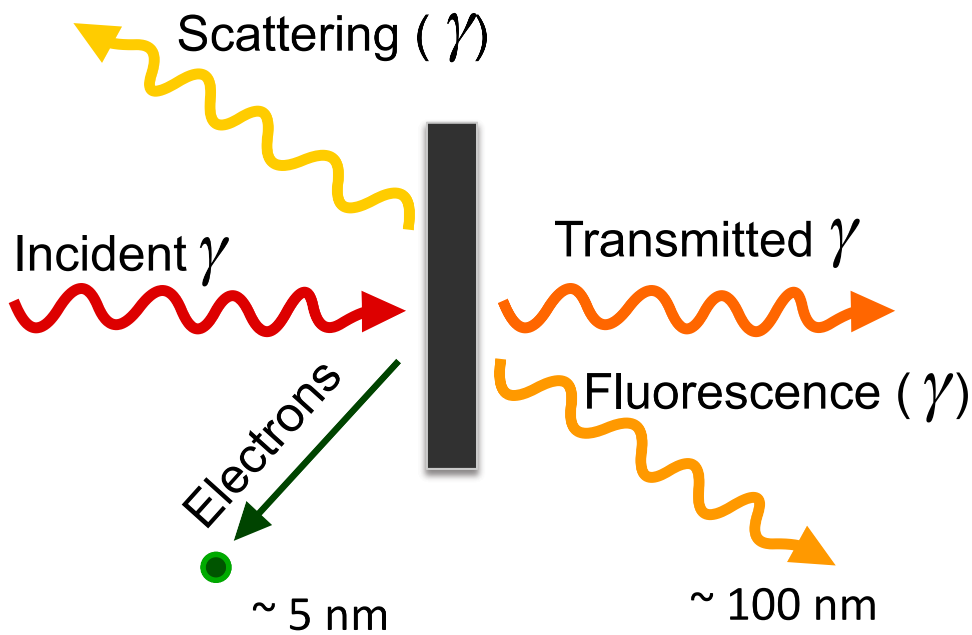

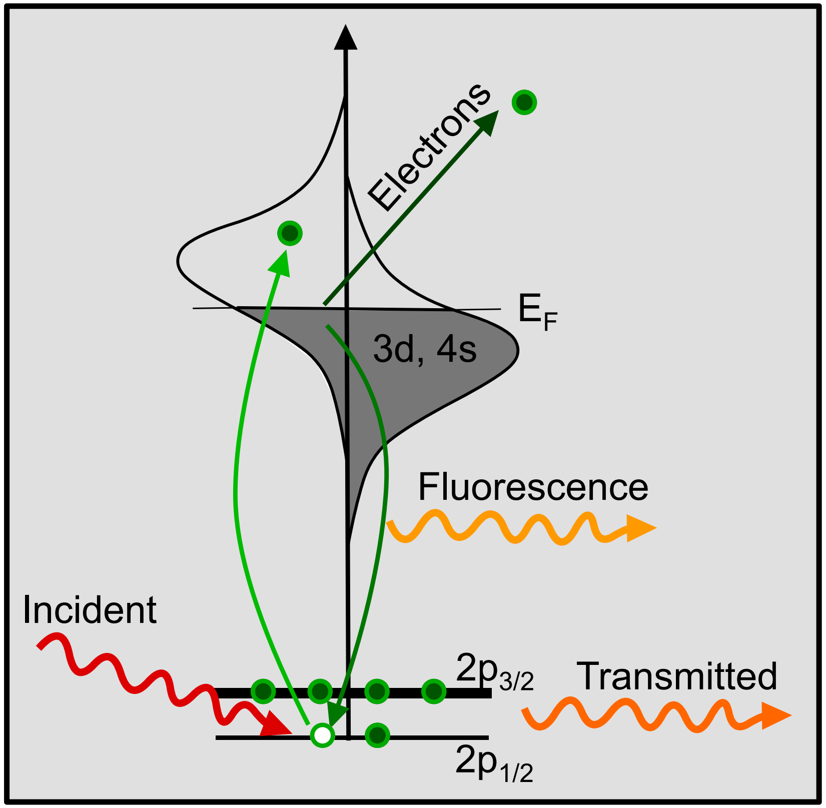

Absorption Spectroscopy

Scattering Diffraction

Photoemission Microscopy

Pump-probe Femtoslicing

X-ray magnetic circular dichroism (XMCD)

X-ray resonant magnetic scattering (XRMS)

X-ray Photoemission electron microscopy (XPEEM)

Transmission x-ray microscopy (TXM)

Scanning Transmission x-ray microscopy (STXM)

Magneto-dichroic x-ray holography

Challenges in magnetism

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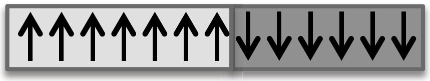
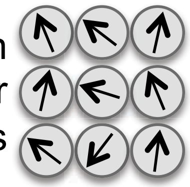
SIZE

Magnetic domains



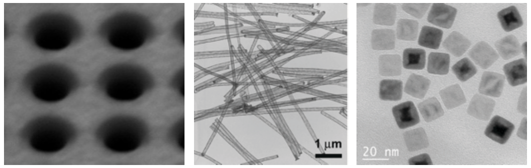
Non collinear structures



~100 µm ~ 1nm

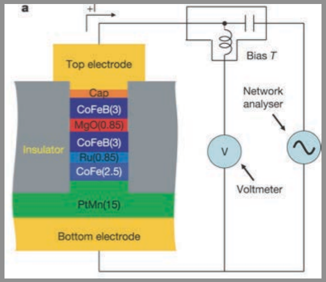
Magnetism: Interplay of interactions on different length scales

Effect of boundary conditions?

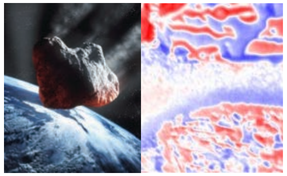


CHEMICAL COMPLEXITY

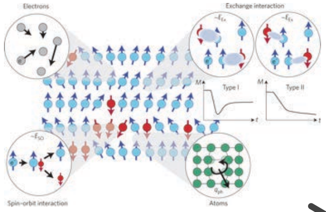
Spintronics:
Need for element specific techniques



TIME



data retention



$\sim 10^8$ years ~10 years ~ femtoseconds = 10^{-15} s

M. Reversal
@ different time scales

Magnetic fields
Spin polarized currents
Laser

How fast the magnetization can be reversed?

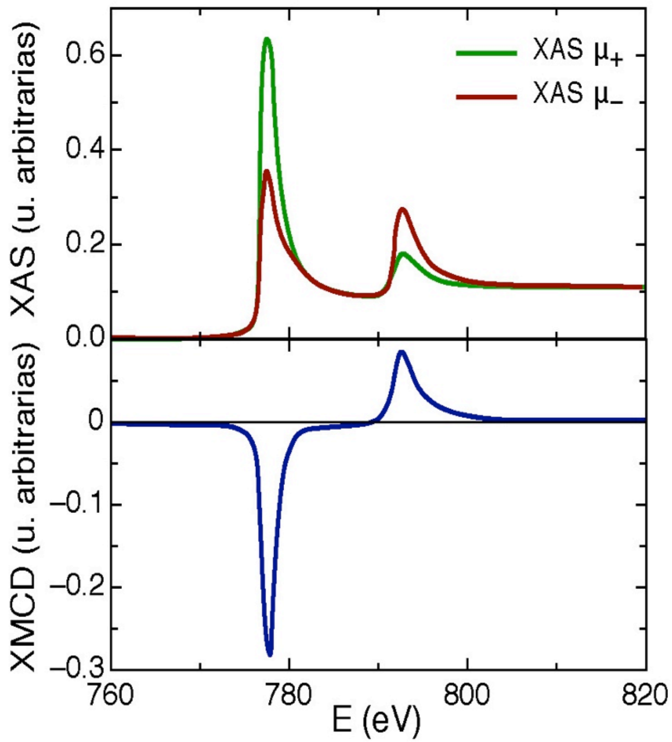
X-ray Magnetic Circular Dichroism $\text{XMCD} = \text{XAS}\mu_{-} - \text{XAS}\mu_{+}$

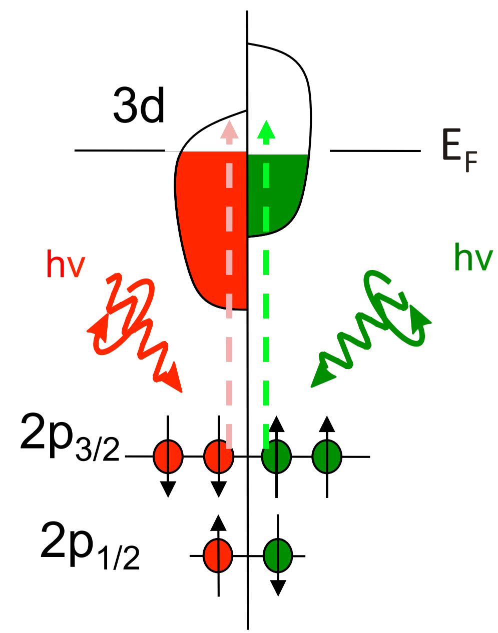
Atomic and **shell** selective magnetometry

Synchrotron radiation

Wide range tuneable energy

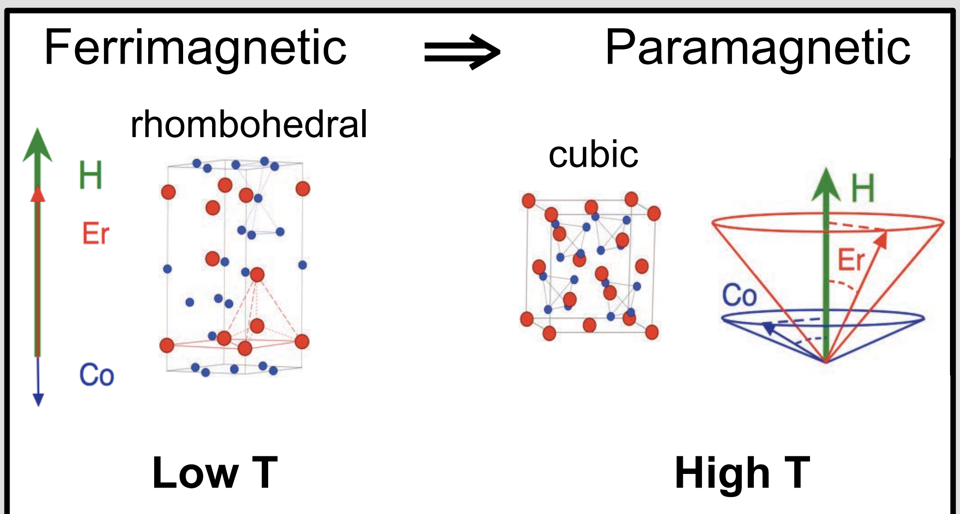
Variable polarization





Selective magnetometry (in $ErCo_2$)

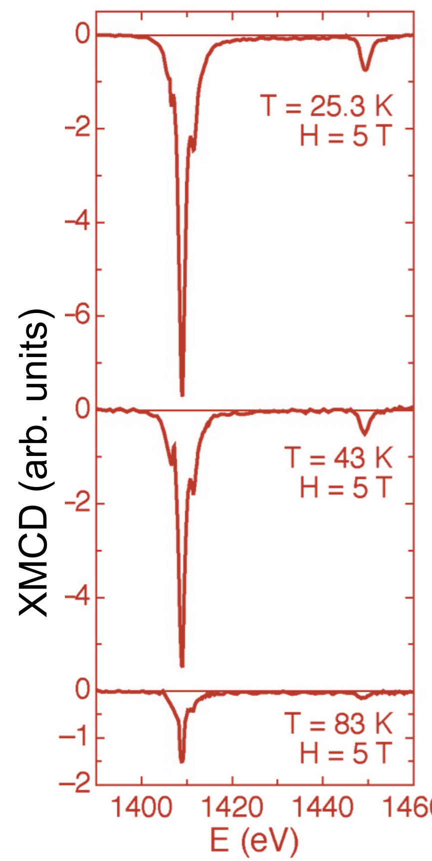
$ErCo_2$: **Co** 3*d* band near the critical condition for the formation of magnetic moment ⇒ very sensitive to H, P, R internal field, etc.



(**Er** is the dominant moment in the system)

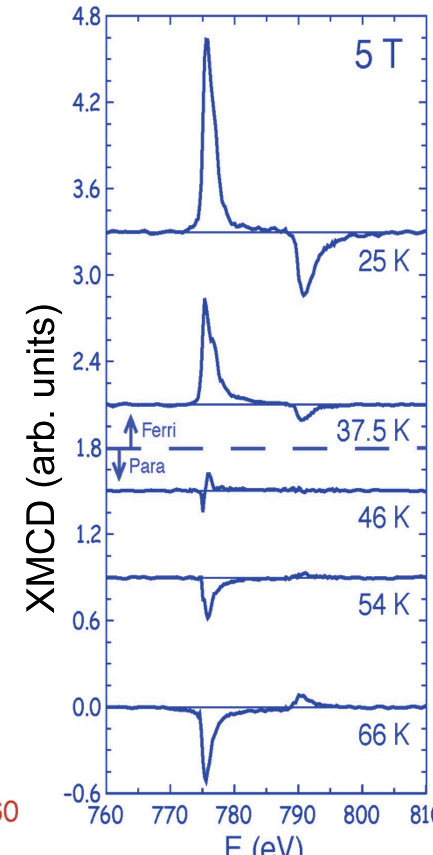
• **Er $M_{4,5}$ edge**

(Er 4f electrons)



• **Co $L_{2,3}$ edge**

(Co 3d band)



Selective magnetometry (in $ErCo_2$)

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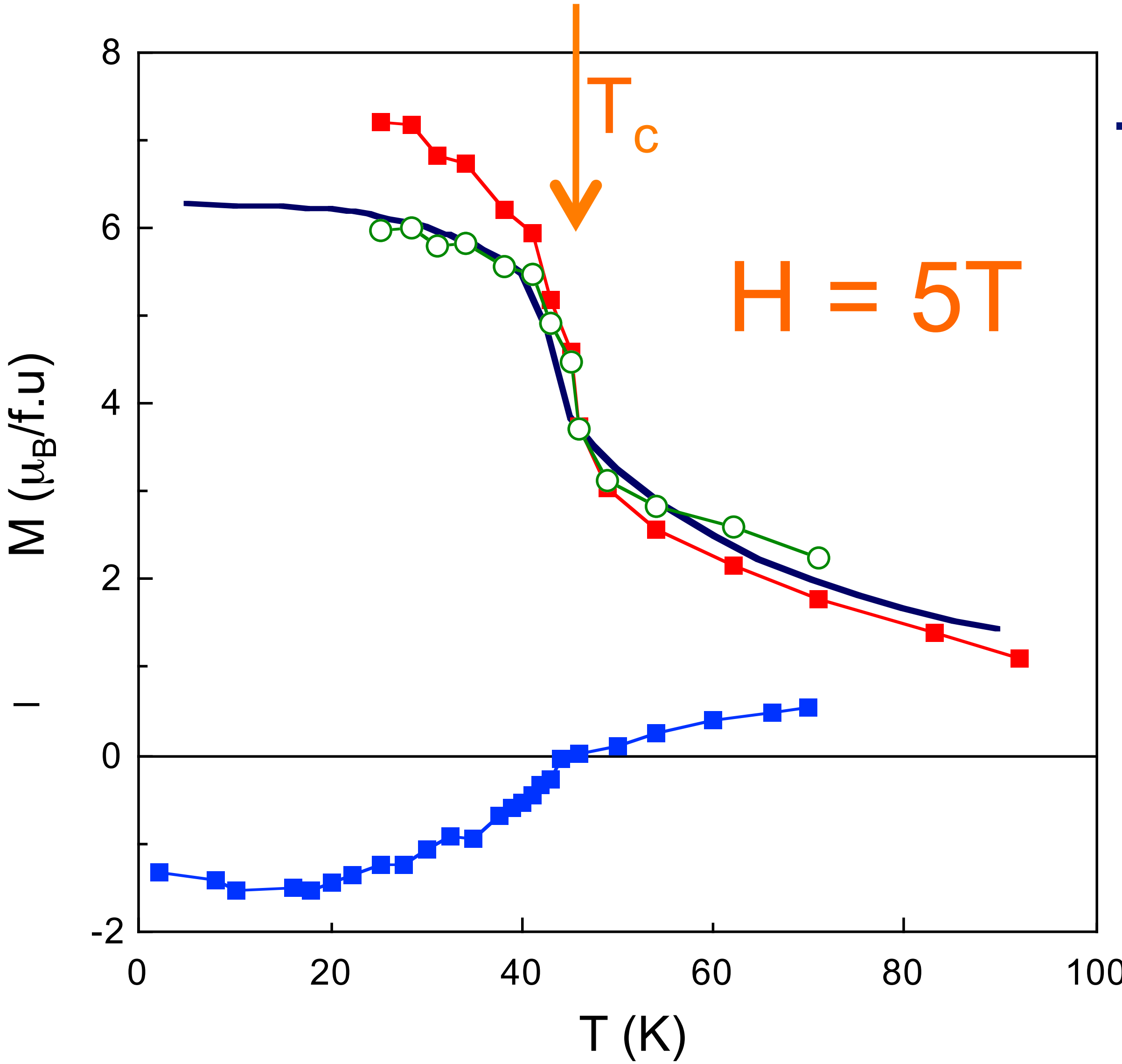

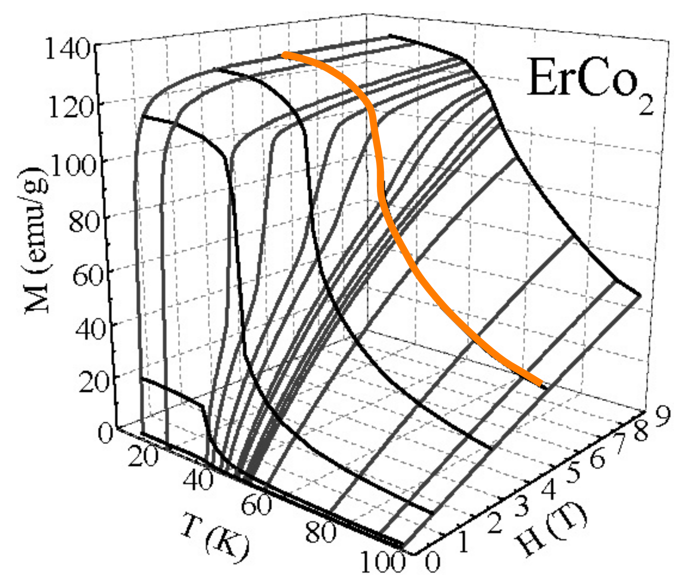

PHYSICAL REVIEW B **76**, 094409 (2007)

Observation of a different magnetic disorder in $ErCo_2$

Julia Herrero-Albillos,* Fernando Bartolomé, and Luis M. García
Anthony T. Young Tobias Funk Javier Campo Gabriel J. Cuello

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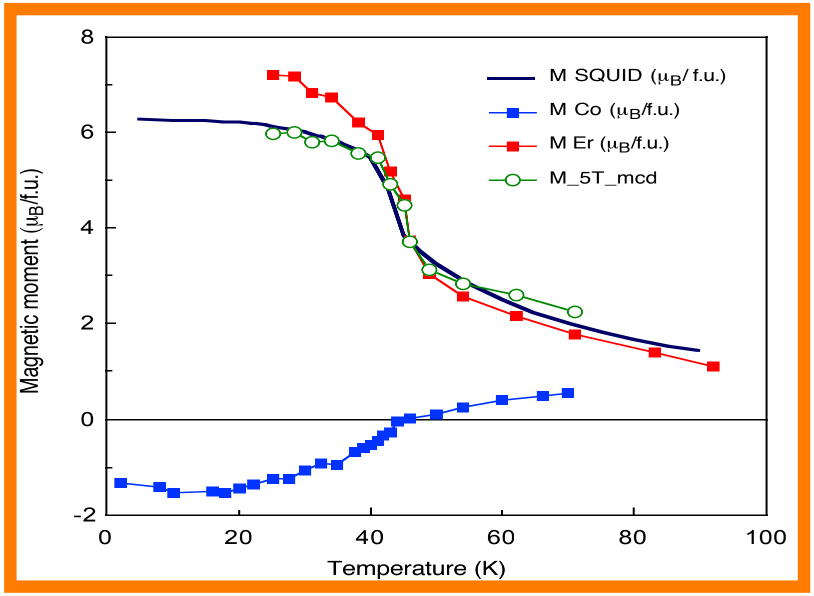
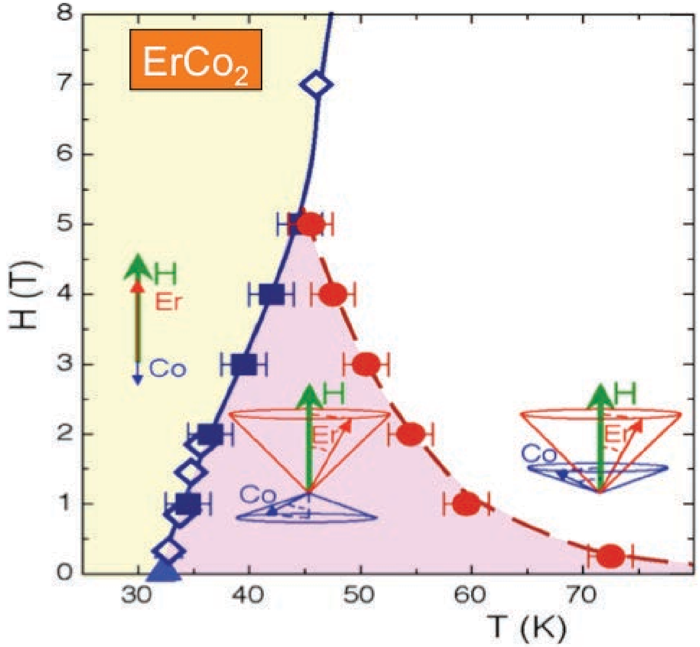
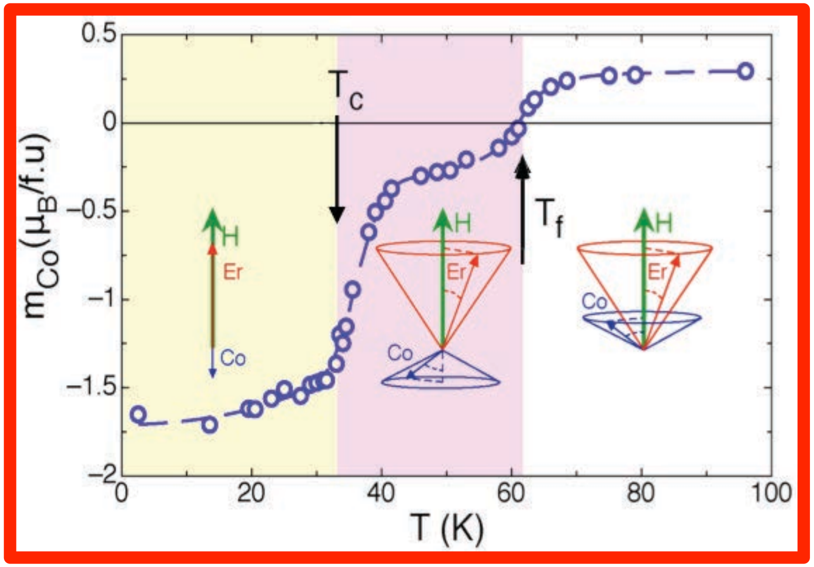
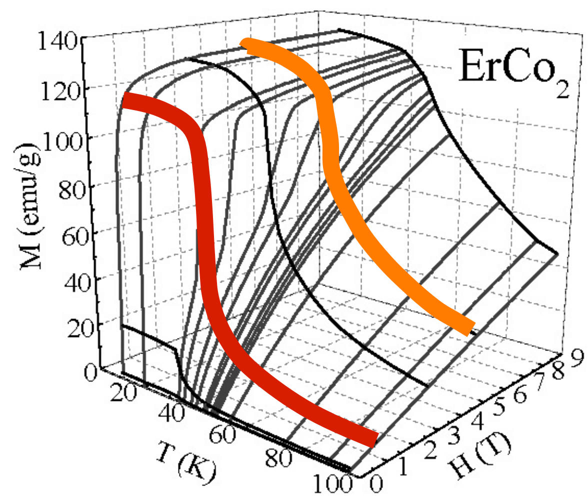


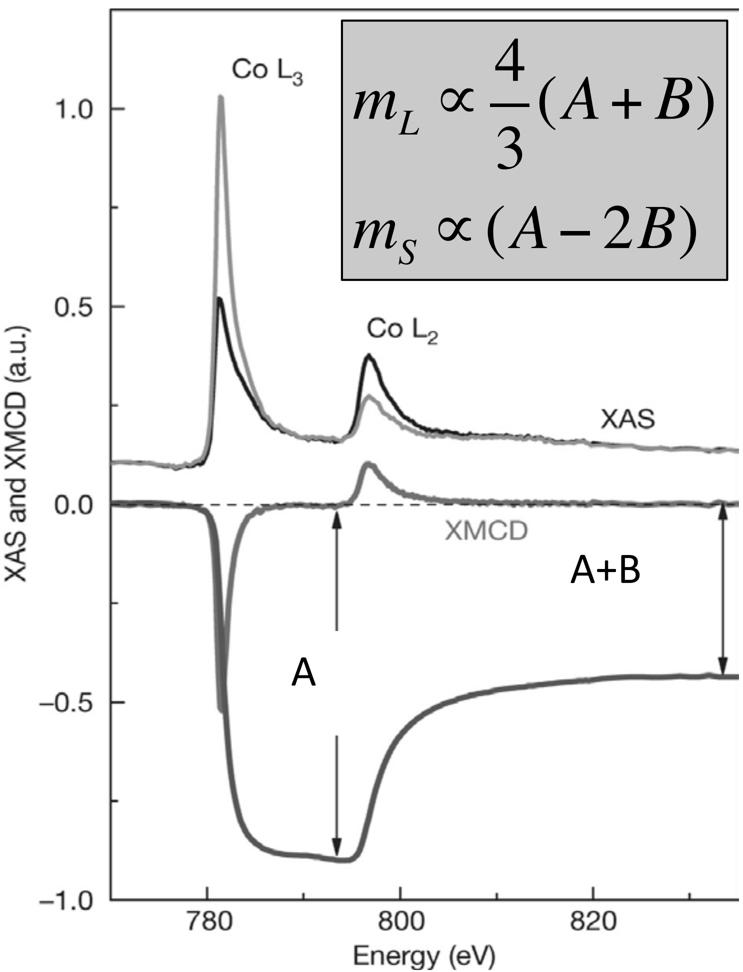


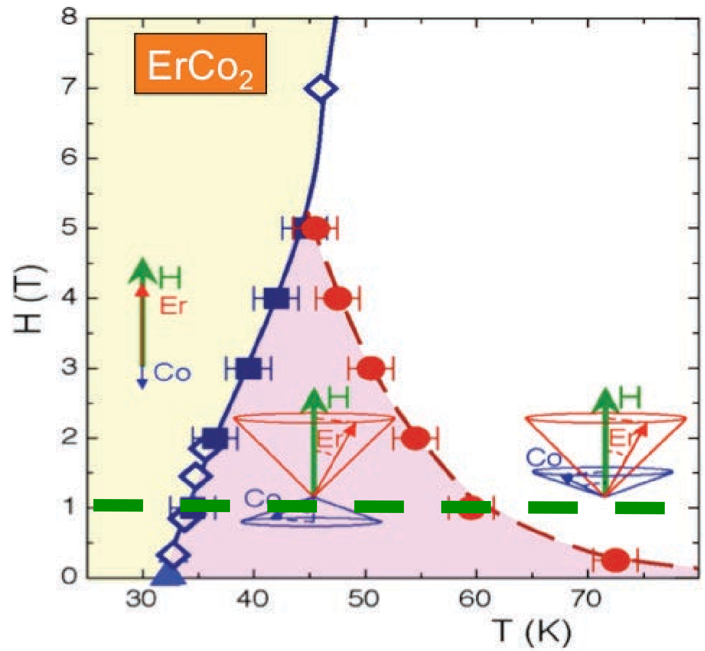


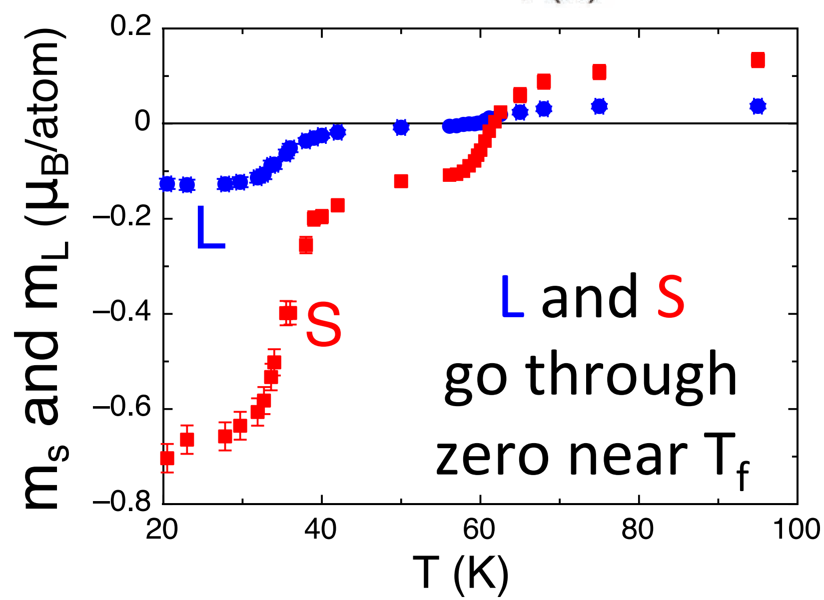


Orbital and spin moments:

According with 3rd Hund's rule, L and S are parallel in the ferrimagnetic and paramagentic phase.







