Elettra Sincrotrone Trieste

Basic concepts for LEEM, XPEEM and applications

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Why do we need photoelectron microscopy?

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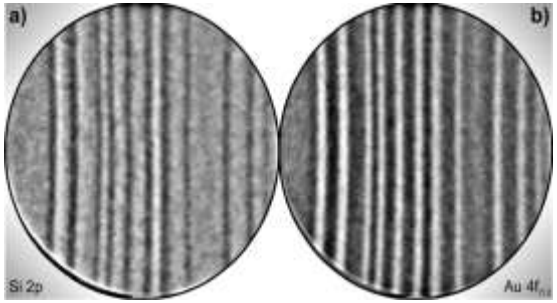
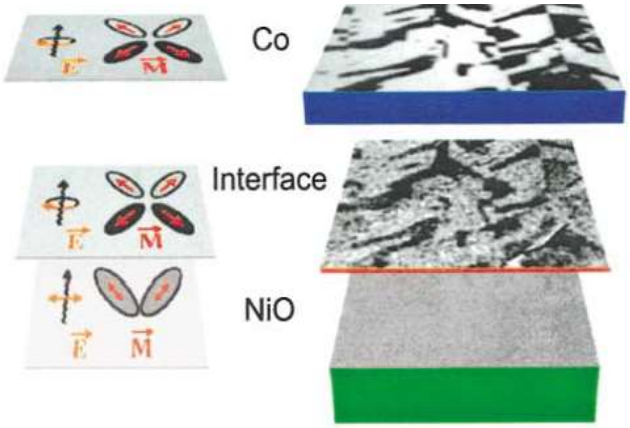
- To combine SPECTROSCOPY and MICROSCOPY to characterise the structural, chemical and magnetic properties of surfaces, interfaces and thin films
- Applications in diverse fields such as surface science, catalysis, material science, magnetism but also geology, soil sciences, biology and medicine.

Surface Science



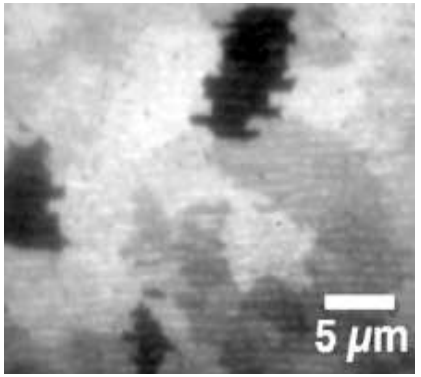
DOI: 10.1103/PhysRevLett.86.5088

Magnetism



DOI: 10.1103/PhysRevLett.87.247201

Biology



PRL **98,** 268102 (2007)

Why does PEEM need synchrotron radiation?

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- High intensity of SR makes measurements faster
- Tuneability – very broad and continuous spectral range from IR to hard X-Rays
- Narrow angular collimation
- Coherence!
- High degree of polarization
- Pulsed time structure of SR – This adds time resolution to photoelectron spectroscopy!
- Quantitative control on SR parameters allows spectroscopy:
    - Absorption Spectroscopy (XAS and variants)
    - Photoemission Spectroscopies (XPS, UPS, ARPES, ARUPS)

$$J = f(h\nu, \varepsilon, \Theta, \Phi; E^{e}_{kin}, \sigma, \theta_e, \varphi_e)$$