EPL, **93** (2011) 17006
doi: 10.1209/0295-5075/93/17006
www.epljournal.org

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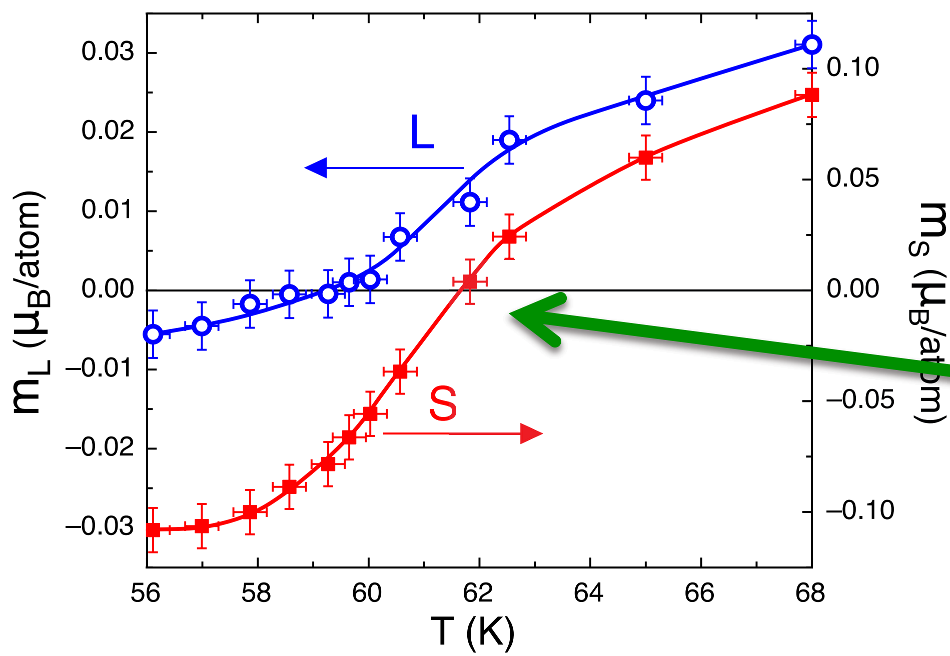
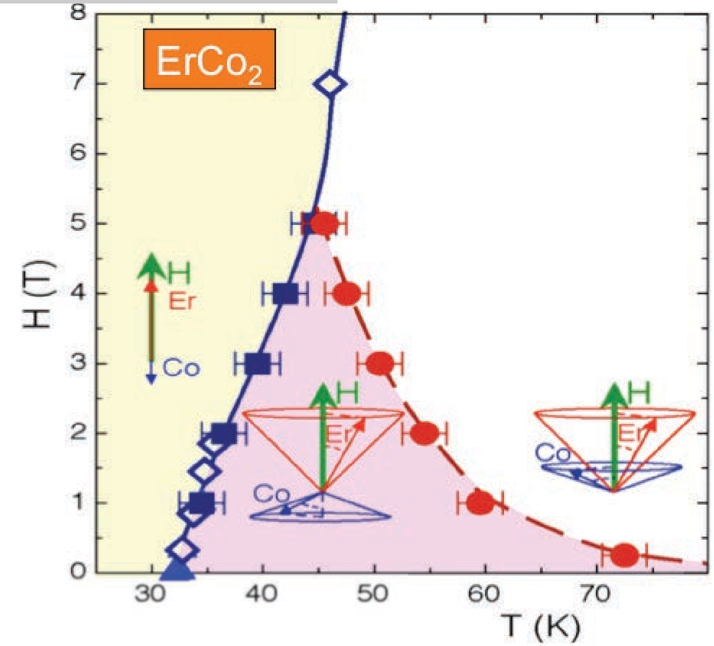
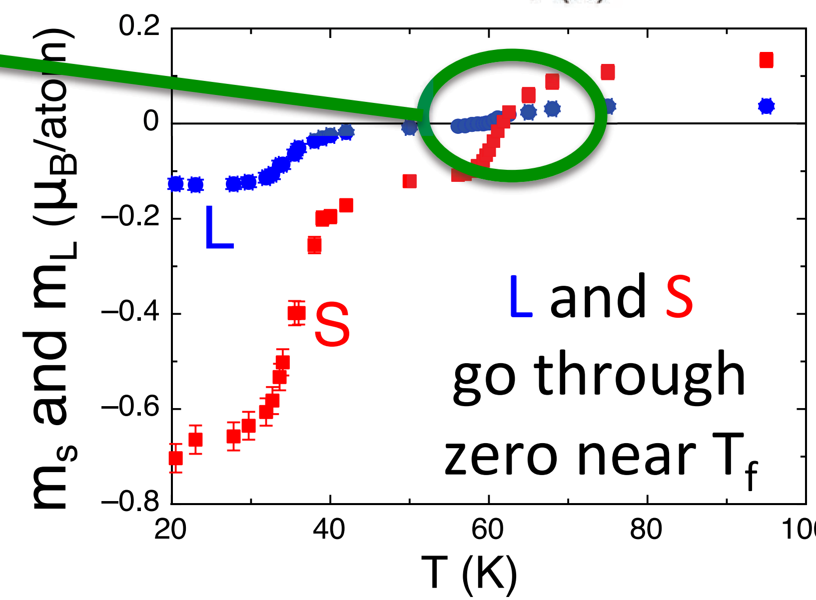
Breakdown of Hund's third rule for intrinsic magnetic moments

J. Herrero-Albillos[1(a)], L. M. García[2], F. Bartolomé[2] and A. T. Young[3]

According with 3rd Hund's rule, L and S should be parallel in the ferrimagnetic and paramagentic phase.







T(L=0) ≠ T(S=0)

Breakdown of Hund's 3er rule

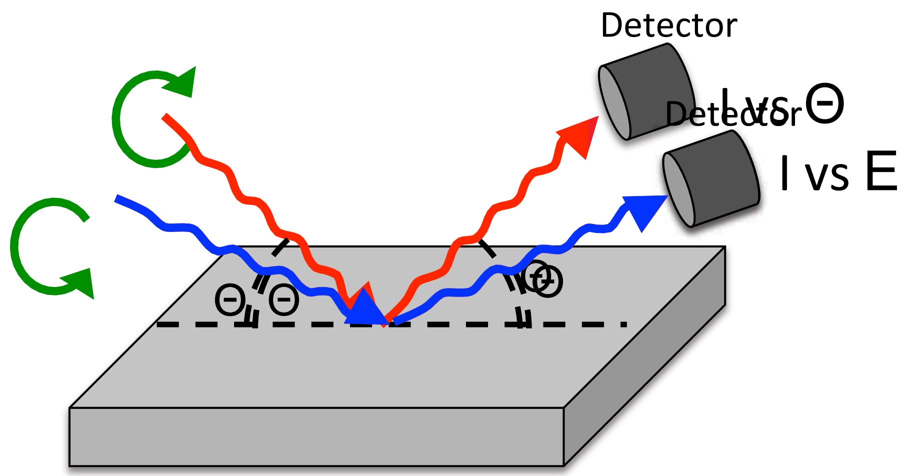
PHYSICAL REVIEW B **72**, 024438 (2005)

Element-specific characterization of the interface magnetism in $[Co_2MnGe/Au]_n$ multilayers by x-ray resonant magnetic scattering

J. Grabis,* A. Bergmann, A. Nefedov, K. Westerholt, and H. Zabel

X-ray resonant magnetic reflectivity

XRMR is the combination of standard x-ray reflectometry with x-ray magnetic circular dichroism which provides chemical and magnetic depth profiles of layered thin-film samples



... It should be mentioned here already that, unfortunately, in XRMS little can be learned by a mere qualitative inspection of the spectra . Only a sophisticated computer-based data analysis and fitting gives the relevant quantitative information. However, with the powerful tools available a corresponding analysis is possible and reliable.

New Journal of Physics > Volume 15 > November 2013
S K Mishra et al 2013 New J. Phys. 15 113042 doi:10.1088/1367-2630/15/11/113042

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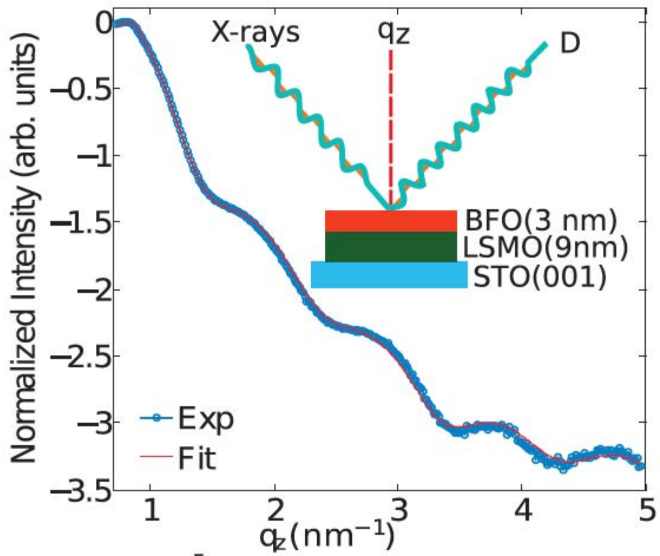
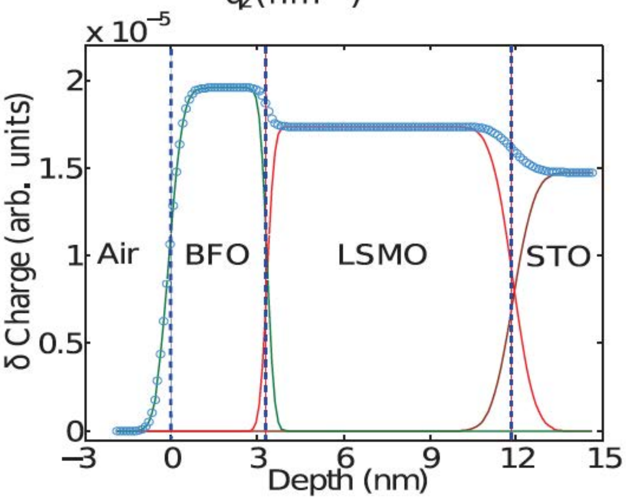
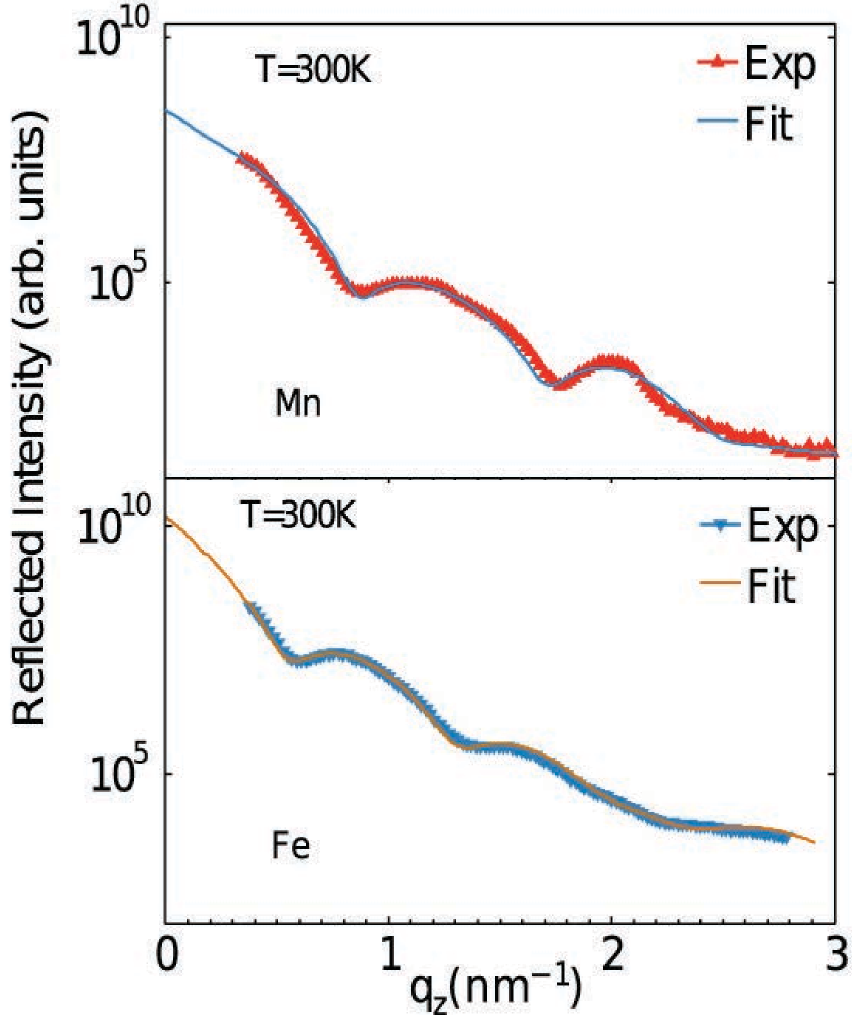
Altered magnetism and new electronic length scales in magneto-electric $La_{2/3}Sr_{1/3}MnO_3$–$BiFeO_3$ heterointerface

S K Mishra[1], D Mazumdar[2], K Tarafdar[3], Lin-Wang Wang[3], S D Kevan[1,4], C Sanchez-Hanke[5], A Gupta[2] and S Roy[1,6]

X-ray resonant magnetic reflectivity







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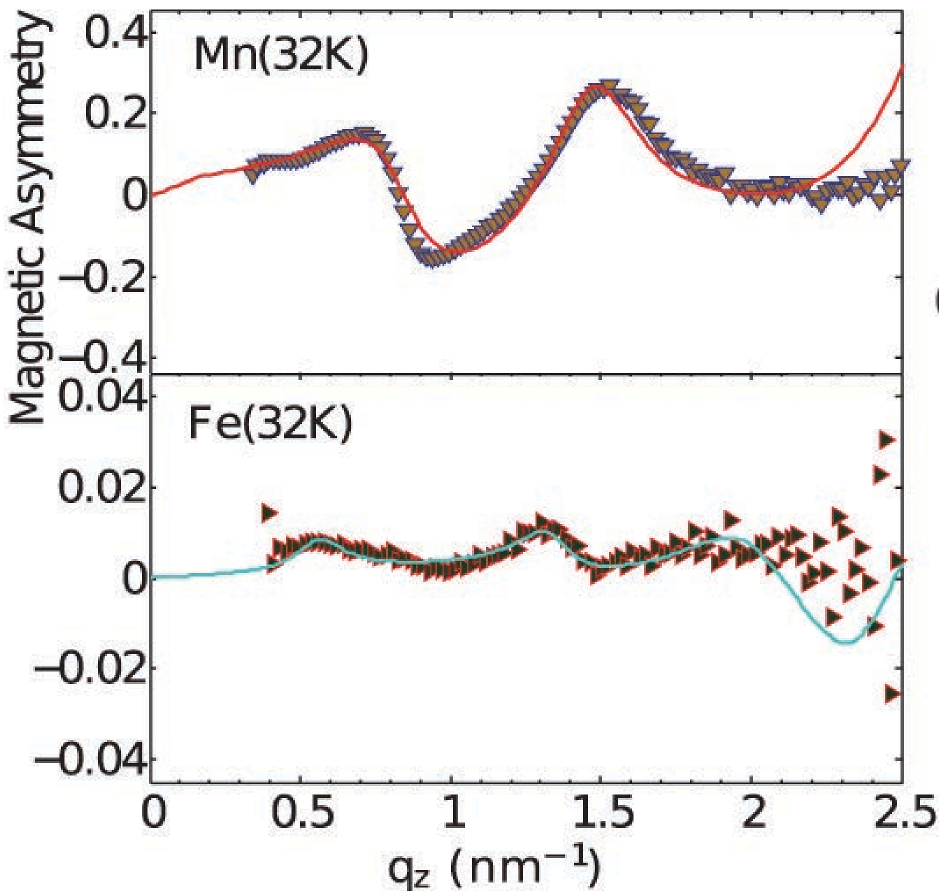
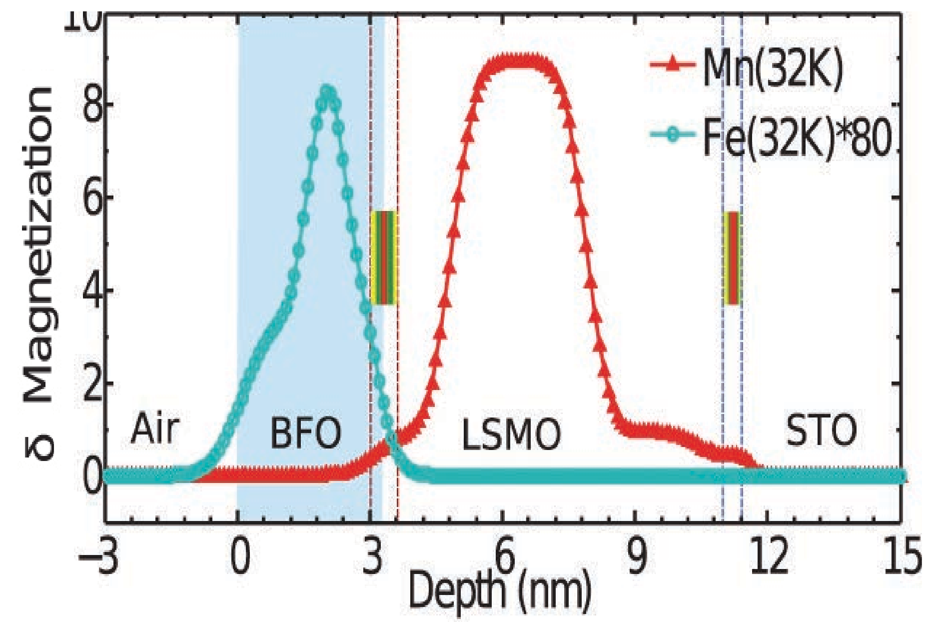
X-ray resonant magnetic reflectivity





Asymmetric suppression of μ_{Mn} in LSMO

Weak μ_{Fe} in BFO near LSMO

Parallel alignments of μ_{Fe} and μ_{Mn}

Presence of dead layers at the interfaces

PHYSICAL REVIEW B **72**, 024438 (2005)

Element-specific characterization of the interface magnetism in $[Co_2MnGe/Au]_n$ multilayers by x-ray resonant magnetic scattering

J. Grabis,* A. Bergmann, A. Nefedov, K. Westerholt, and H. Zabel

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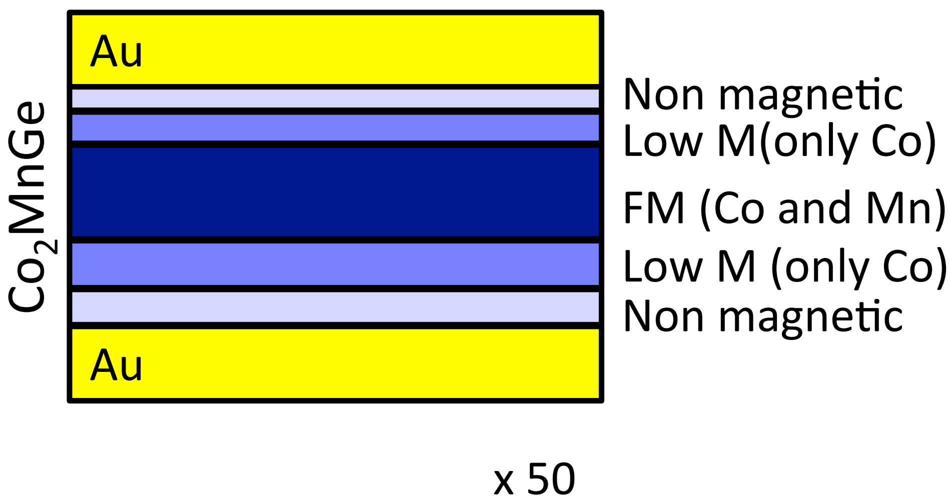
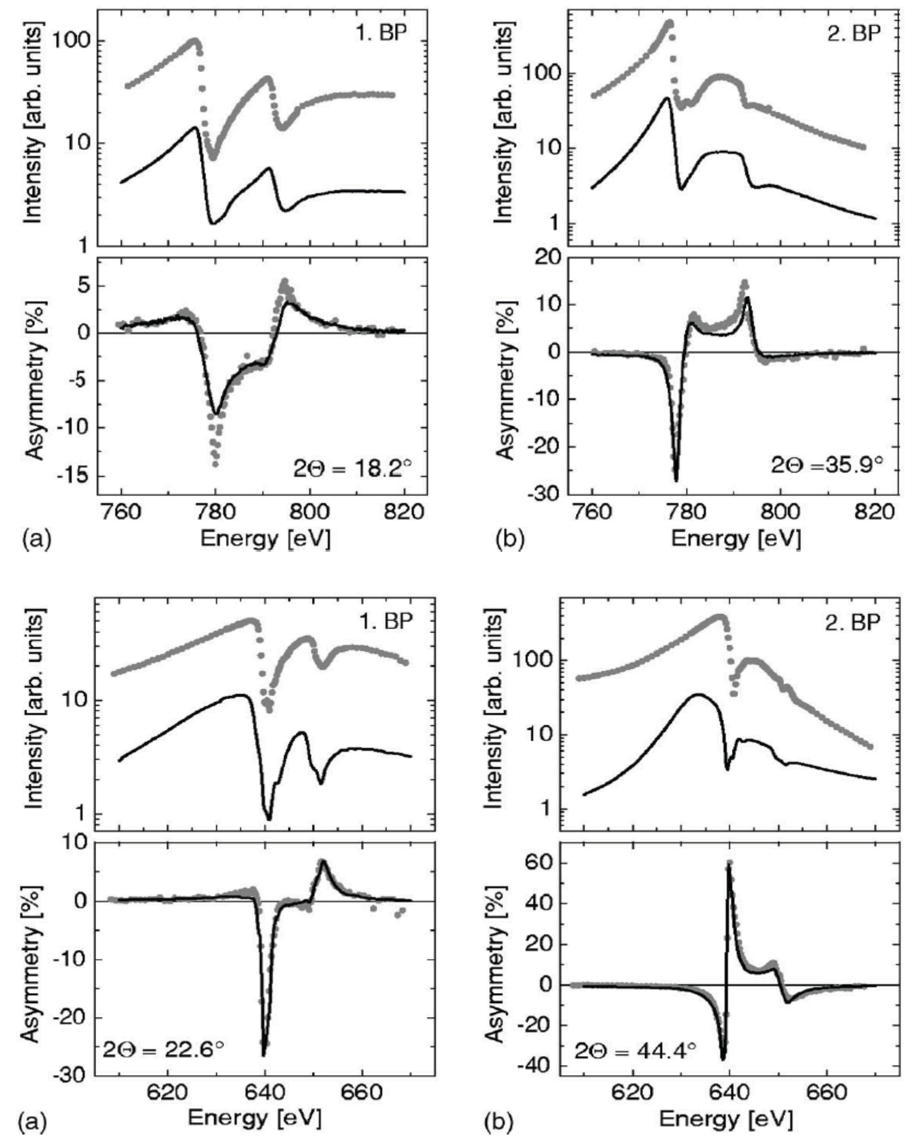
Different profile for Mn and Co spins and asymmetric with respect to the growth direction.





Magnetism at the interfaces is critical. Non magnetic interlayers can be detrimental for spintronic applications (failure to reach theoretical 100% spin polarization)

Challenges in magnetism

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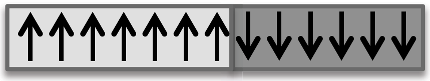
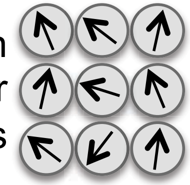
SIZE

Magnetic domains



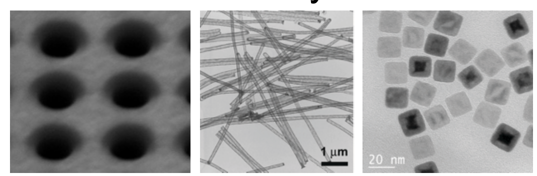
Non collinear structures



~100 µm ~ 1nm

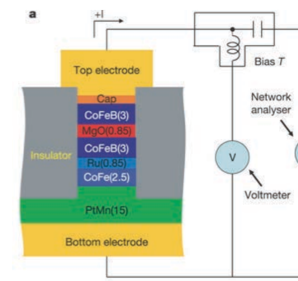
Magnetism: Interplay of interactions on different length scales

Effect of boundary conditions?

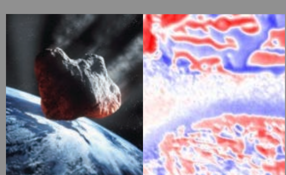


CHEMICAL COMPLEXITY

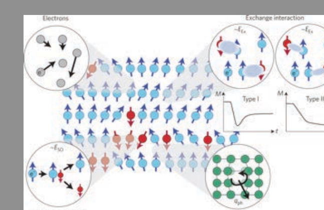
Spintronics:
Need for element specific techniques



TIME



data retention



$\sim 10^8$ years ~10 years ~ femtoseconds

M. Reversal @ different time scales

Magnetic fields → 200 ps
Spin polarized currents (fundamental limit @ 2 ps)
Laser → ~ fs?

How fast the magnetization can be reversed?

Pump and Probe experiments

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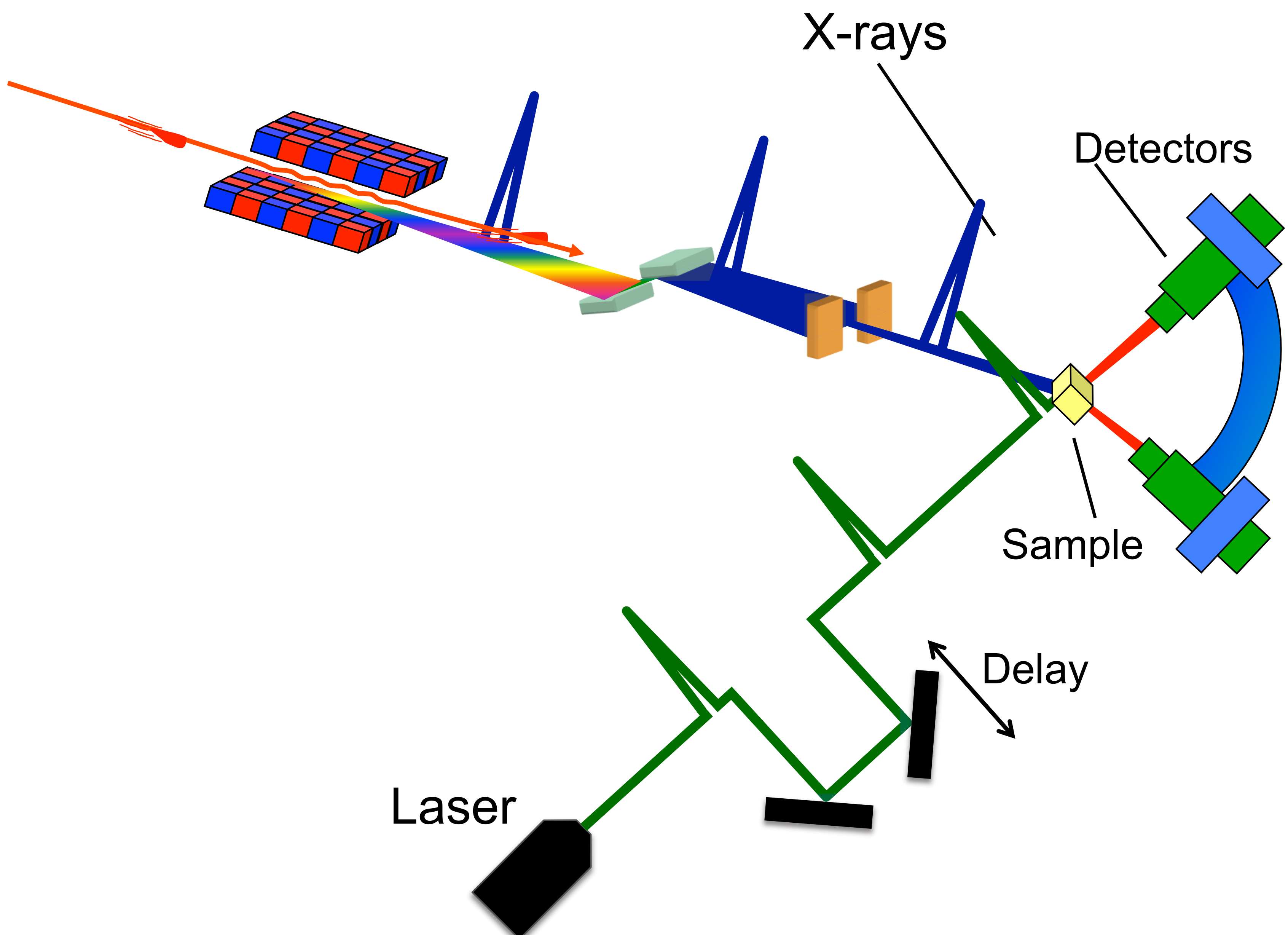
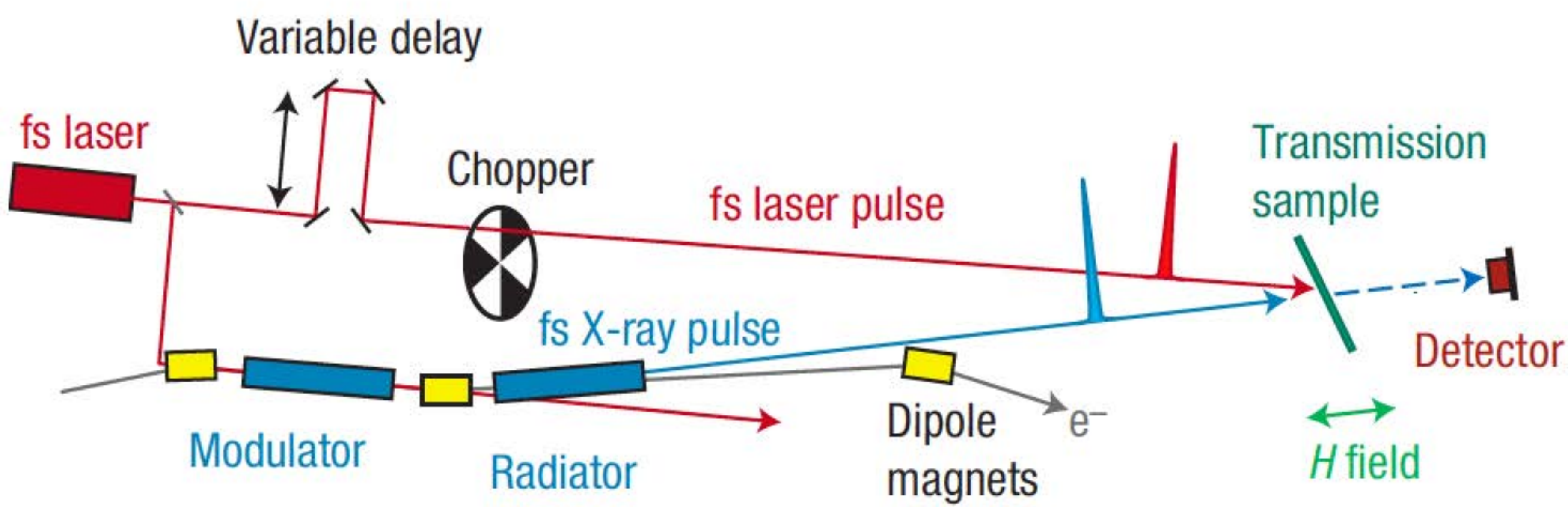


 nature materials | VOL 6 | OCTOBER 2007 | www.nature.com/naturematerials

Femtosecond modification of electron localization and transfer of angular momentum in nickel

C. STAMM[1], T. KACHEL[1], N. PONTIUS[1], R. MITZNER[1,2], T. QUAST[1], K. HOLLDACK[1], S. KHAN[1]*, C. LUPULESCU[1†], E. F. AZIZ[1], M. WIETSTRUK[1], H. A. DÜRR[1‡] AND W. EBERHARDT[1]



nature Vol 465 | 27 May 2010 | doi:10.1038/nature09070

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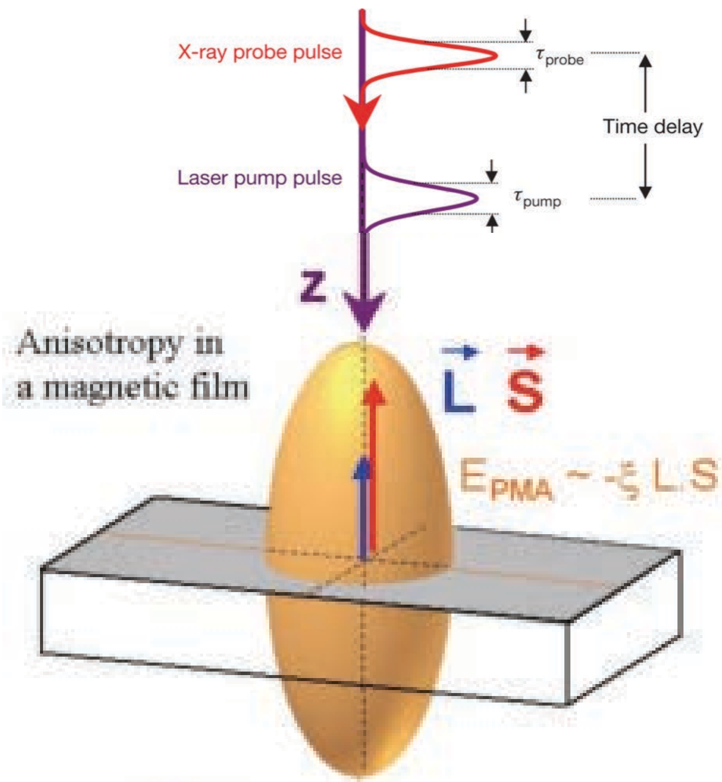
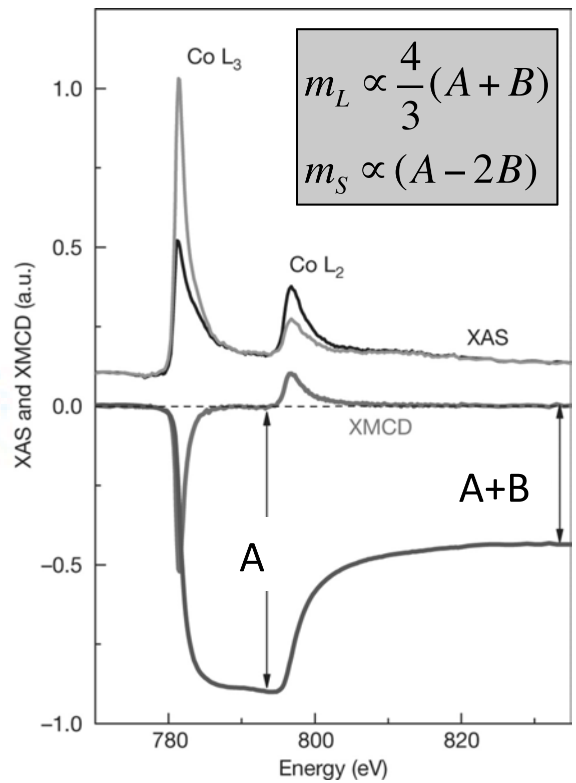
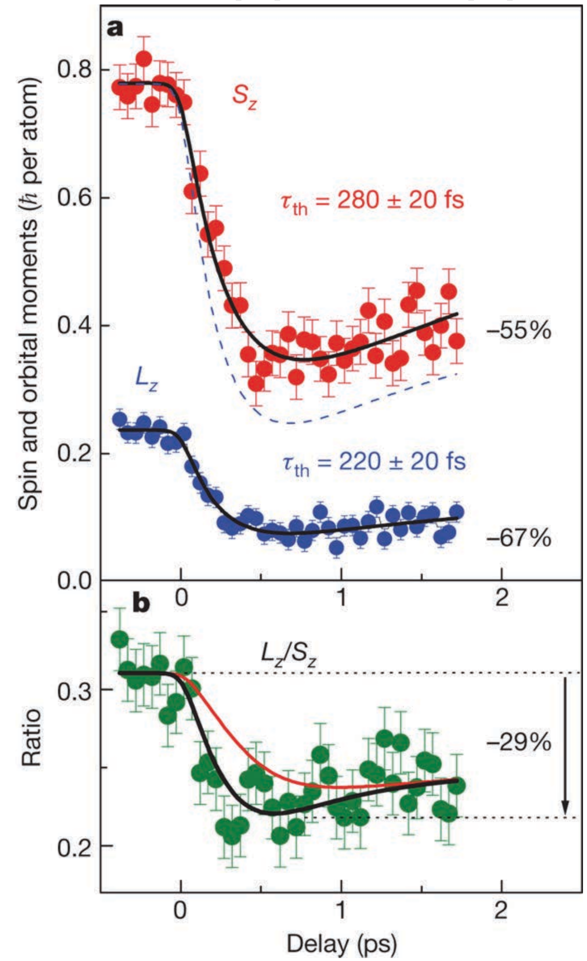
Distinguishing the ultrafast dynamics of spin and orbital moments in solids

C. Boeglin[1], E. Beaurepaire[1], V. Halté[1], V. López-Flores[1], C. Stamm[2], N. Pontius[2], H. A. Dürr[2]† & J.-Y. Bigot[1]





L(t) ≠ S(t)



Absorption of fs laser generates ultrafast changes in the electronic and spin structure

Ultrafast control of information in magnetic recording media??

Challenges in magnetism

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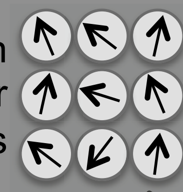
SIZE

Magnetic domains

↑↑↑↑↑↑↑↓↓↓↓↓↓

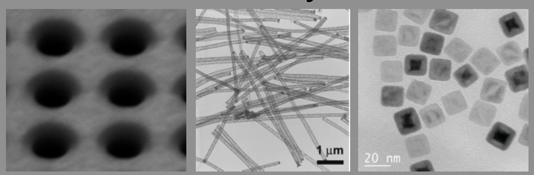
Non collinear structures



~100 µm ~ 1nm

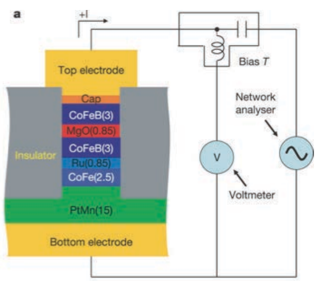
Magnetism: Interplay of interactions on different length scales

Effect of boundary conditions?

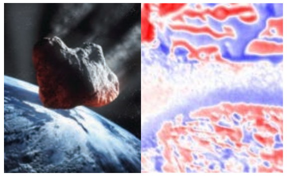


CHEMICAL COMPLEXITY

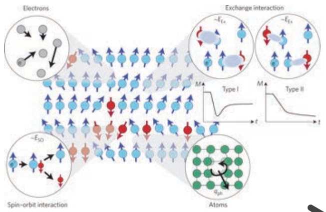
Spintronics:
Need for element specific techniques



TIME



data retention



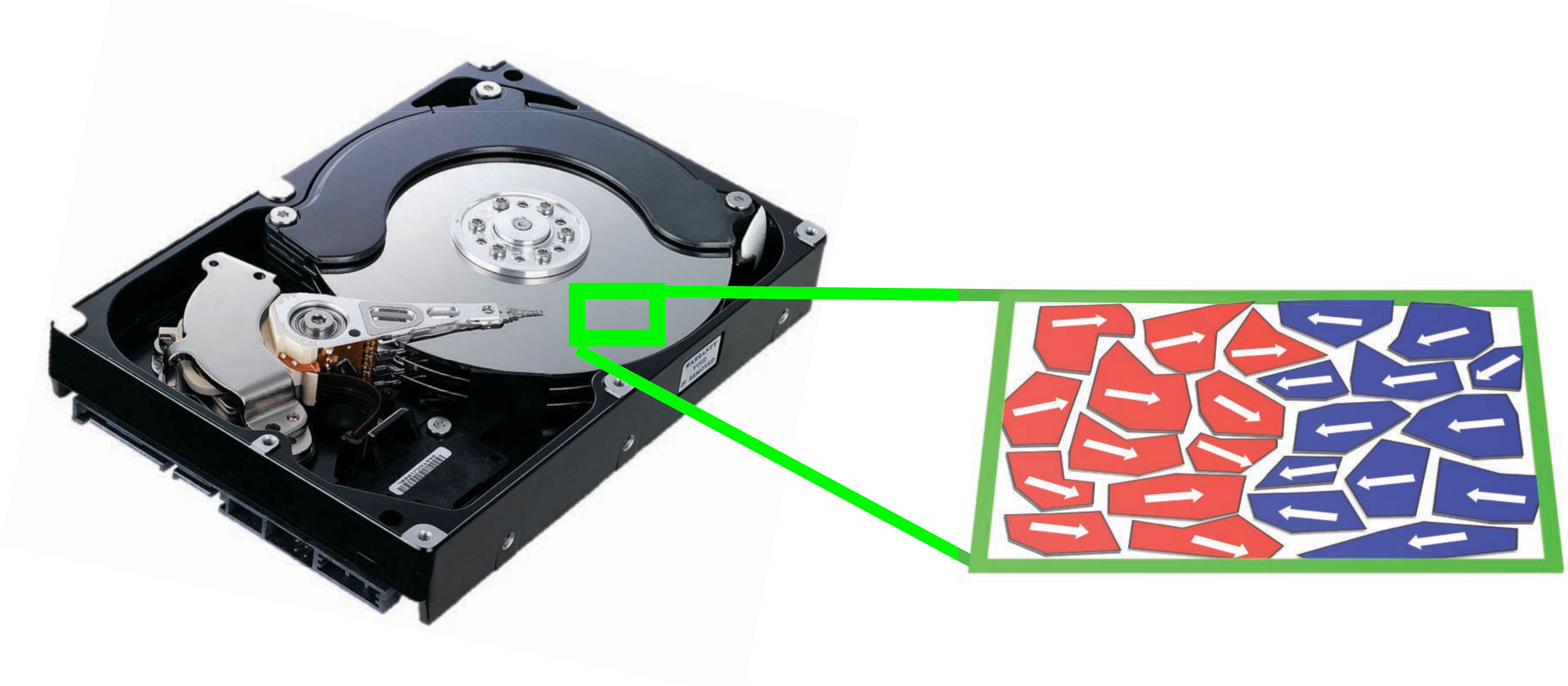
~10^8 years ~10 years ~ femtoseconds

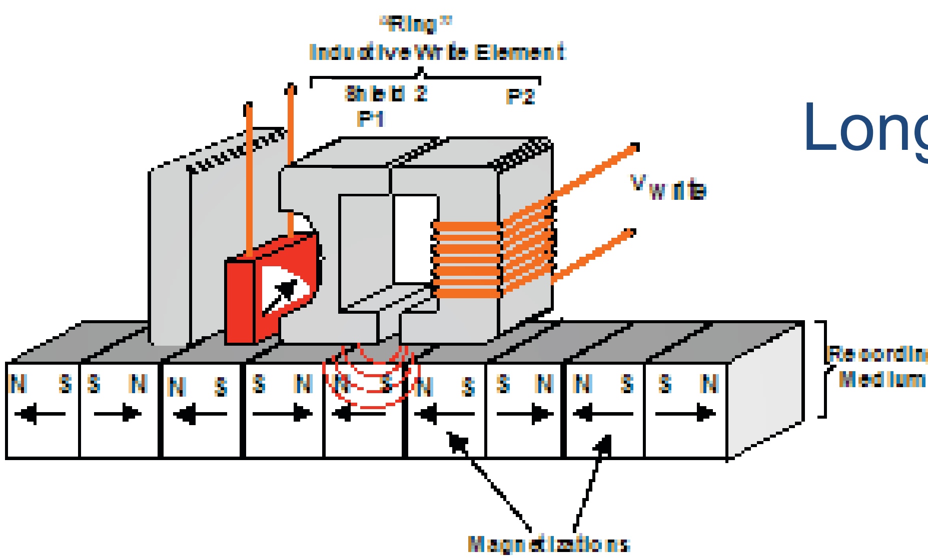
M. Reversal @ different time scales

Magnetic fields
Spin polarized currents
Laser

How fast the magnetization can be reversed?

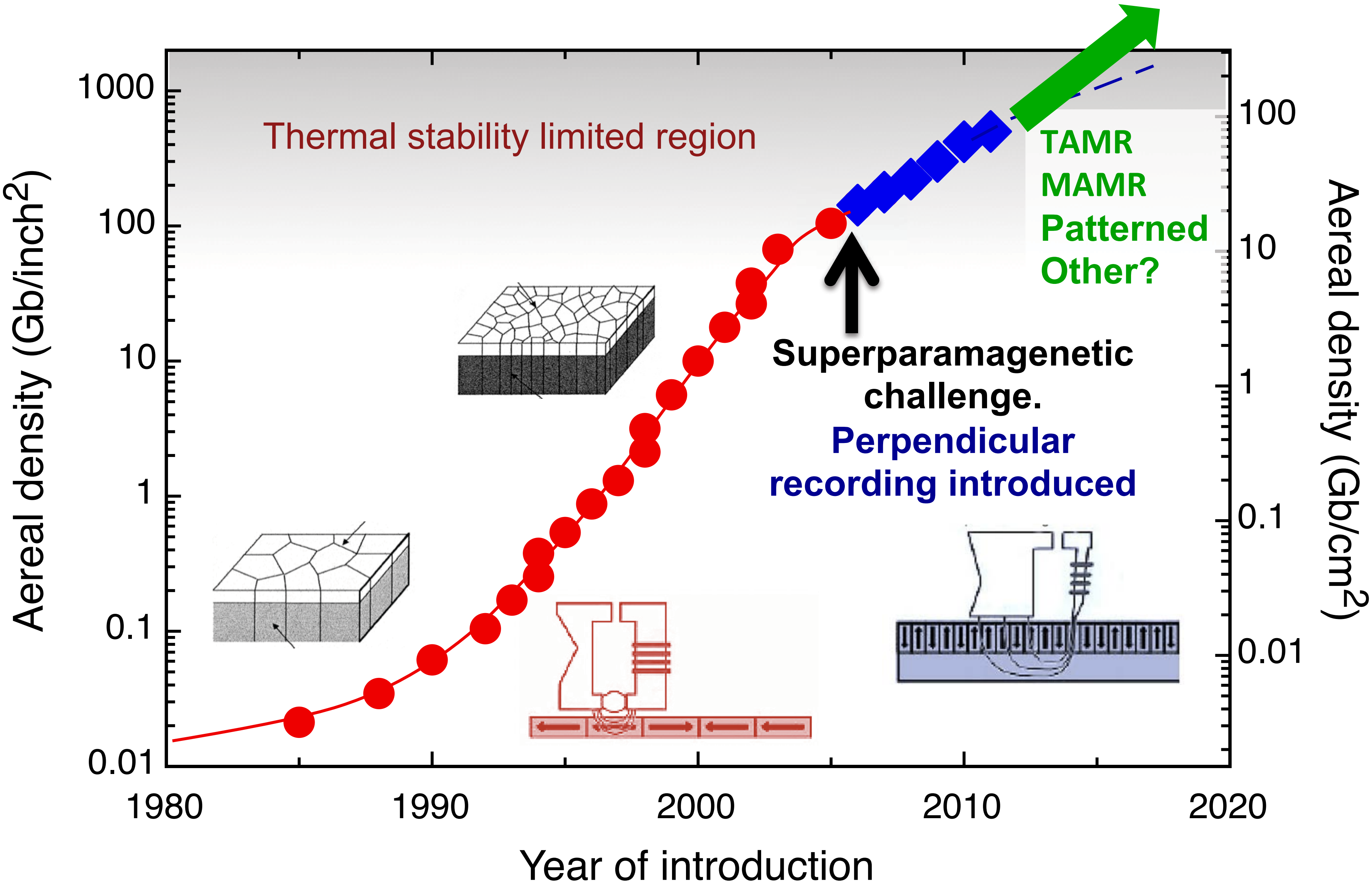
Magnetic Recording Media





Longitudinal recording

Magnetic Recording Media



TAMR (or HAMR): Thermally Assisted Magnetic Recording technology
MAMR: Microwave Assisted Magnetic Recording technology

IEEE TRANSACTIONS ON MAGNETICS, VOL. 49, NO. 2, FEBRUARY 2013 693

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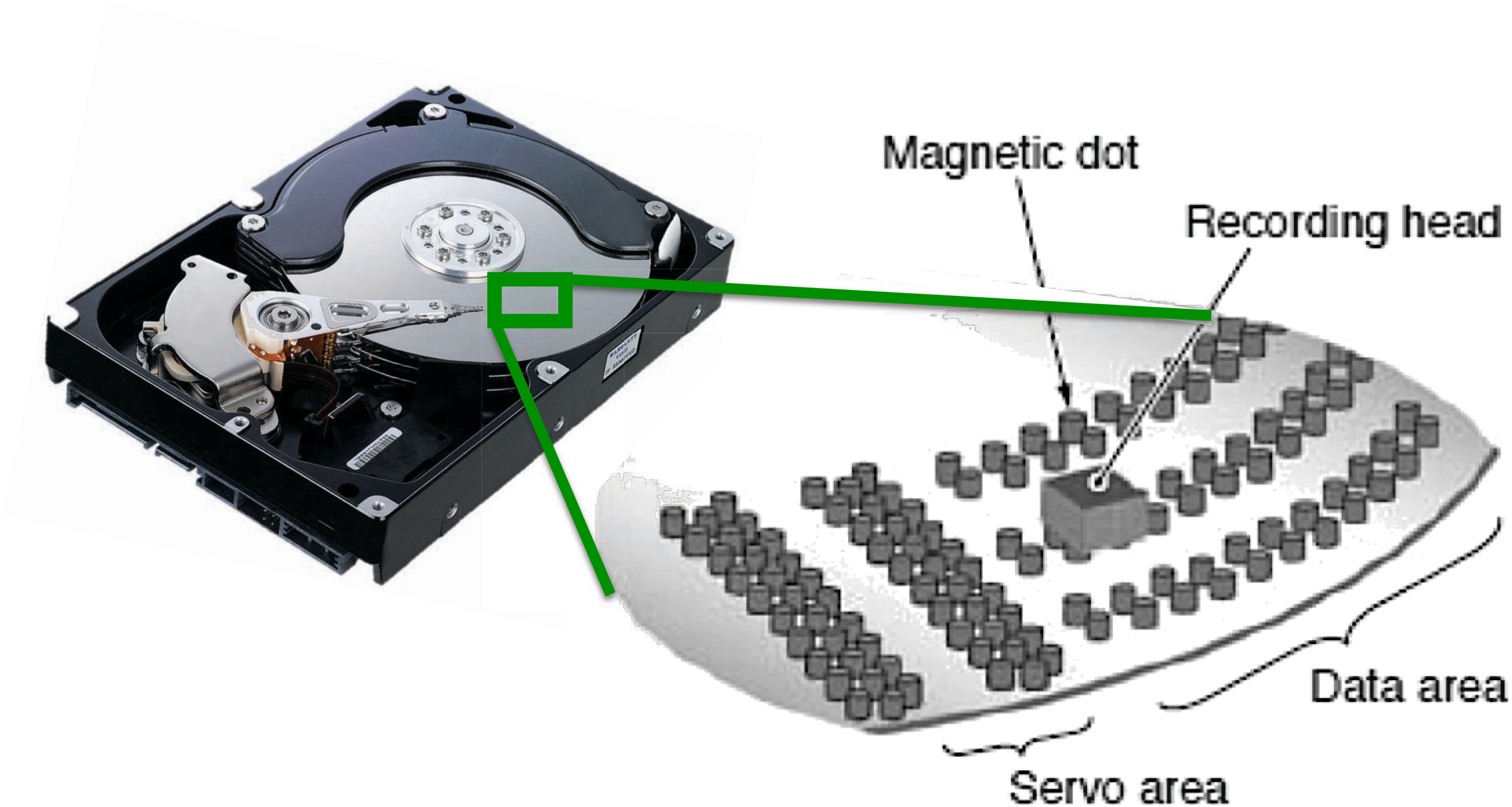
5 Tdots/in^2 Bit Patterned Media Fabricated by a Directed Self-Assembly Mask

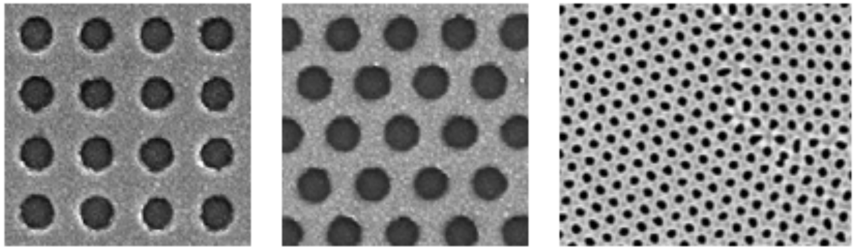
Akira Kikitsu, Tomoyuki Maeda, Hiroyuki Hieda, Ryosuke Yamamoto, Naoko Kihara, and Yoshiyuki Kamata

Toshiba Corporation, R&D Center, Storage Materials and Devices Laboratory, Kawasaki, Kanagawa 212-8582, Japan

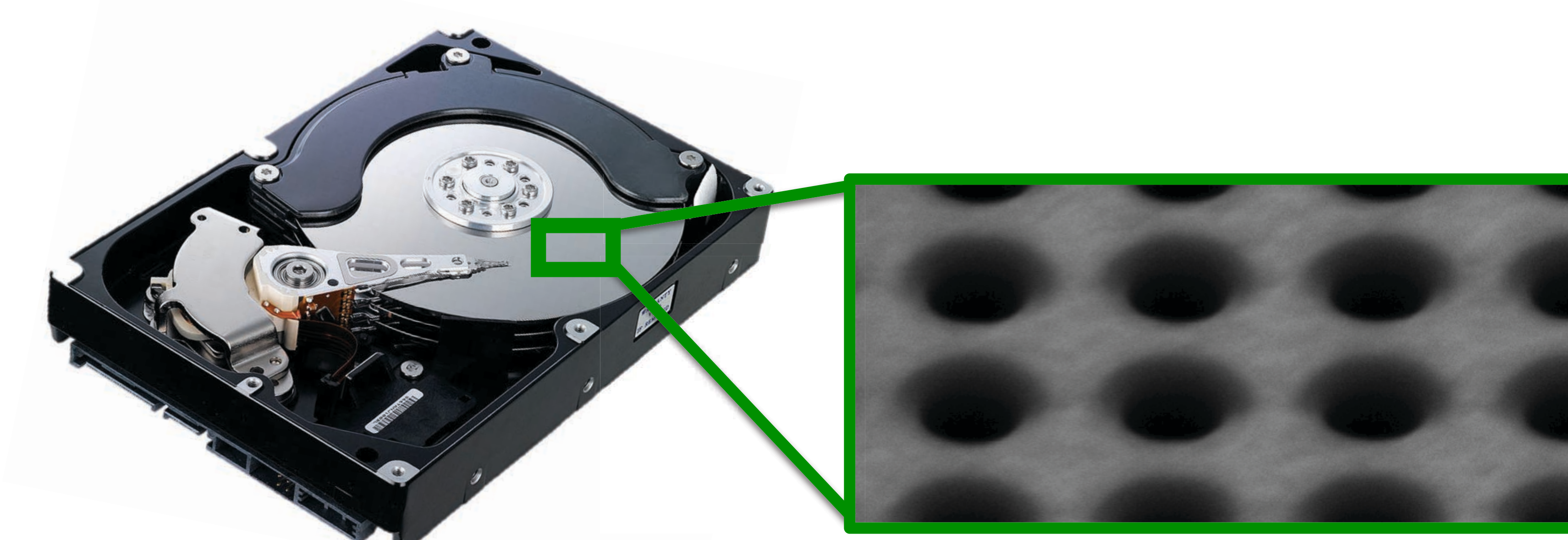


Schematic image of BPM

Magnetic Antidot arrays



Magnetic thin film with an array of non-magnetic inclusions or holes



Magnetic Antidot arrays

Store bits of information in individual magnetic entities

Control of magnetic properties (Enhancement of coercivity, control of the anisotropy)

Photo Emission Electron Microscopy

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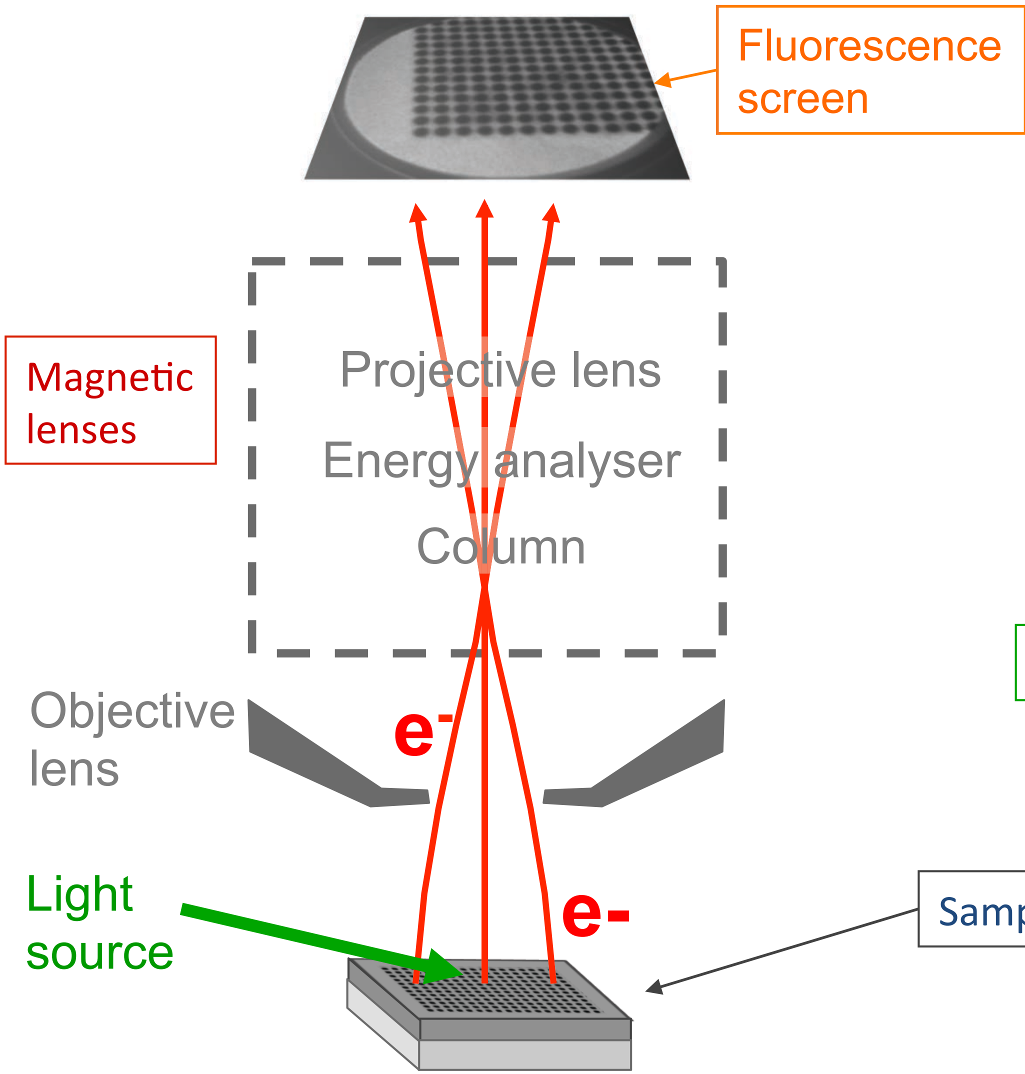
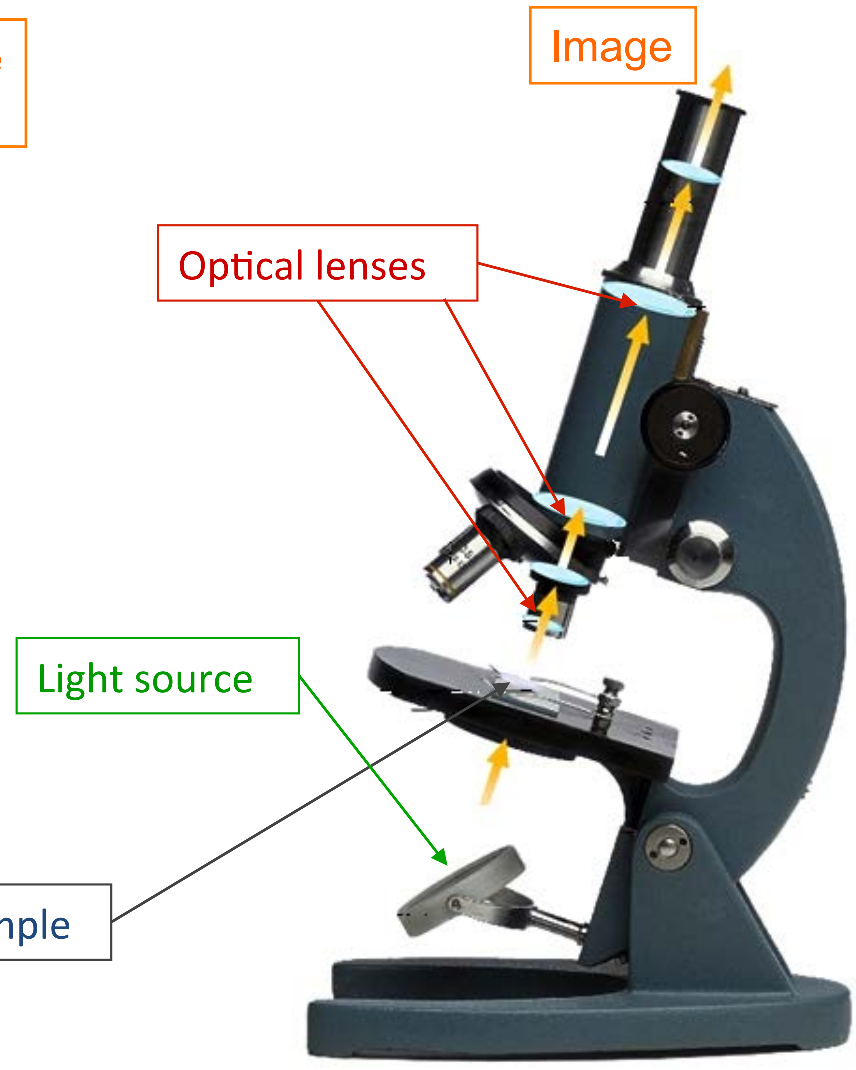
Photo Emission Electron Microscopy

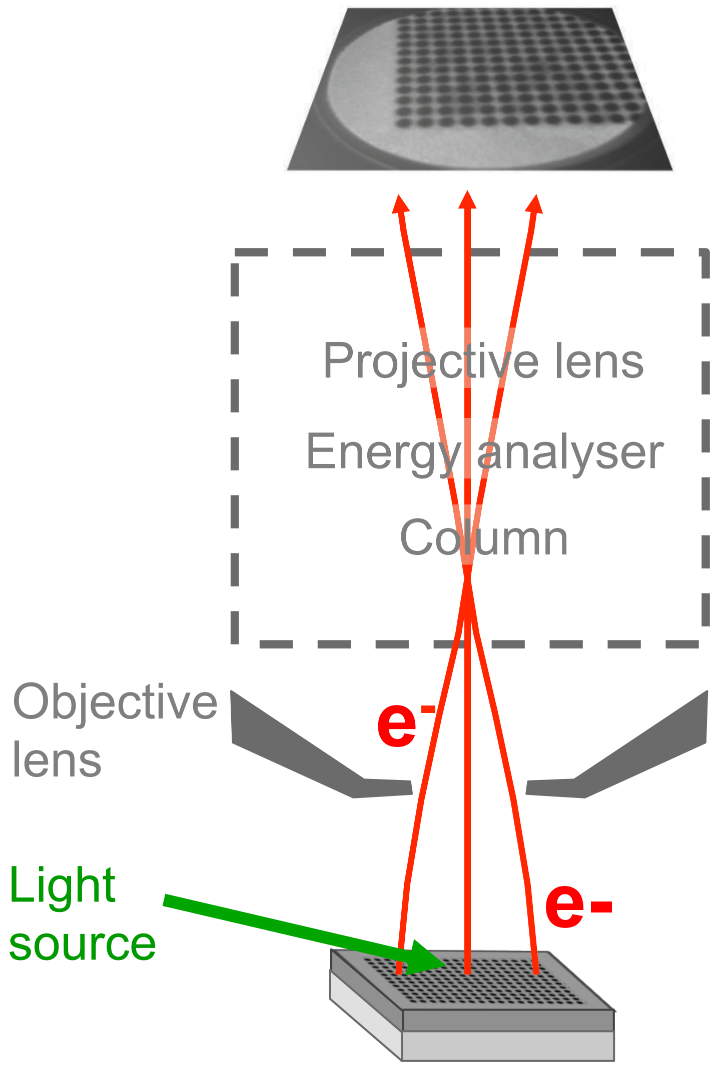


Sample

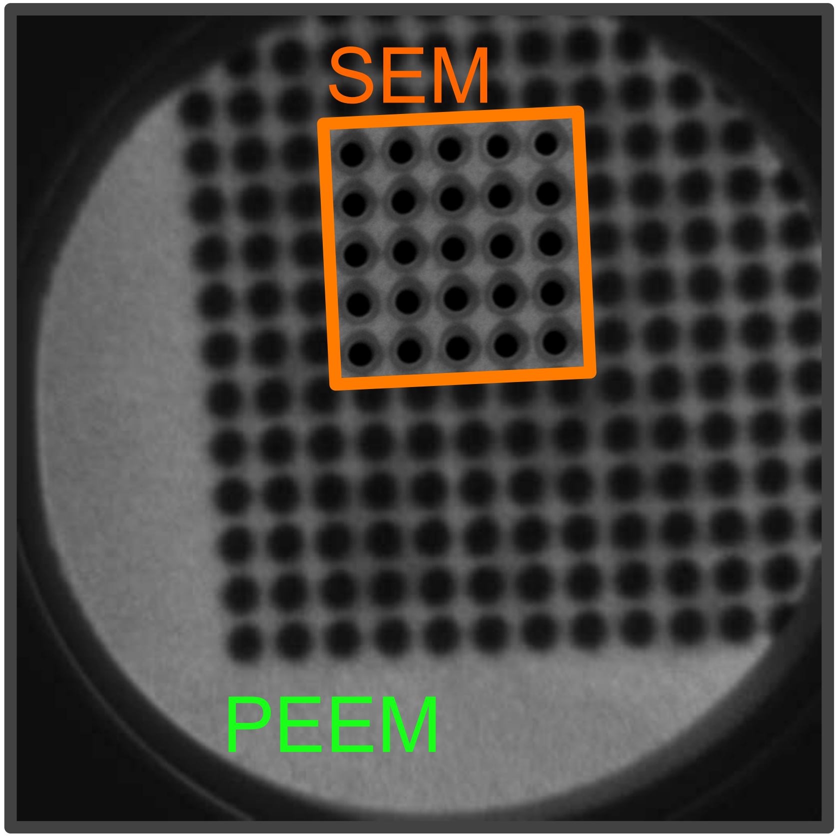
Optical Microscope



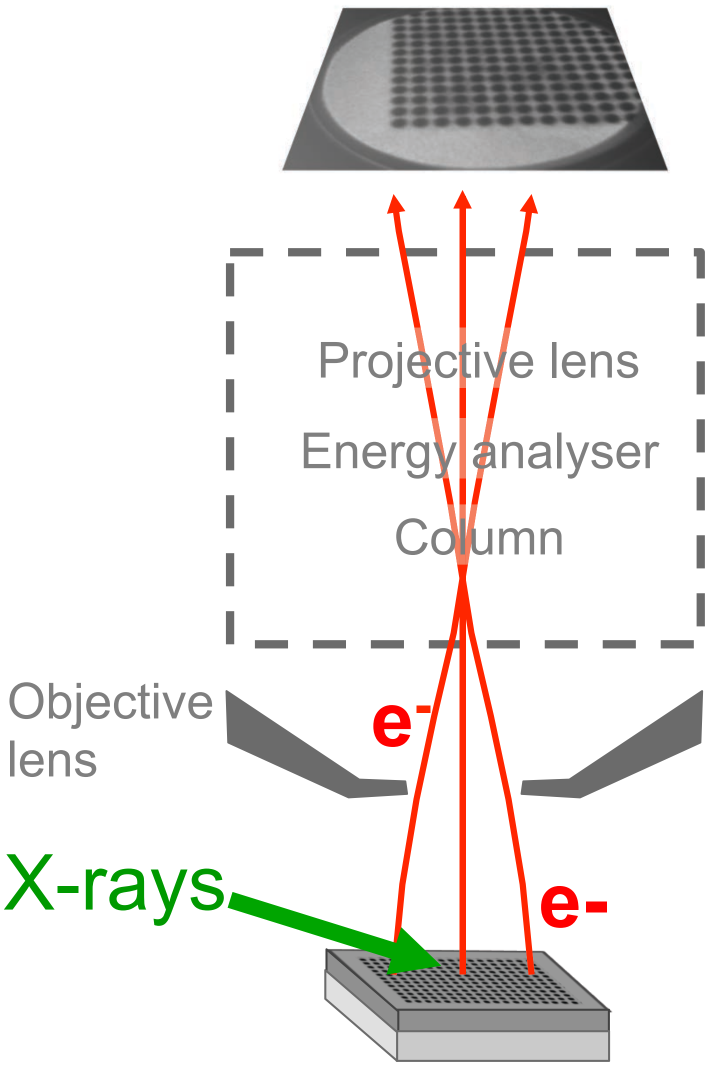
PhotoEmission Electron Microsopy



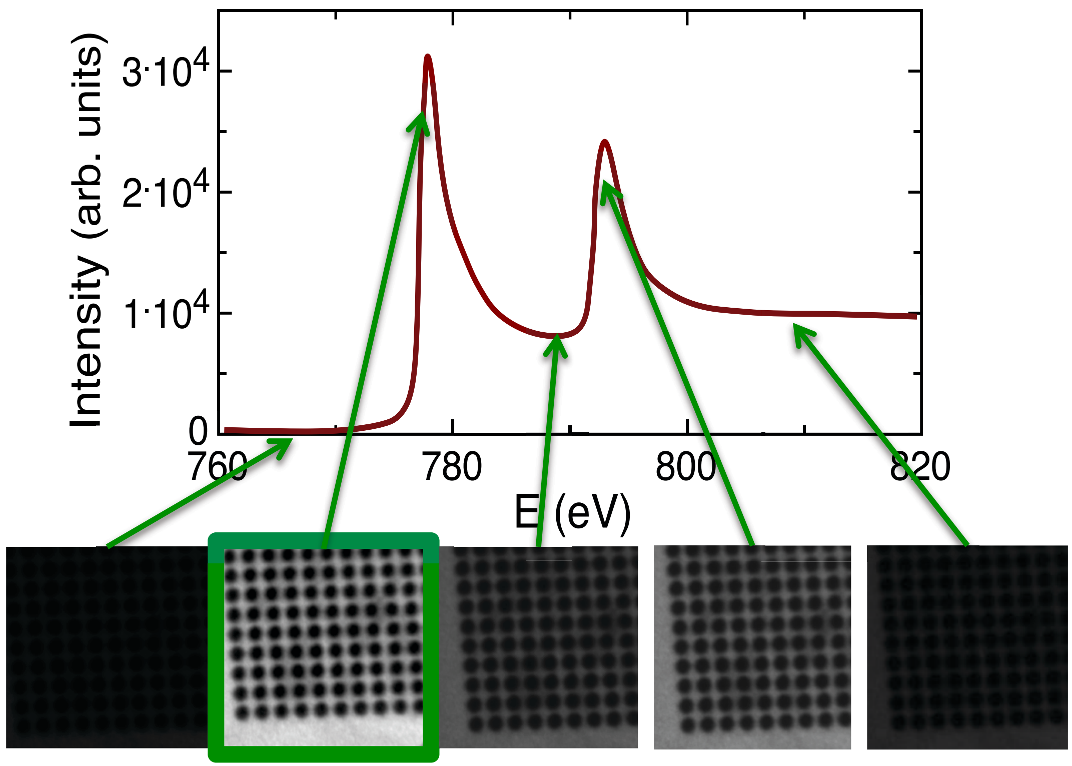
- Imaging: spatial resolution (~ 30 nm)



X-PEEM: spectro-microscopy

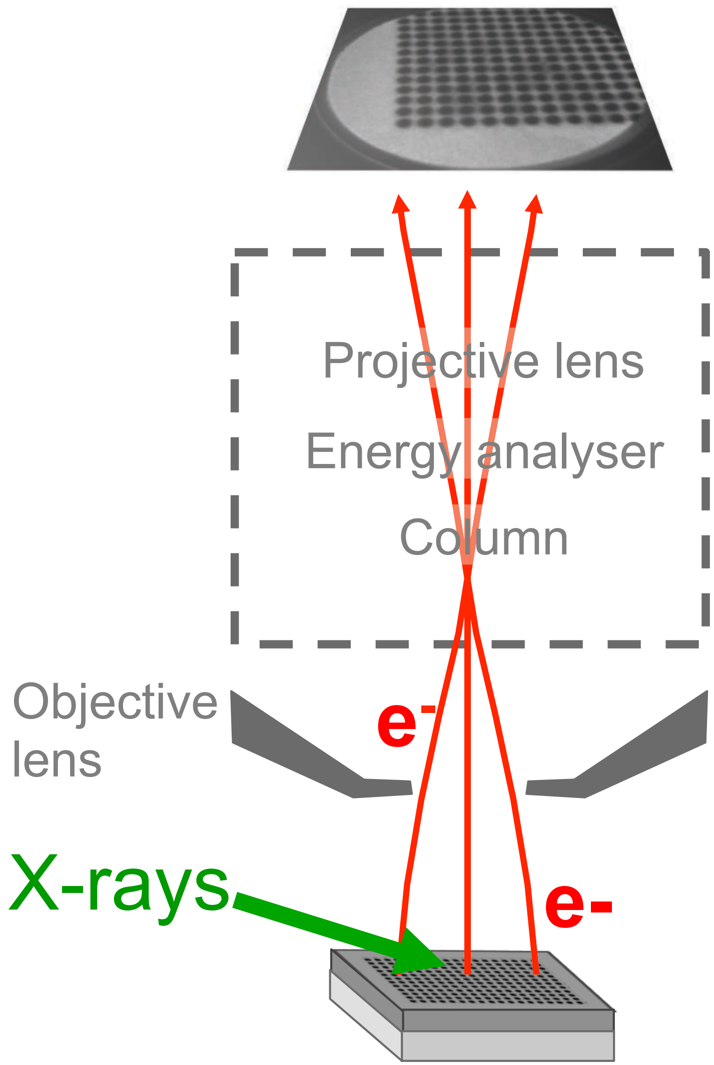


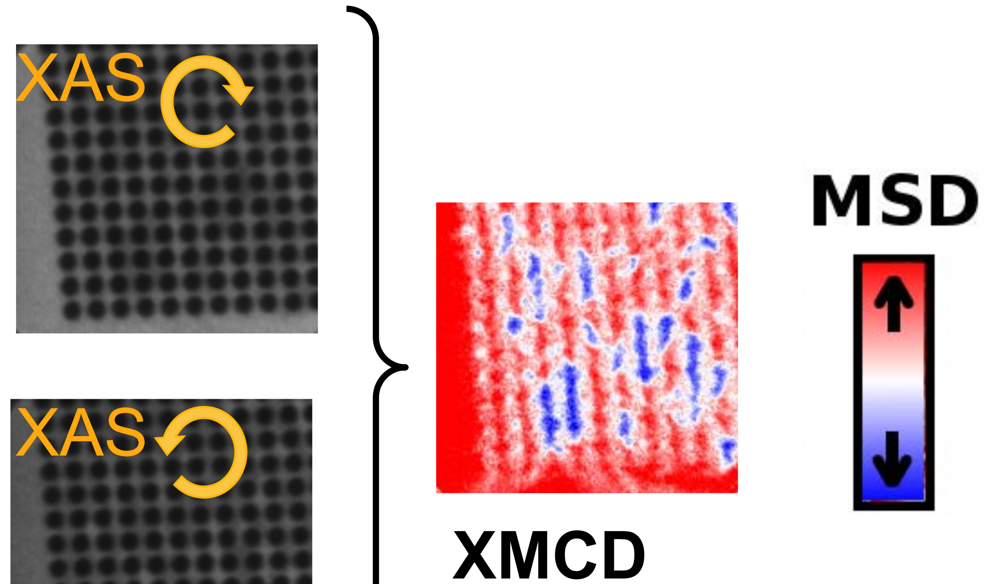
- Imaging: spatial resolution (~ 30 nm)
- Spectroscopy and element specific images



Magnetic spectro-microscopy

- Imaging: spatial resolution (~ 30 nm)
- Spectroscopy and element specific images
- Access to buried layers
- XMCD: magnetic spectroscopy and imaging





Element and band selective

Magnetization sensitive

Magnetic antidot to dot crossover in Co and Py nano-patterned thin films
Submitted

C. Castán-Guerrero,[1,2,*] J. Herrero-Albillos,[1,3,4] J. Bartolomé,[1,2] F. Bartolomé,[1,2] L. A. Rodríguez,[5,2,6] C. Magén,[5,2,3] F. Kronast,[7] P. Gawronski,[8] O. Chubykalo-Fesenko,[9] K. J. Merazzo,[9] P. Vavassori,[10] P. Strichovanec,[5,2] J. Sesé,[5,2] and L. M. García[1,2]

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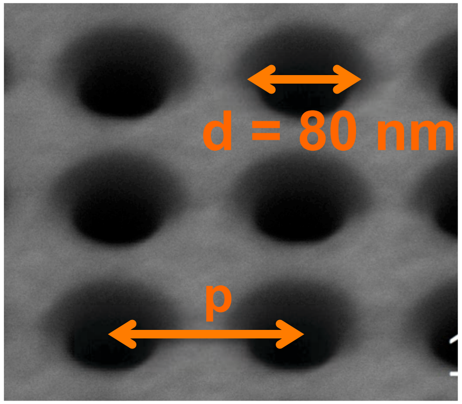
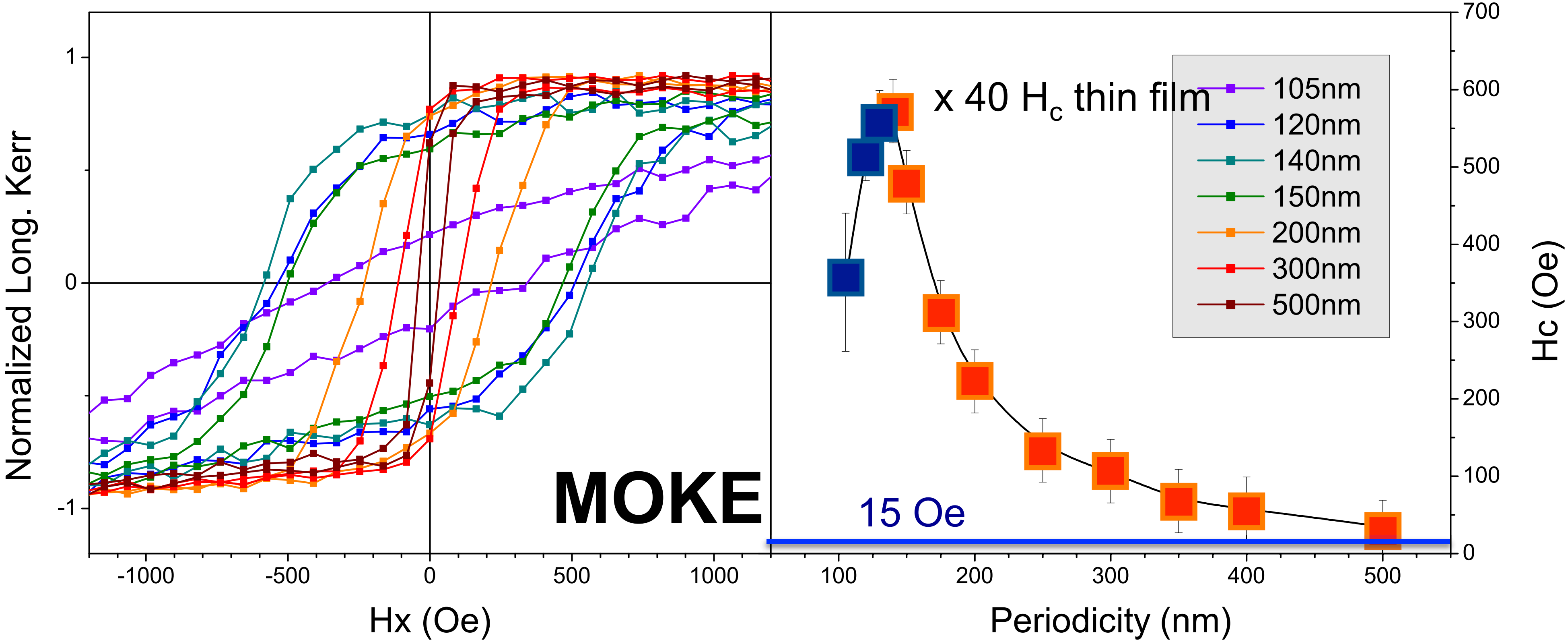


MOKE Hysteresis loops

Nominal antidot diameter: d = 80 nm

Periodicity: p = 500 – 105 nm



Magnetic antidot to dot crossover in Co and Py nano-patterned thin films

Submitted

C. Castán-Guerrero,[1,2,*] J. Herrero-Albillos,[1,3,4] J. Bartolomé,[1,2] F. Bartolomé,[1,2] L. A. Rodríguez,[5,2,6] C. Magén,[5,2,3] F. Kronast,[7] P. Gawronski,[8] O. Chubykalo-Fesenko,[9] K. J. Merazzo,[9] P. Vavassori,[10] P. Strichovanec,[5,2] J. Sesé,[5,2] and L. M. García[1,2]

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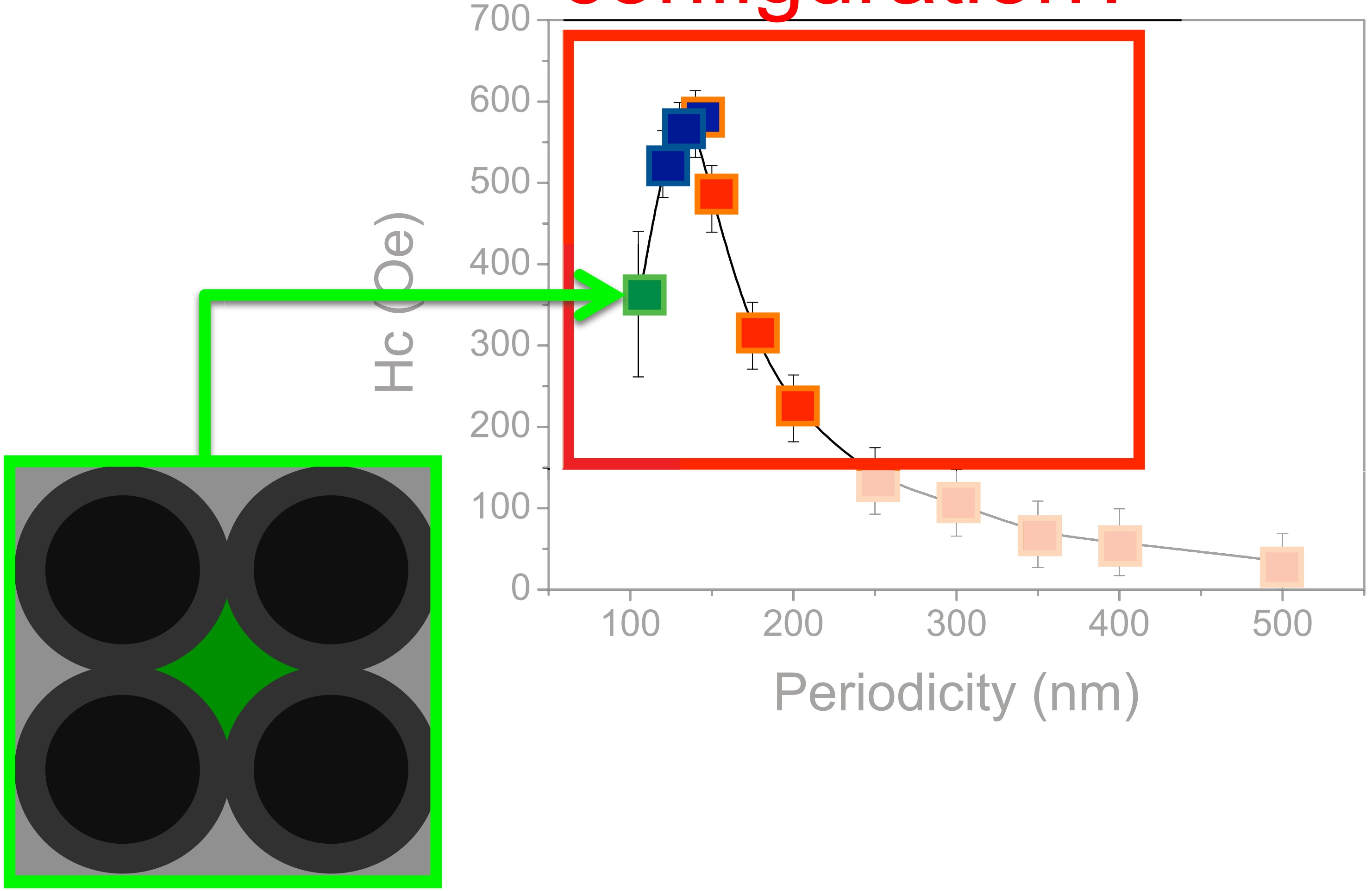
Domain configuration?



Coercive field vs geometry

Magnetic antidot to dot crossover in Co and Py nano-patterned thin films
Submitted

C. Castán-Guerrero,[1,2,*] J. Herrero-Albillos,[1,3,4] J. Bartolomé,[1,2] F. Bartolomé,[1,2] L. A. Rodríguez,[5,2,6] C. Magén,[5,2,3] F. Kronast,[7] P. Gawronski,[8] O. Chubykalo-Fesenko,[9] K. J. Merazzo,[9] P. Vavassori,[10] P. Strichovanec,[5,2] J. Sesé,[5,2] and L. M. García[1,2]

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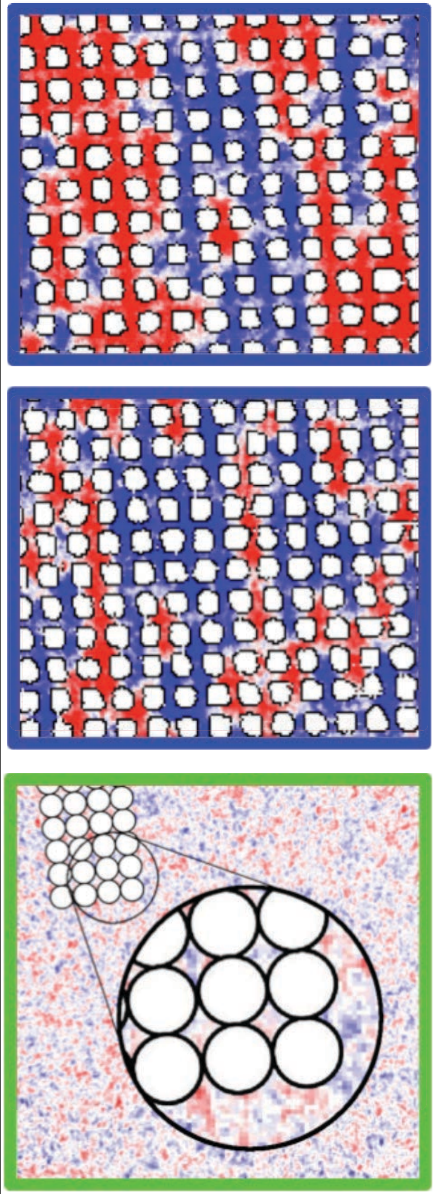
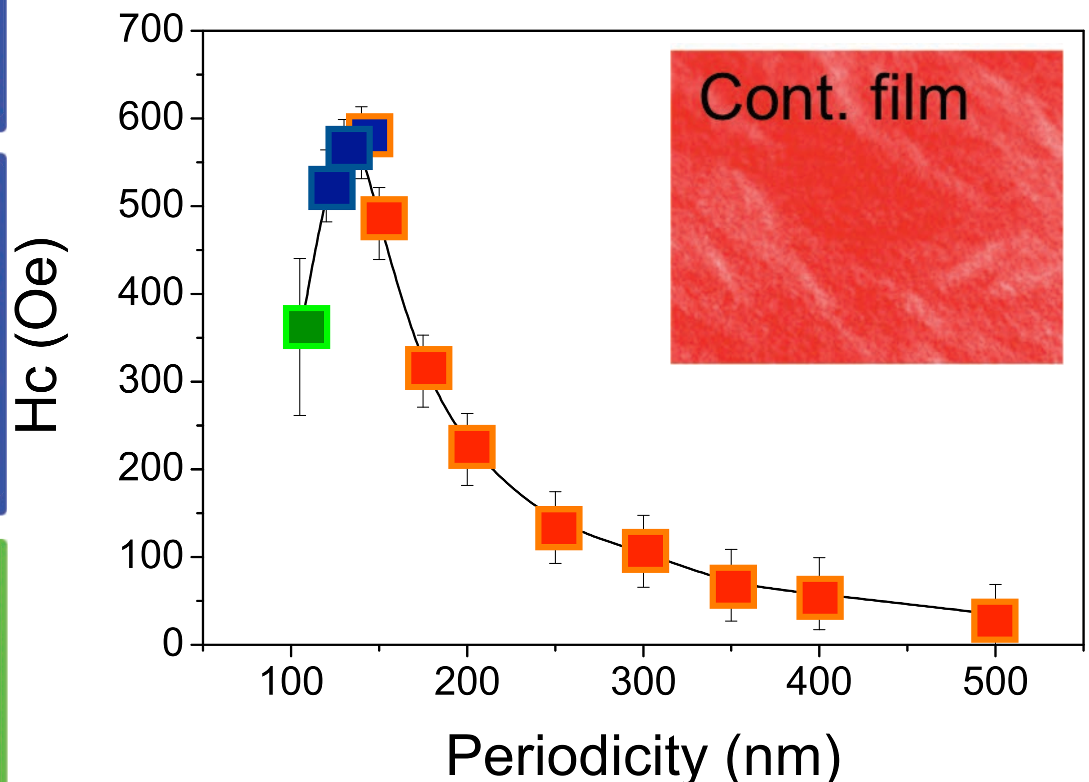
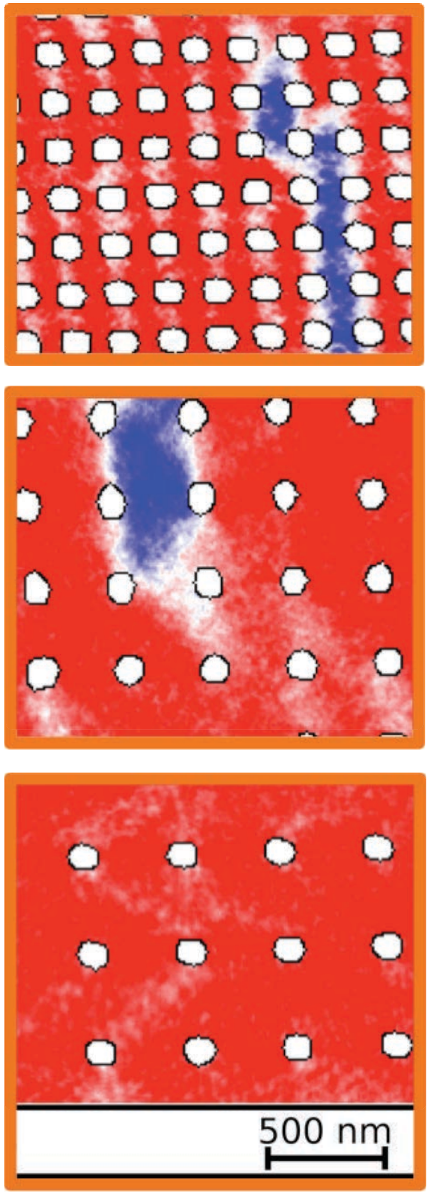
X-PEEM: XMCD images





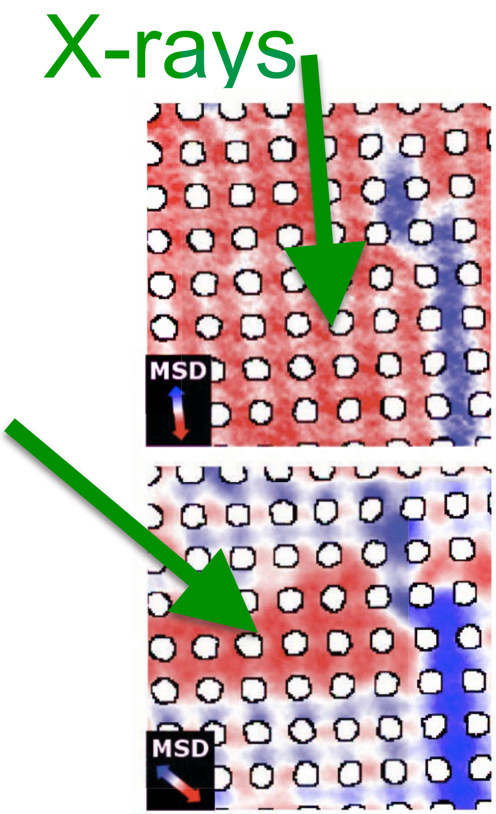


2D magnetization maps

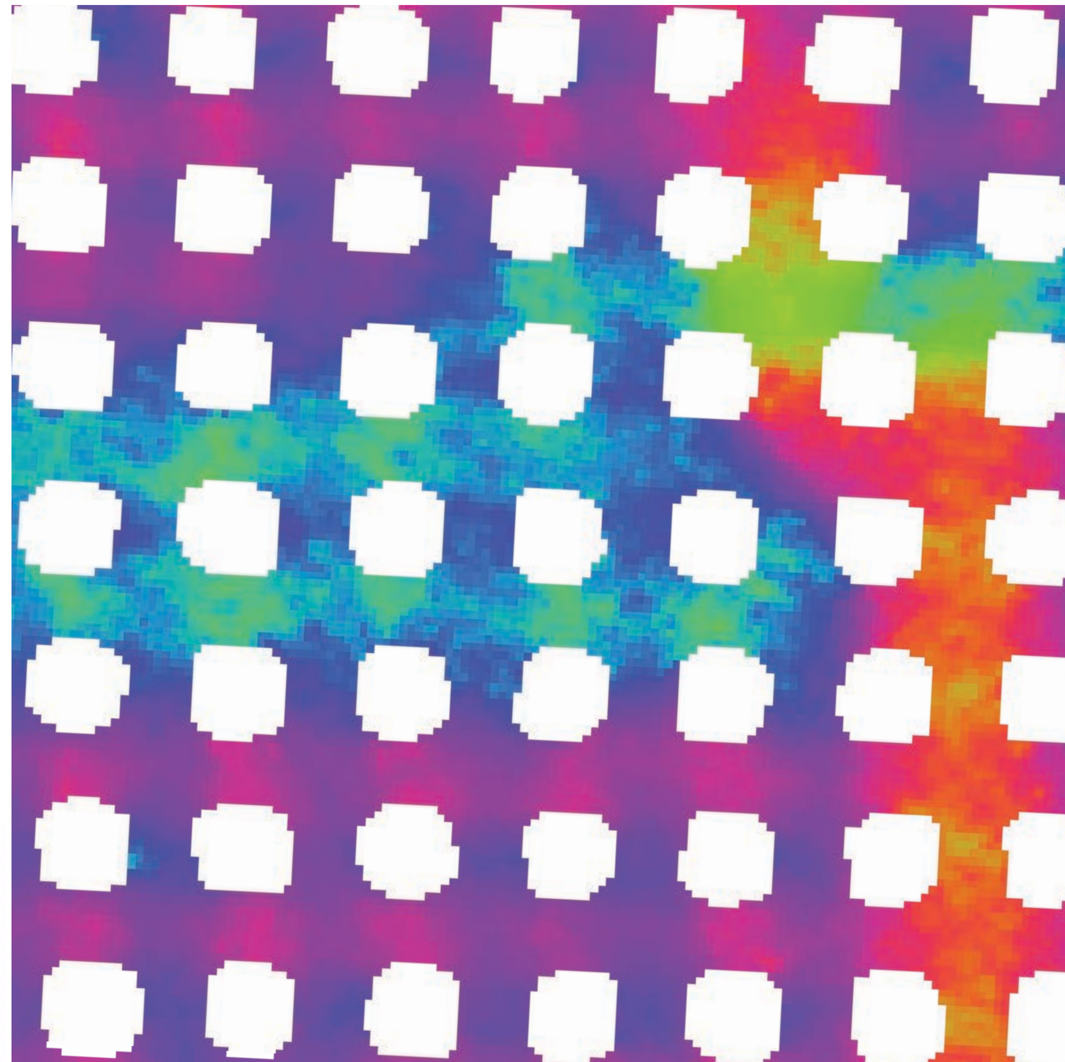
XPEEM images.

Red and blue areas:

DOMAINS (projected)



2D magnetization map



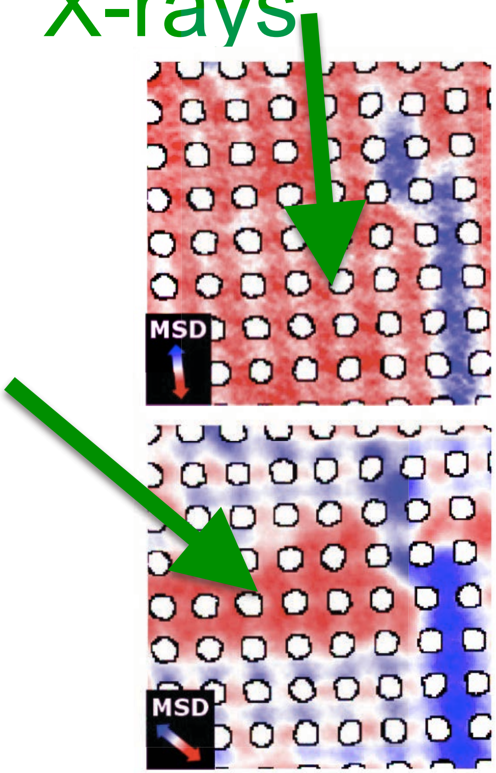
2D magnetization maps

XPEEM images.

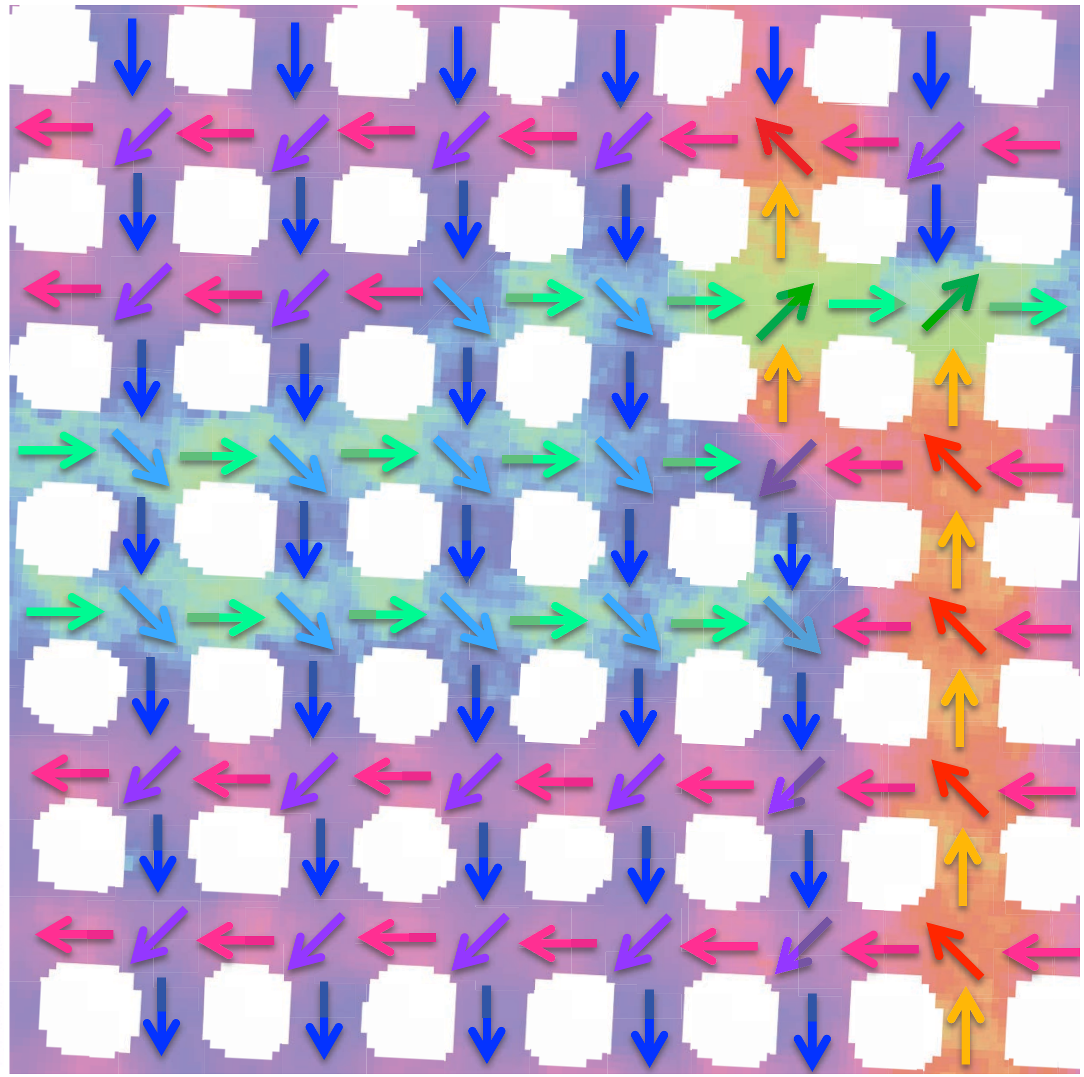
Red and blue areas:

DOMAINS (projected)

X-rays



2D magnetization map



Chemical and magnetic microscopy

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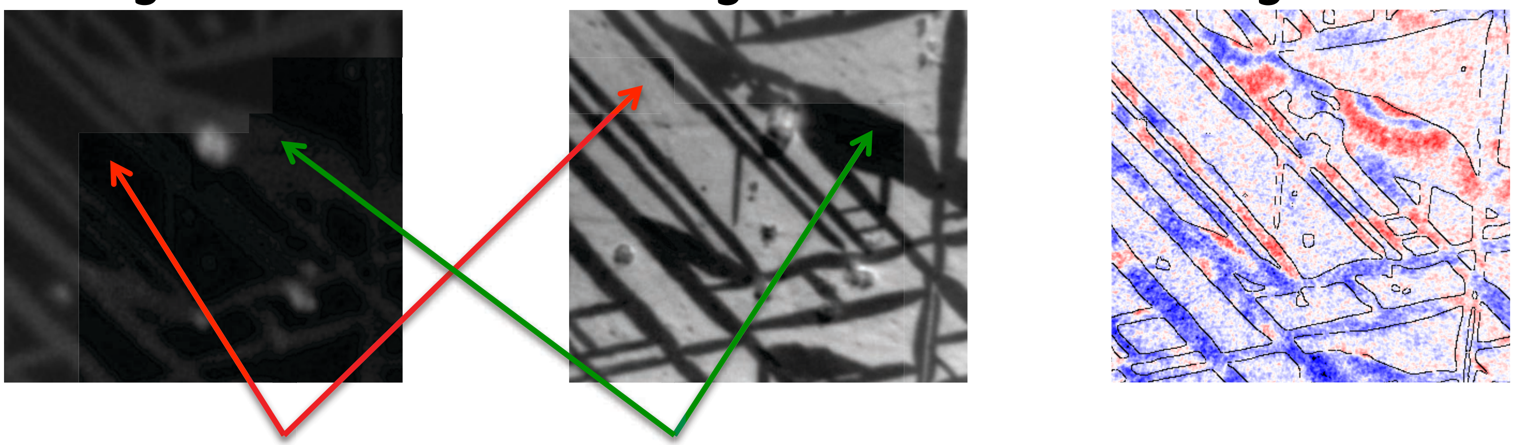
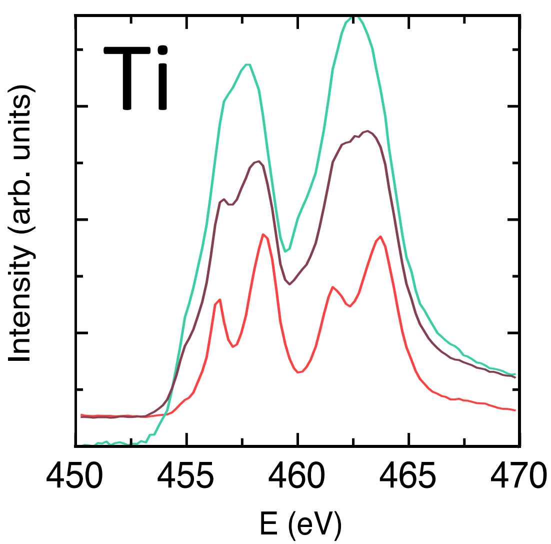
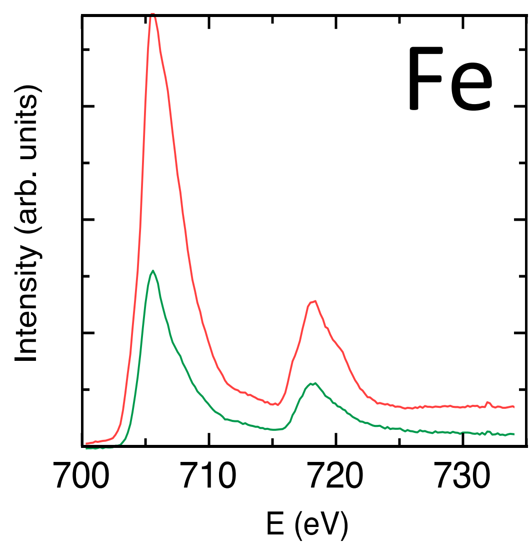
Titanomagnetite (FM) - Titanohematite (PM/AF/FM) intergrowths

Ti L_3 XAS | **Fe L_3 XAS** | **Fe L_3 XMCD**



Fe_3O_4-Fe_2TiO_4 | Fe_2O_3-$FeTiO_3$





Richard Harrison
James F.J. Bryson
Gerrit van der Laan
Simon A.T. Redfern
Florian Kronast

X-PEEM: imaging with magnetic field

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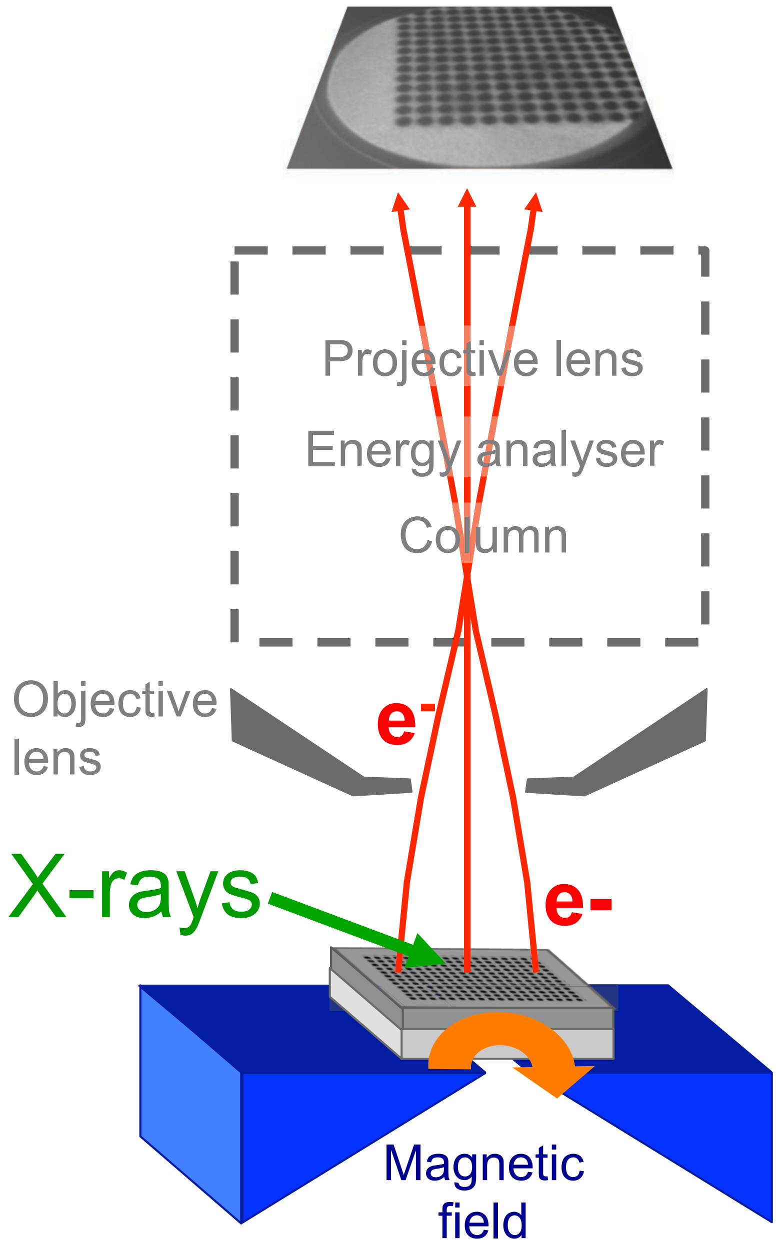
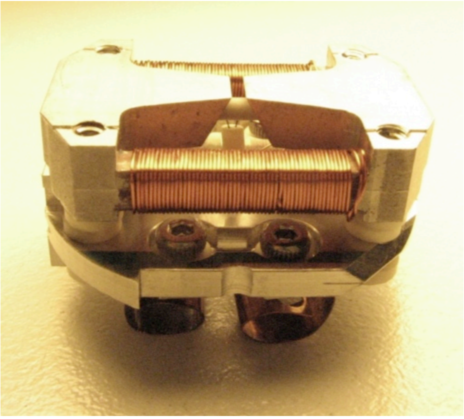


- Imaging: spatial resolution (~ 30 nm)
- Spectroscopy and element specific images
- Access to buried layers
- XMCD: magnetic spectroscopy and imaging
- In-plane magnetic field while imaging (up to 100 mT)

Custom made sample holders:

No deterioration of spatial resolution

Low remanence field



Hysteresis loops of individual pixels

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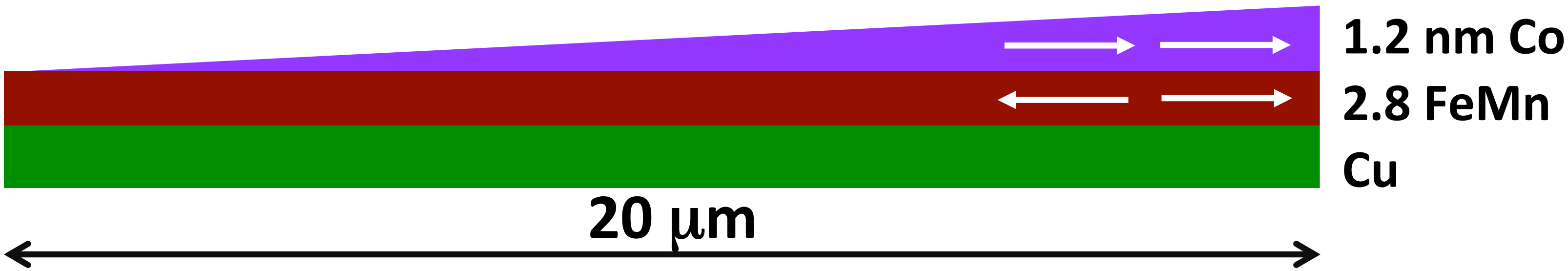
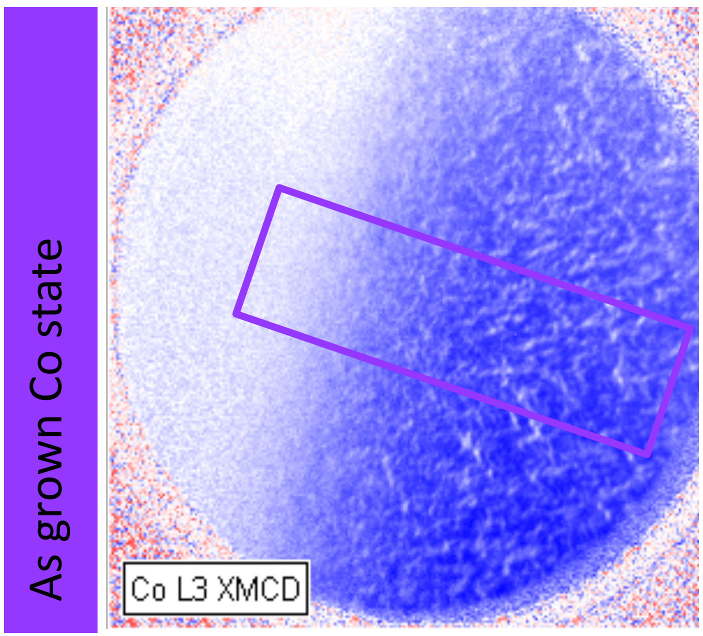


Co L3 edge XMCD

<u>Co wedge:</u>
Study the influence of the FM thickness.

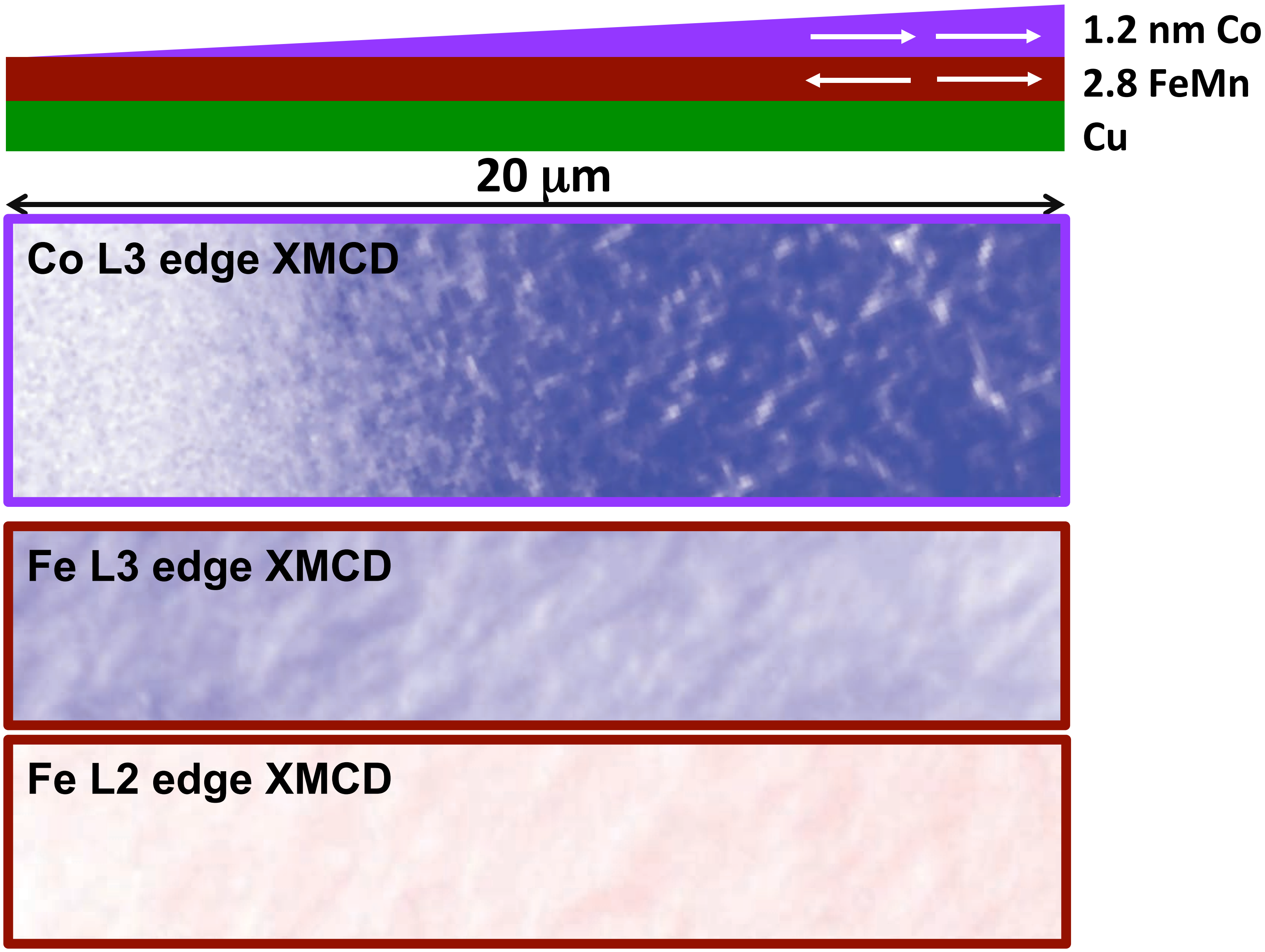
<u>X-PEEM:</u>
Image from zero to several
Nanometers thick simultaneously!

Fe L2 edge XMCD

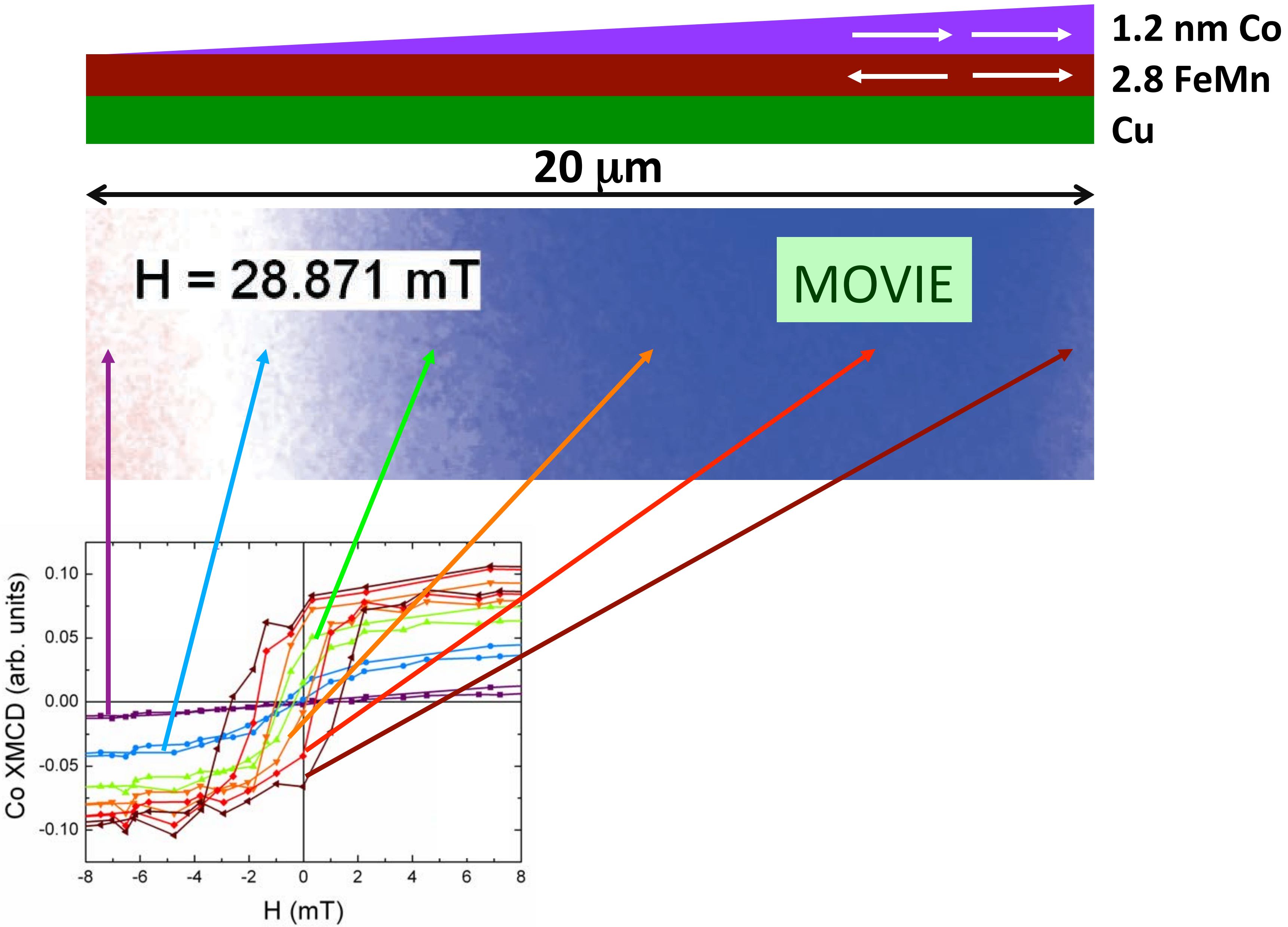


Hysteresis loops of individual pixels

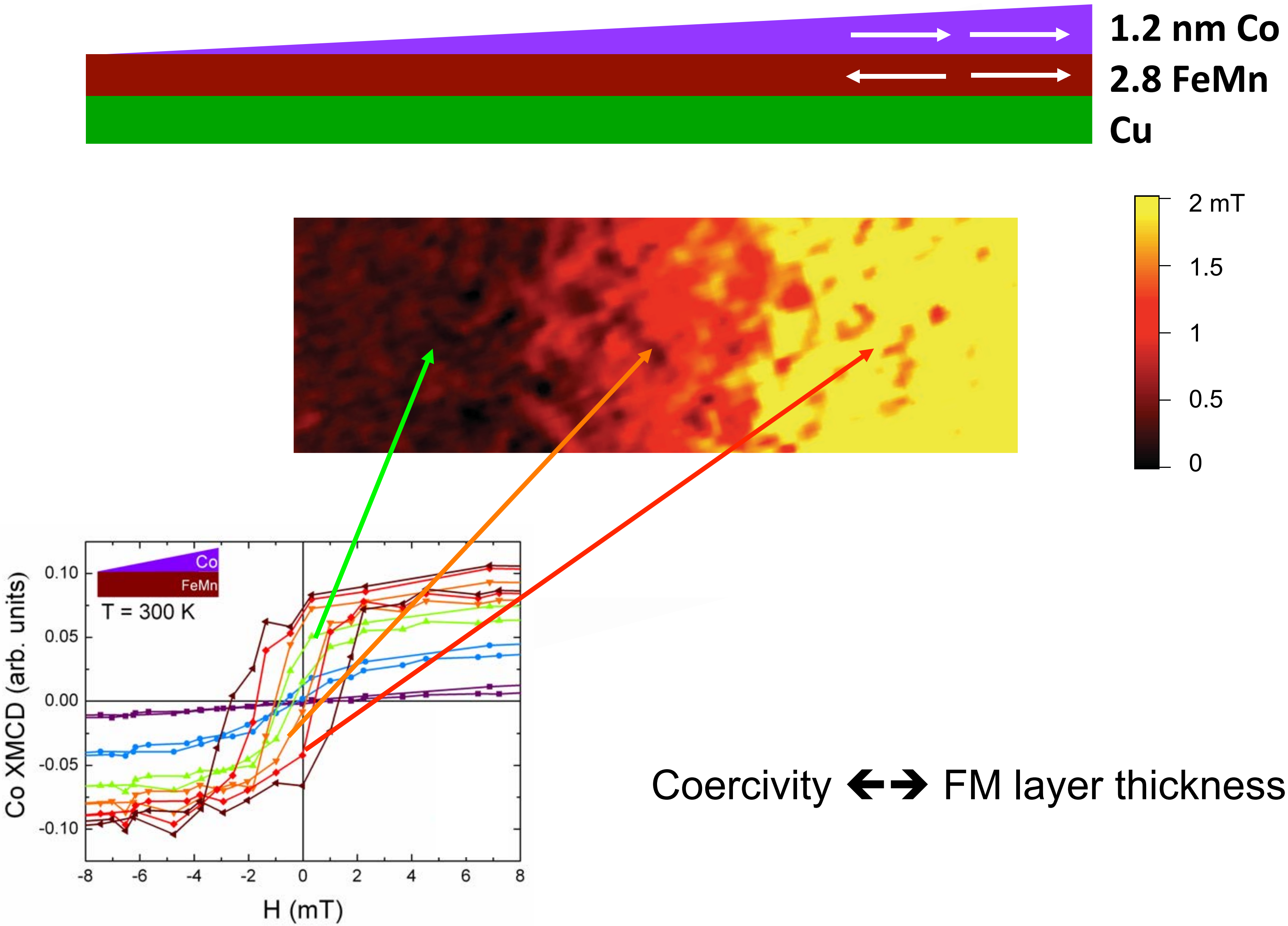
Centro Universitario de la Defensa Zaragoza



Hysteresis loops of individual pixels



Hysteresis loops of individual pixels



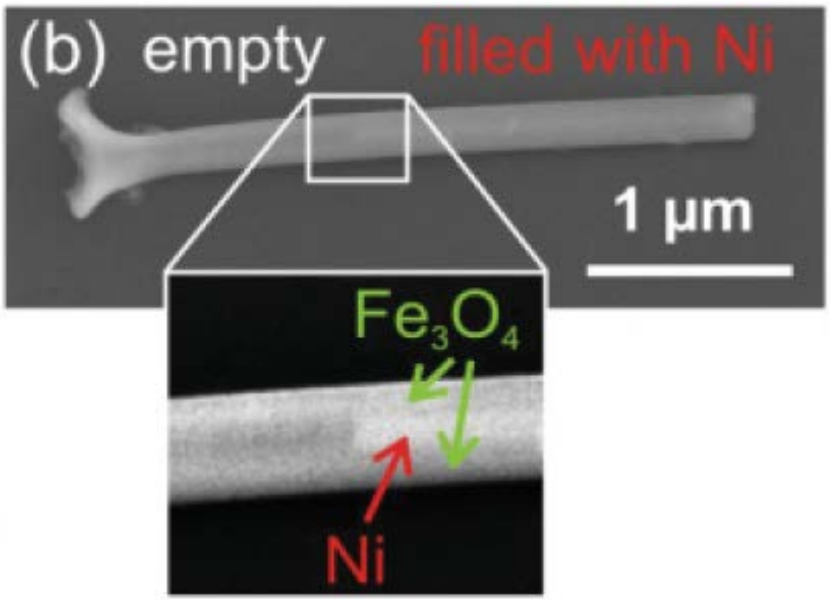
Coercivity ⇔ FM layer thickness

PHYSICAL REVIEW B 84, 174406 (2011)

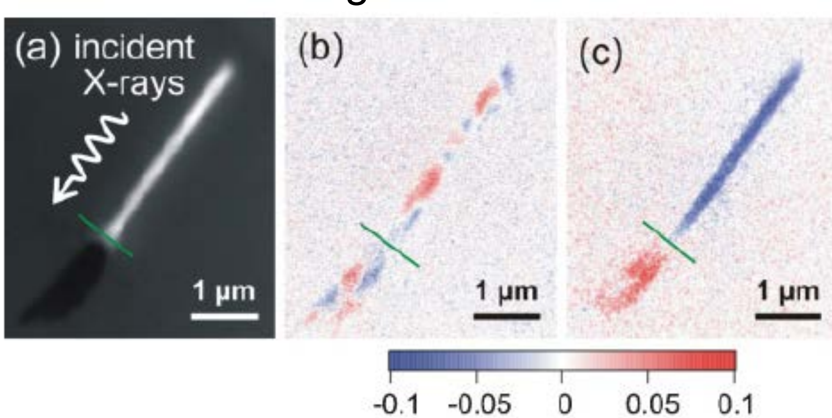
Centro Universitario de la Defensa Zaragoza

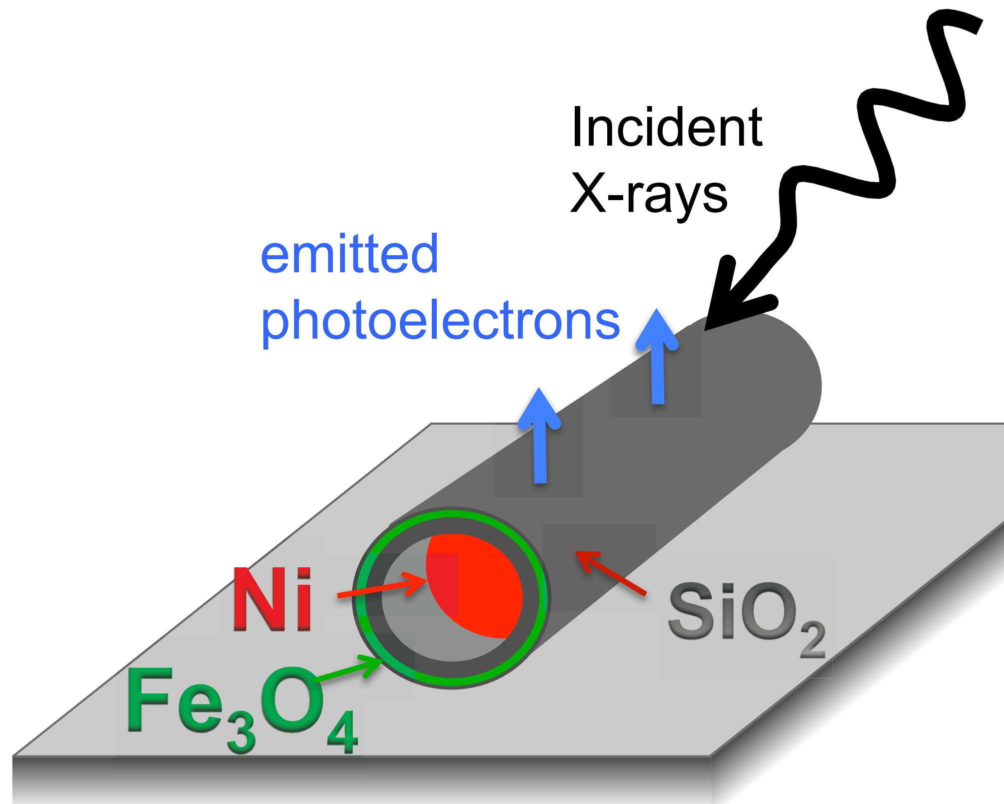
Photoemission electron microscopy of three-dimensional magnetization configurations in core-shell nanostructures

Judith Kimling,[1,*] Florian Kronast,[2,†] Stephan Martens,[1] Tim Böhnert,[1] Michael Martens,[1] Julia Herrero-Albillos,[2,‡] Logane Tati-Bismaths,[2] Ulrich Merkt,[1] Kornelius Nielsch,[1] and Guido Meier[1]

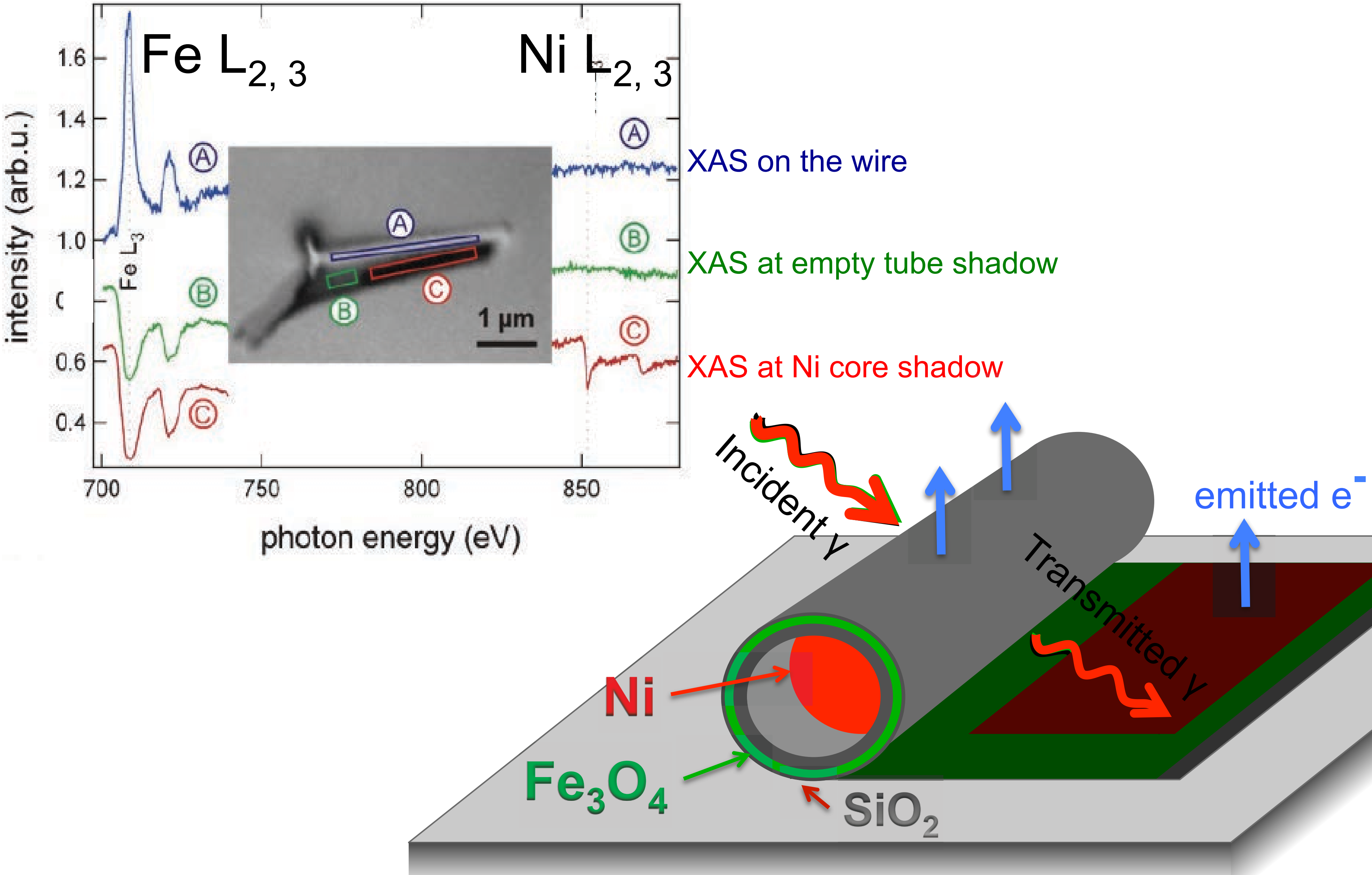


Fe_3O_4 tube magnetization
Virgin state Saturated state

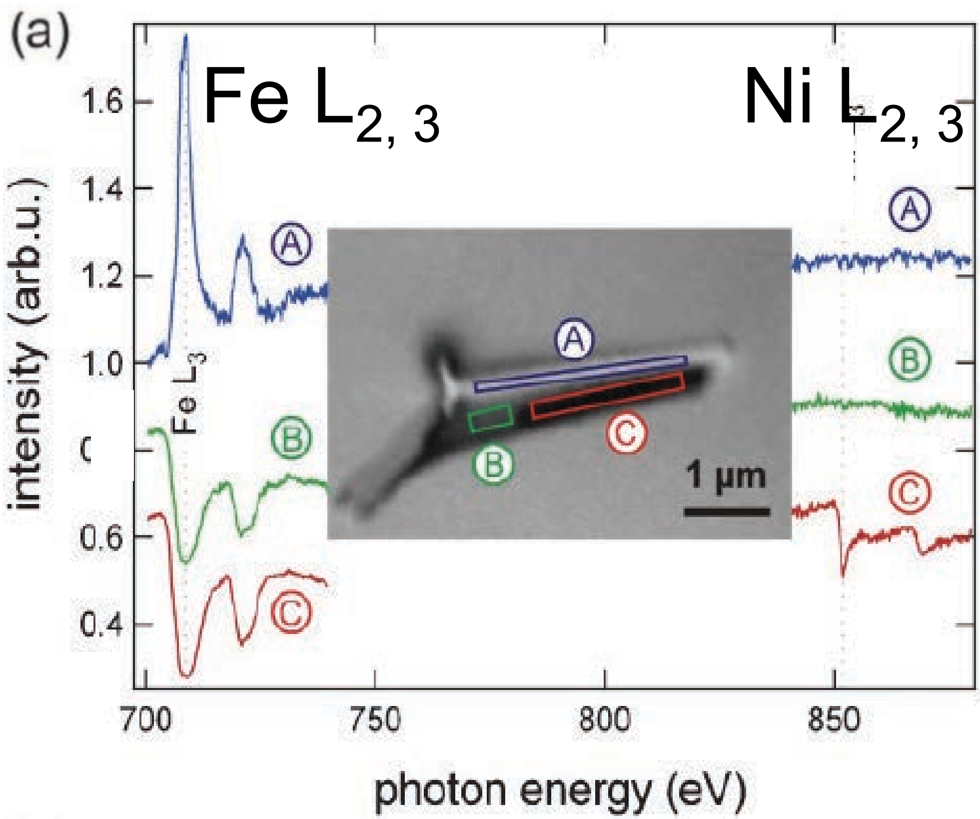


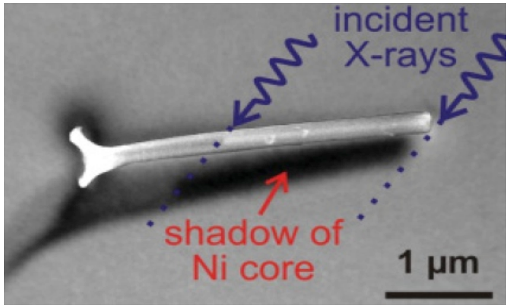


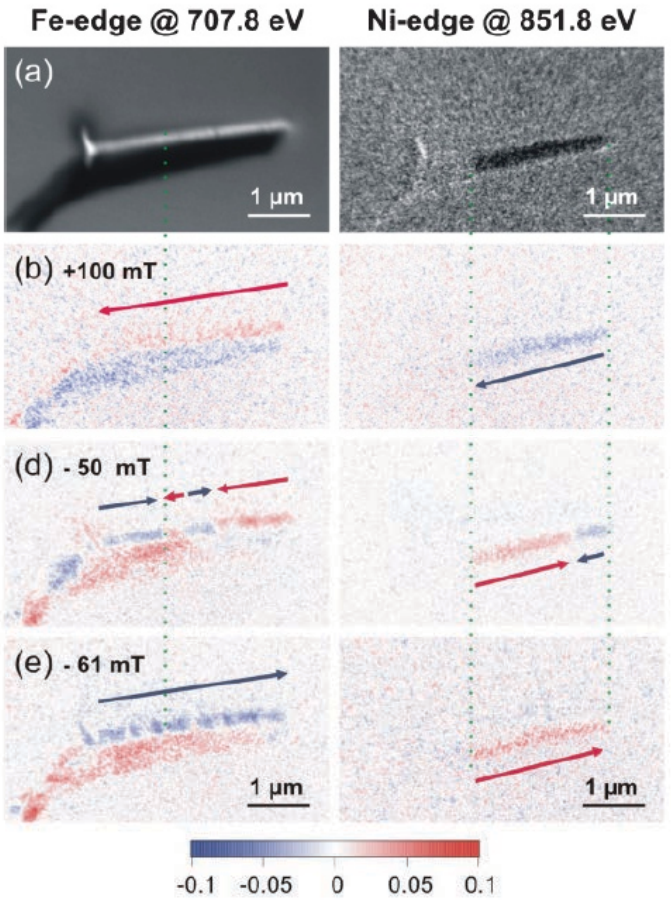
Probing bulk and surface in nanomagnets



Probing bulk and surface in nanomagnets







PHYSICAL REVIEW B 84, 174406 (2011)

Photoemission electron microscopy of three-dimensional magnetization configurations in core-shell nanostructures

Judith Kimling,[1,*] Florian Kronast,[2,†] Stephan Martens,[1] Tim Böhnert,[1] Michael Martens,[1] Julia Herrero-Albillos,[2,‡] Logane Tati-Bismaths,[2] Ulrich Merkt,[1] Kornelius Nielsch,[1] and Guido Meier[1]

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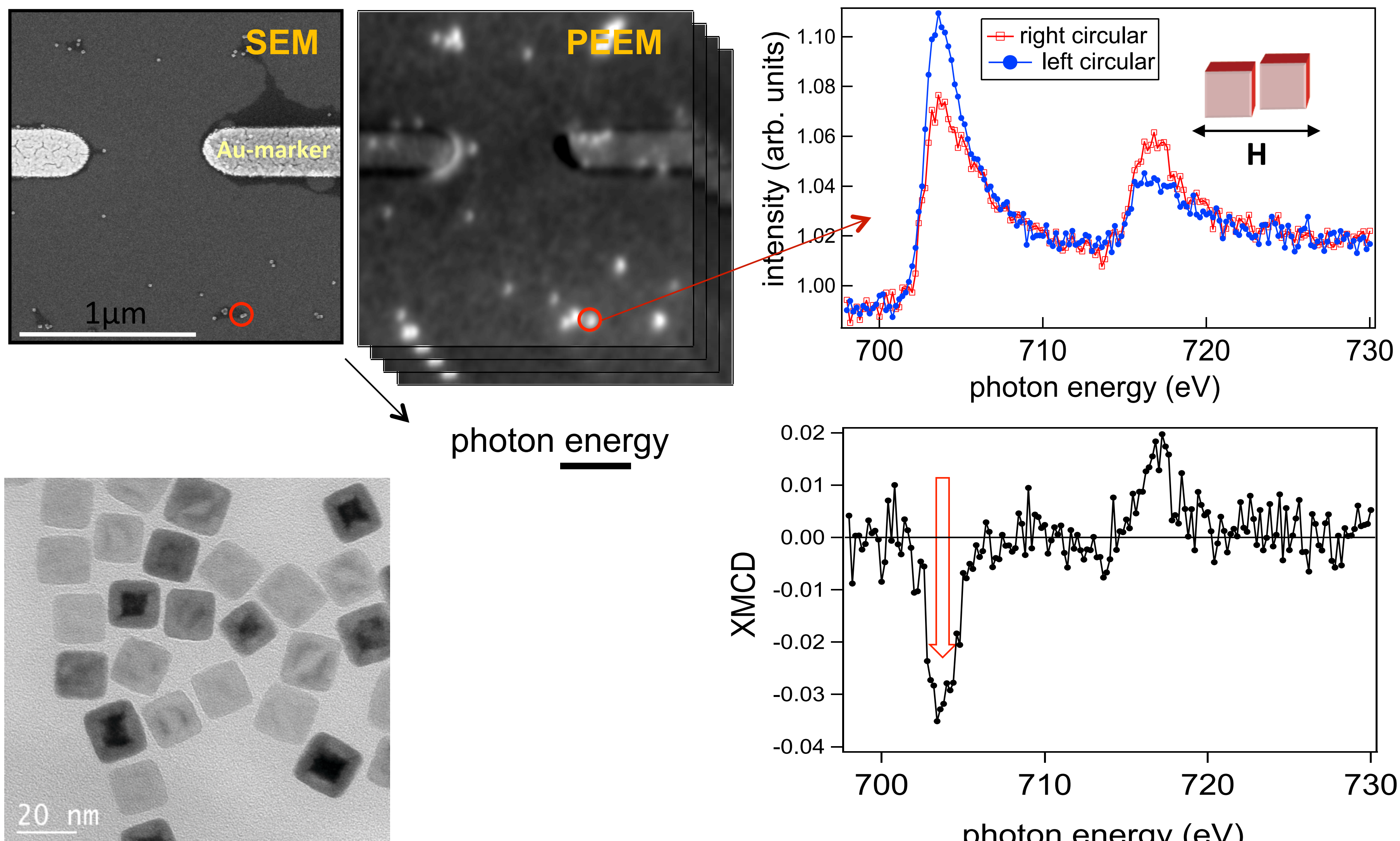
Element-Specific Magnetic Hysteresis of Individual 18 nm Fe Nanocubes

Florian Kronast,† Nina Friedenberger,‡ Katharina Ollefs,‡ Sebastian Gliga,‖ Logane Tati-Bismaths,⊥ Ronja Thies,† Andreas Ney,‡ Ramona Weber,† Christoph Hassel,‡ Florian M. Römer,‡ Anastasia V. Trunova,‡ Christian Wirtz,‡ Riccardo Hertel,§ Hermann A. Dürr,# and Michael Farle*,‡



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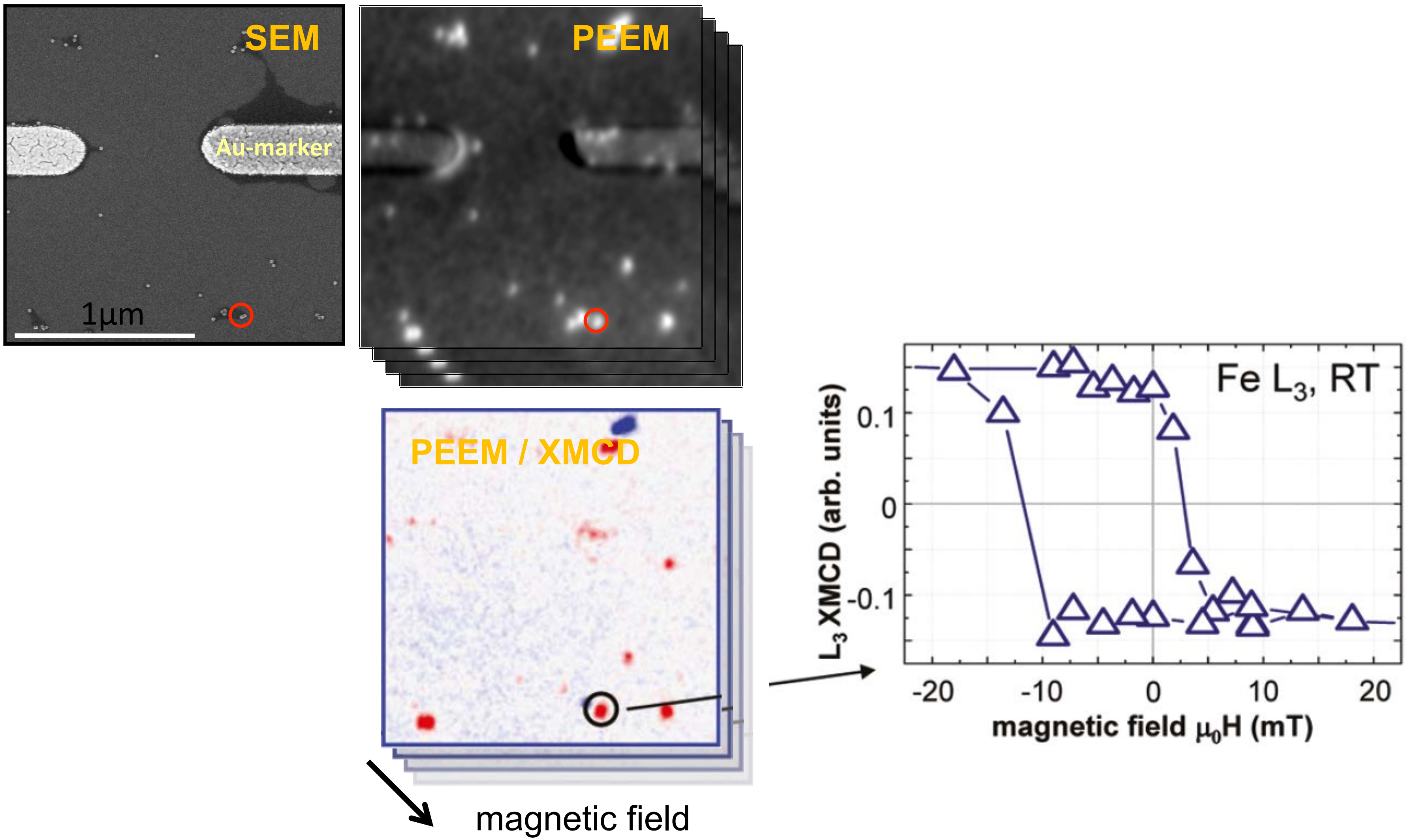

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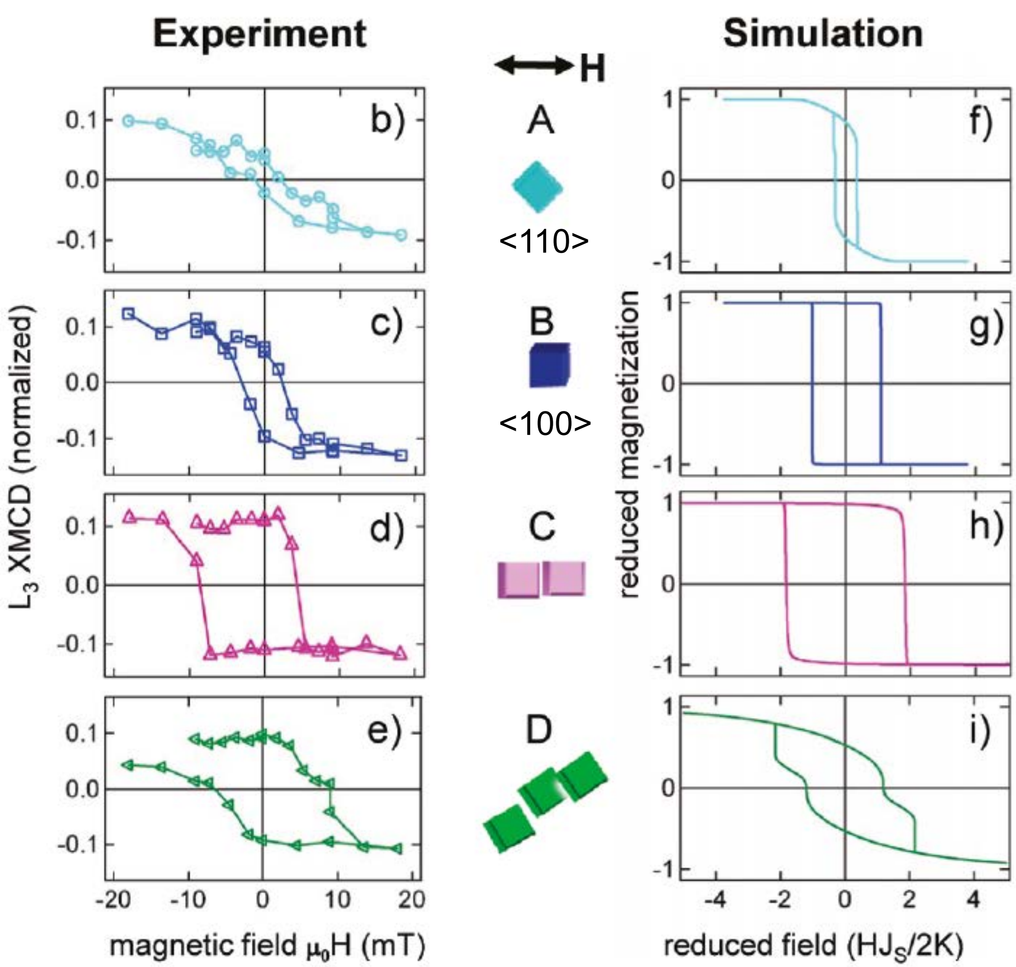

strongly reduced coercitive field close to the blocking temperature

evidence for magnetocrystalline anisotropy

dipolar coupling enhances shape anisotropy and increases blocking temperature

complex switching in non-collinear alignments

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

PHYSICAL REVIEW B **85**, 184427 (2012)

X-ray photoemission electron microscopy studies of local magnetization in Py antidot array thin films

K. J. Merazzo,[1,*] C. Castán-Guerrero,[2] J. Herrero-Albillos,[2,3] F. Kronast,[4] F. Bartolomé,[2] J. Bartolomé,[2] J. Sesé,[5] R. P. del Real,[1] L. M. García,[2] and M. Vázquez[1]

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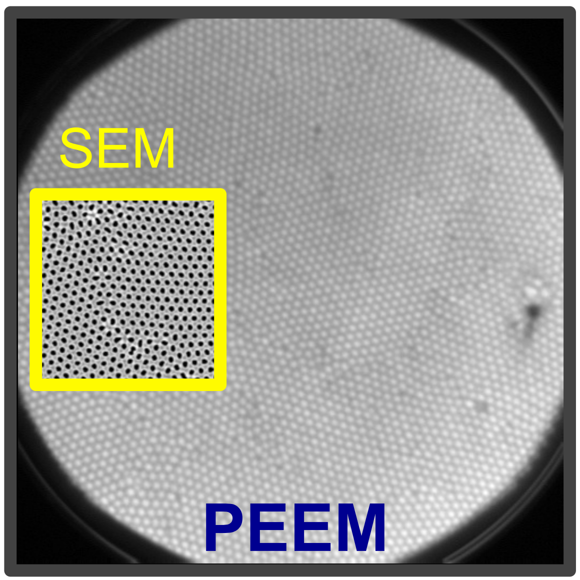

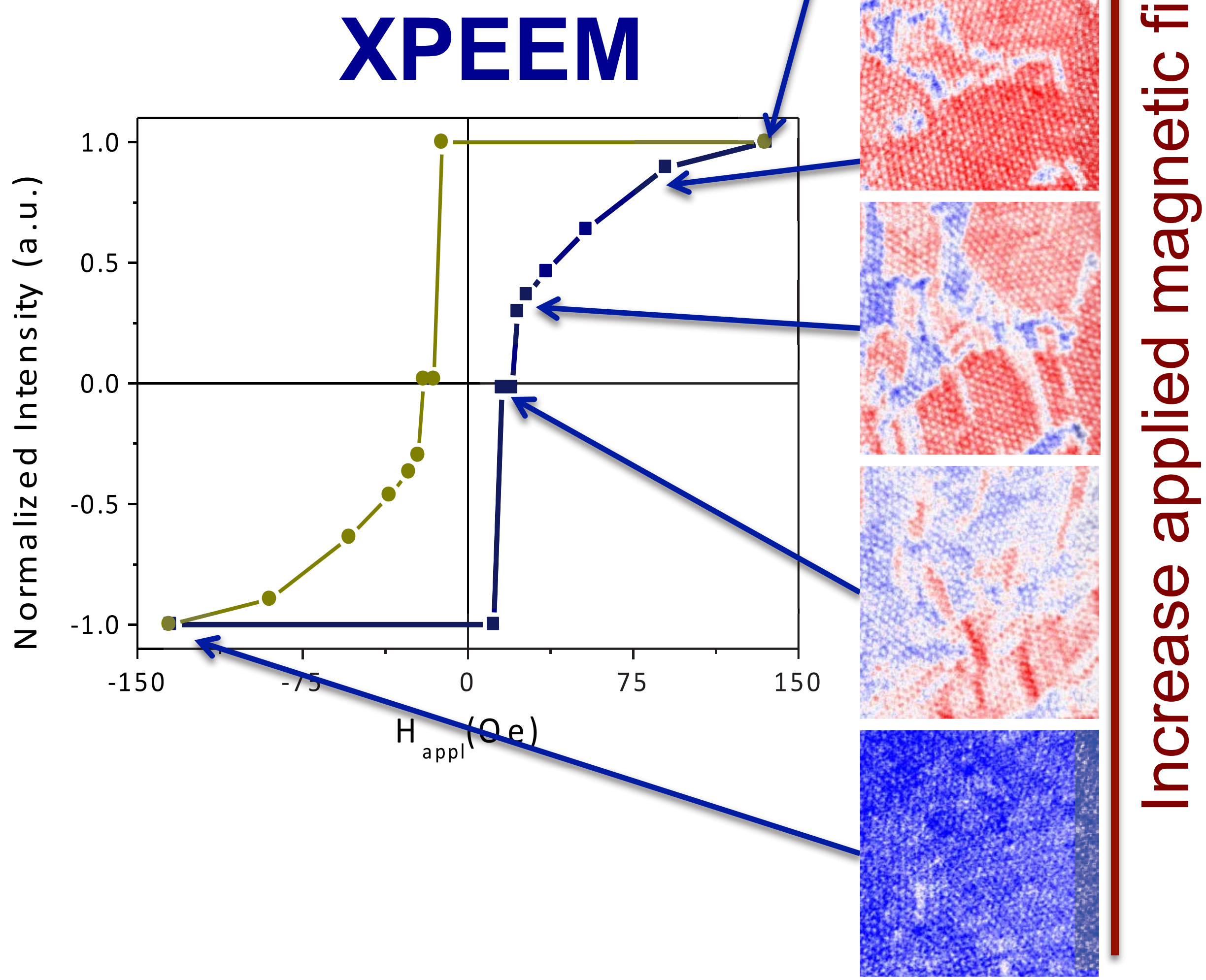

PHYSICAL REVIEW B **85**, 184427 (2012)

Centro Universitario de la Defensa Zaragoza

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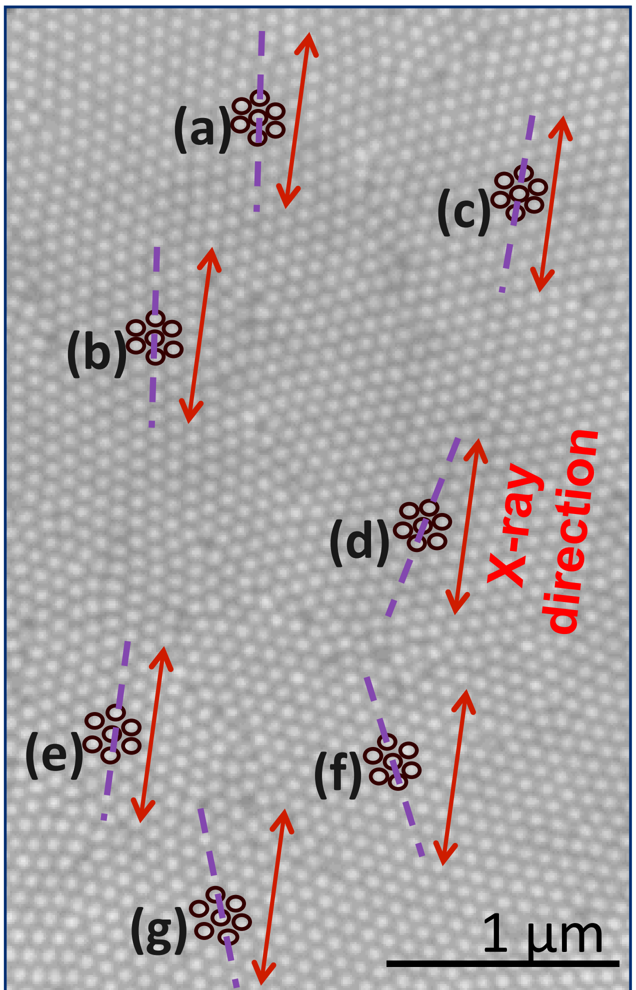

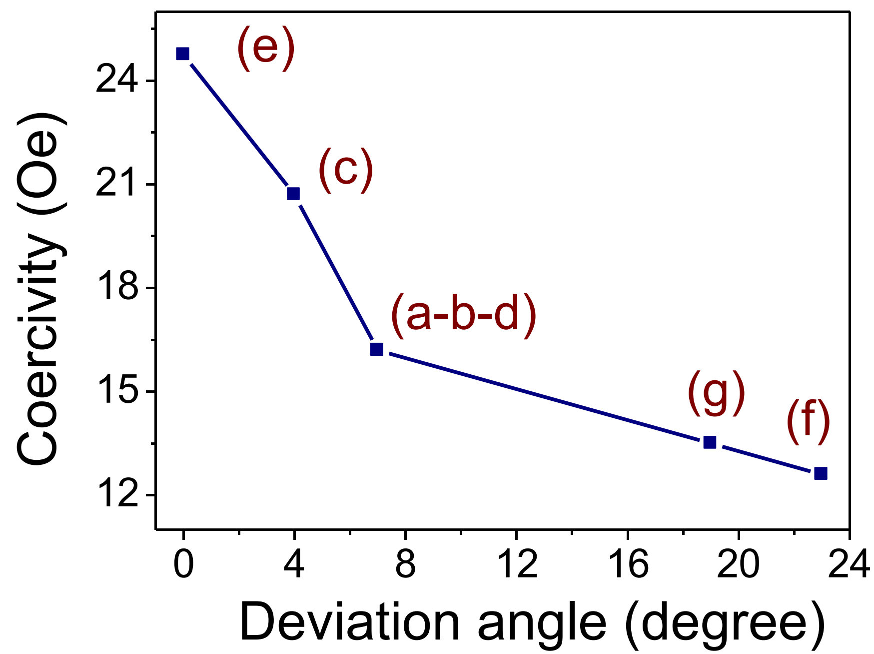

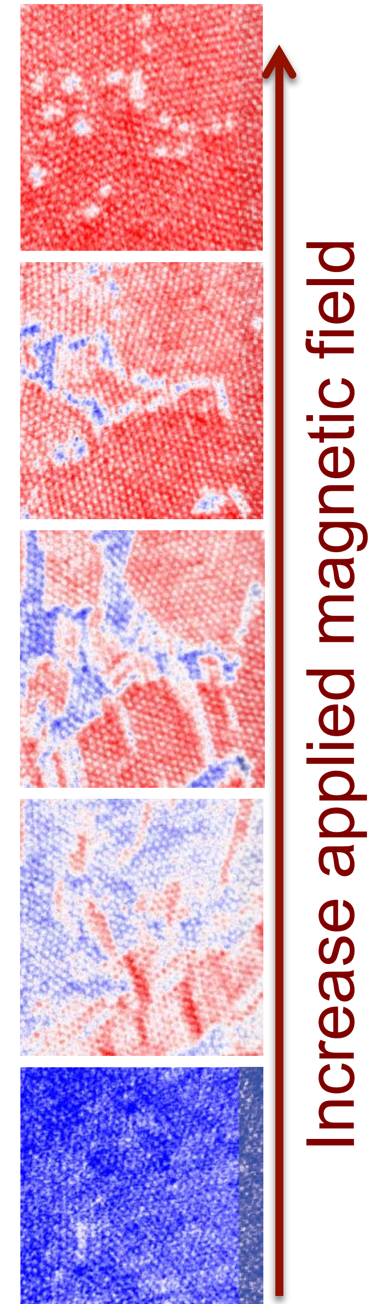

Contents lists available at SciVerse ScienceDirect

Journal of Electron Spectroscopy and Related Phenomena

journal homepage: www.elsevier.com/locate/elspec

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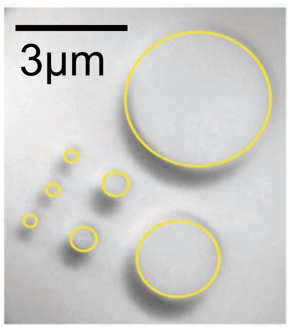
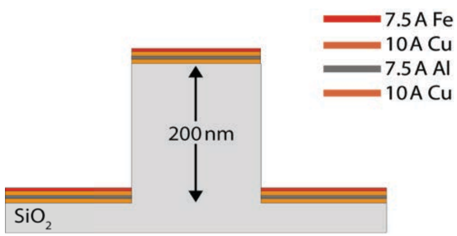
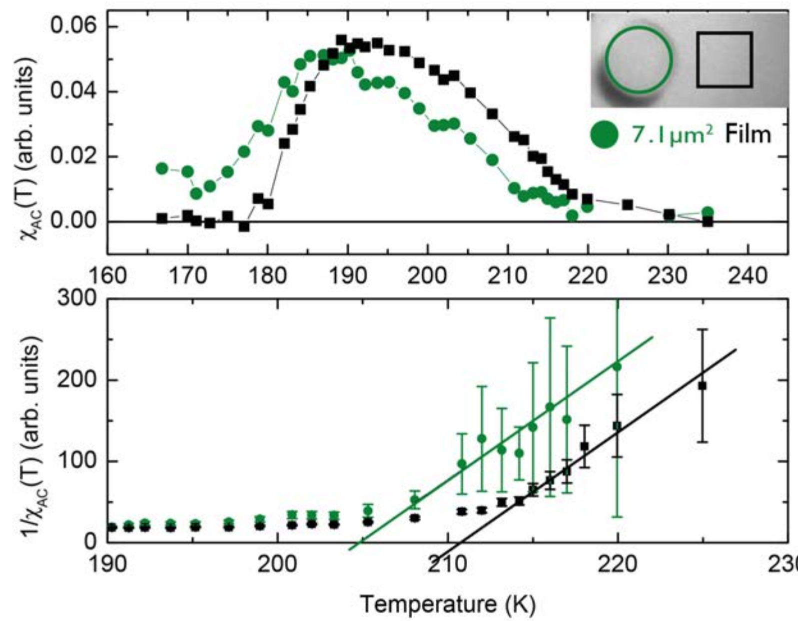
Imaging magnetic responses of nanomagnets by XPEEM

O. Sandig[a,b], J. Herrero-Albillos[a,d,e], F.M. Römer[c], N. Friedenberger[c], J. Kurde[b], T. Noll[a], M. Farle[c], F. Kronast[a,*]

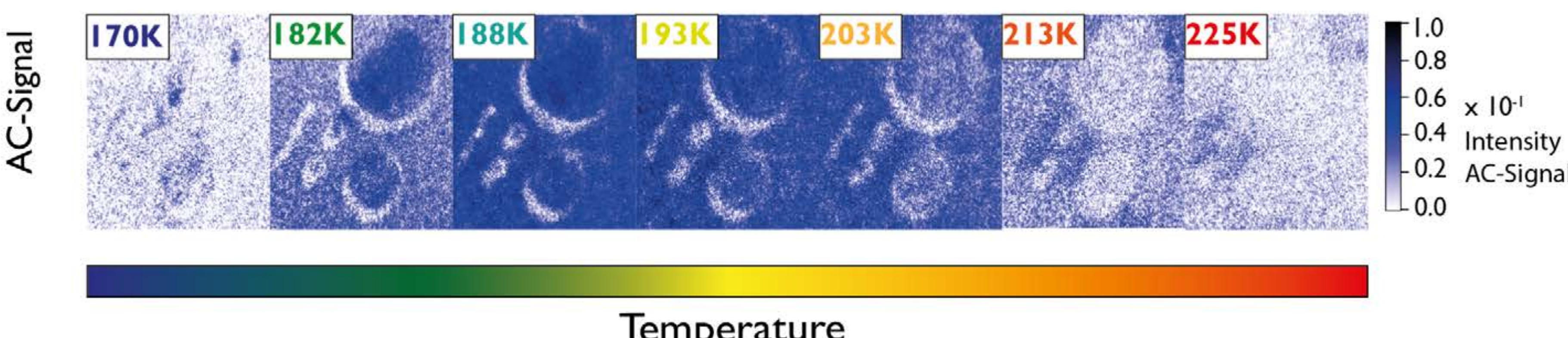






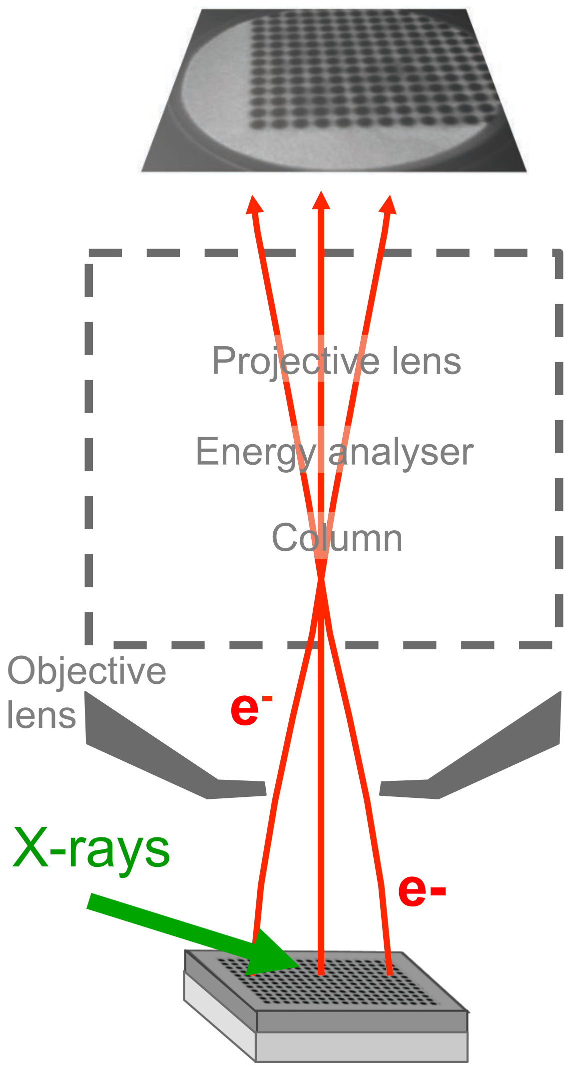
$$\chi(T) = \frac{C}{T - T_C}$$

$$C = \frac{1}{3k_B}\mu_0 n \mu^2$$

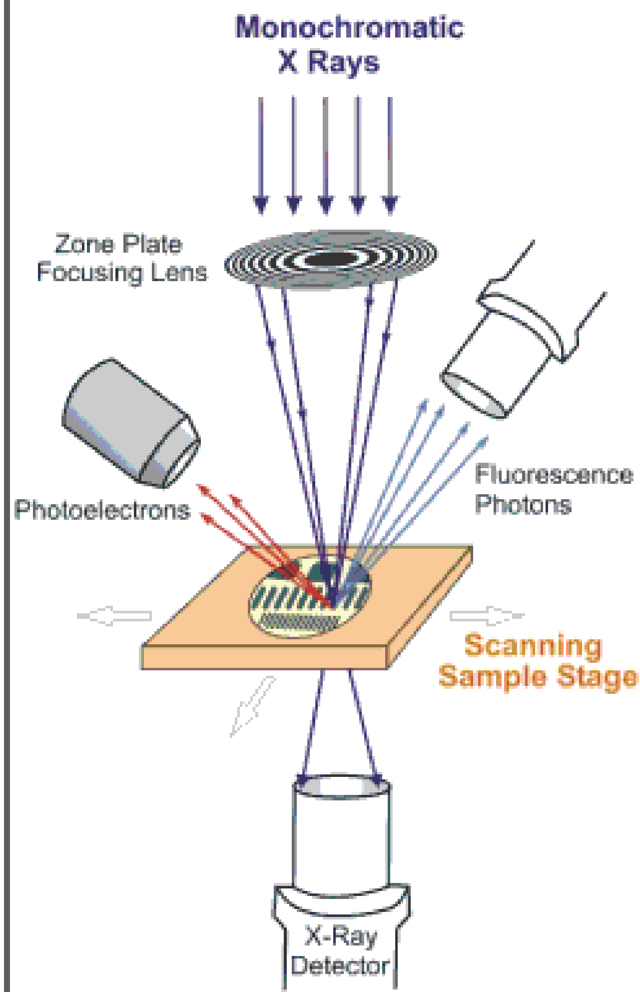


X-ray microscopes

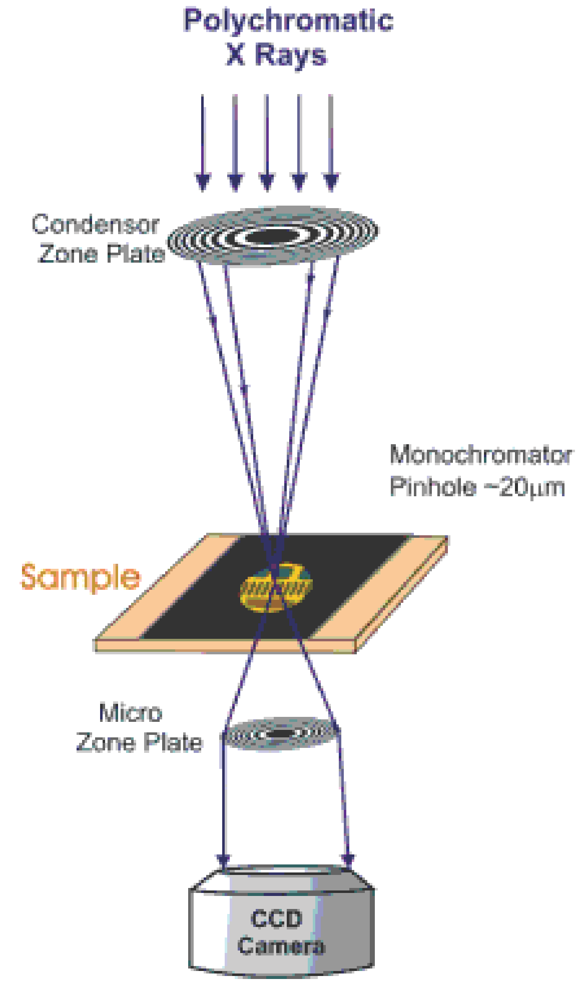
X-Ray PhotoEmission Electron Microscopy (XPEEM)



Scanning Transmission X-ray Microscopy (STXM)



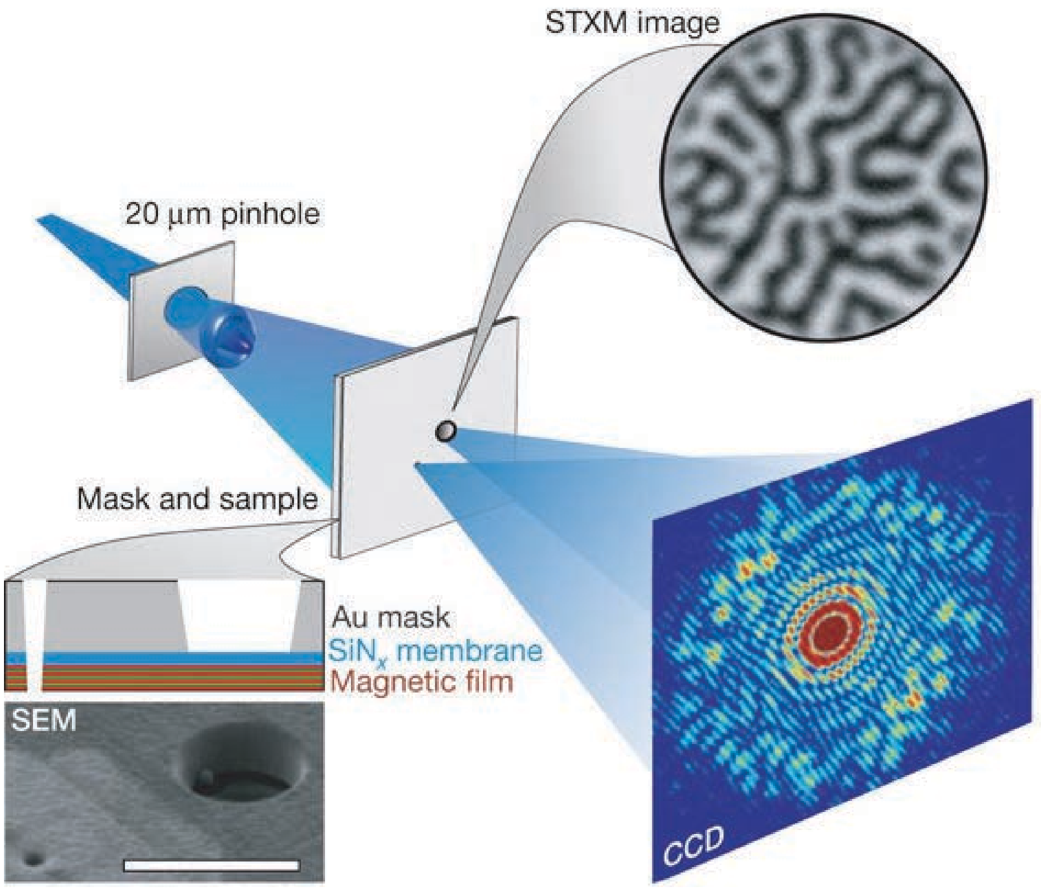
Transmission X-ray Microscopy (TXM)

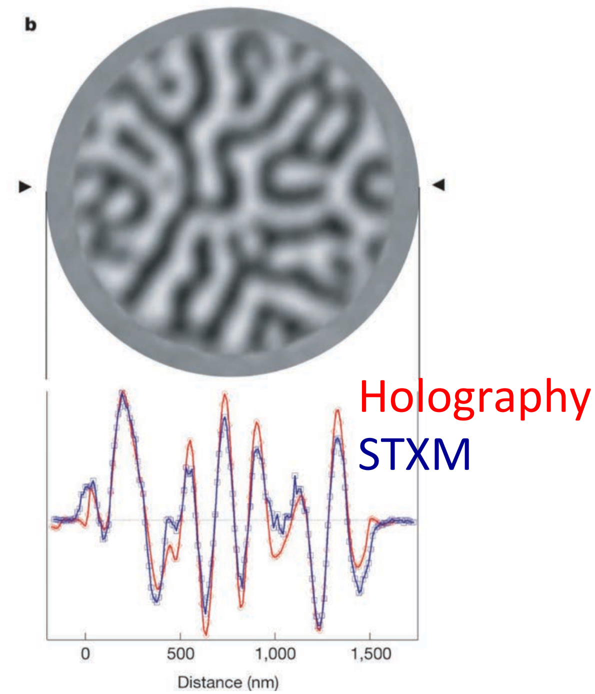


Nature **432**, 885-888 (16 December 2004) | doi:10.1038/nature03139; Received 8 July 2004; Accepted 28 October 2004

Lensless imaging of magnetic nanostructures by X-ray spectro-holography

S. Eisebitt[1], J. Lüning[2], W. F. Schlotter[2,3], M. Lörgen[1], O. Hellwig[1,4], W. Eberhardt[1] & J. Stöhr[2]





50 nm resolution

Synchrotron radiation techniques for magnetism

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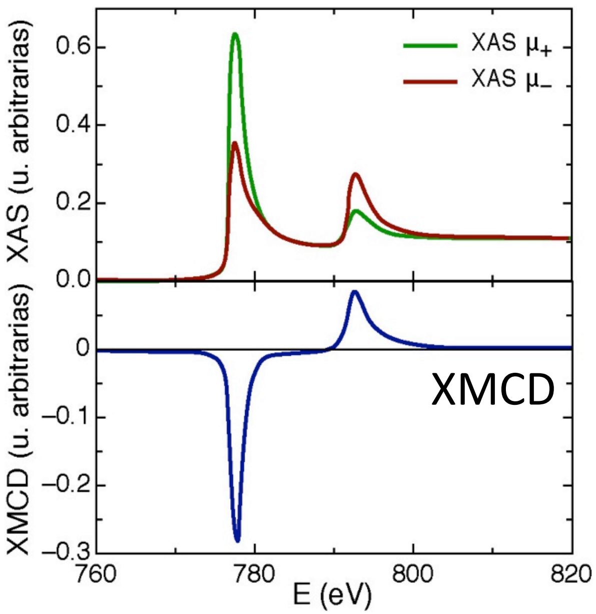
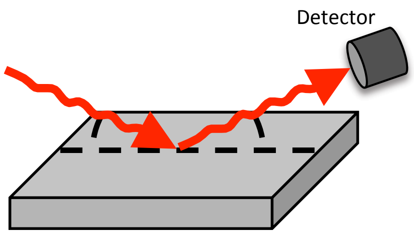


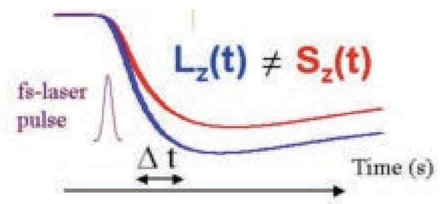
Absorption	Scattering	Photoemission	Pump-probe
Spectroscopy	Diffraction	Microscopy	Femtoslicing

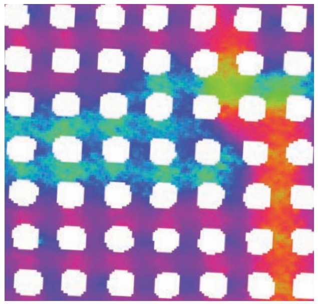
X-ray magnetic circular dichroism (XMCD)   X-ray resonant magnetic scattering (XRMS)

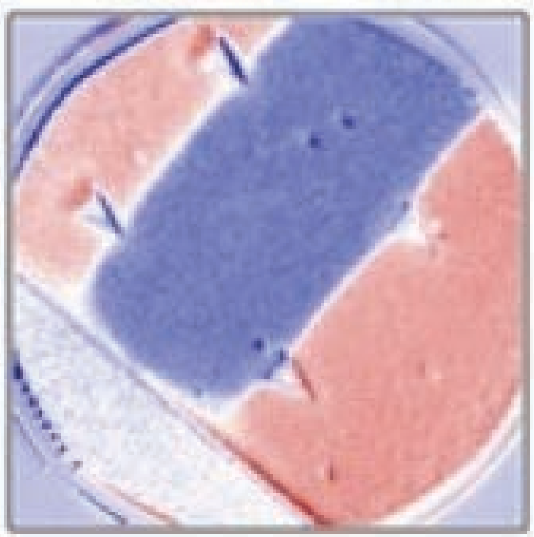
X-ray Photoemission electron microscopy (XPEEM)   Transmission x-ray microscopy (TXM)

Scanning Transmission x-ray microscopy (STXM)   Magneto-dichroic x-ray holography









Novel Frontiers in Magnetism

2014, Feb 09 -- Feb 15

Organizers:
A. Labarta (U. Barcelona)
B. Martínez (ICMB Barcelona - CSIC)
F. Bartolomé (ICMA - CSIC - U. Zaragoza)

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Marcela Bonilla	Richard Harrison	James F.J. Bryson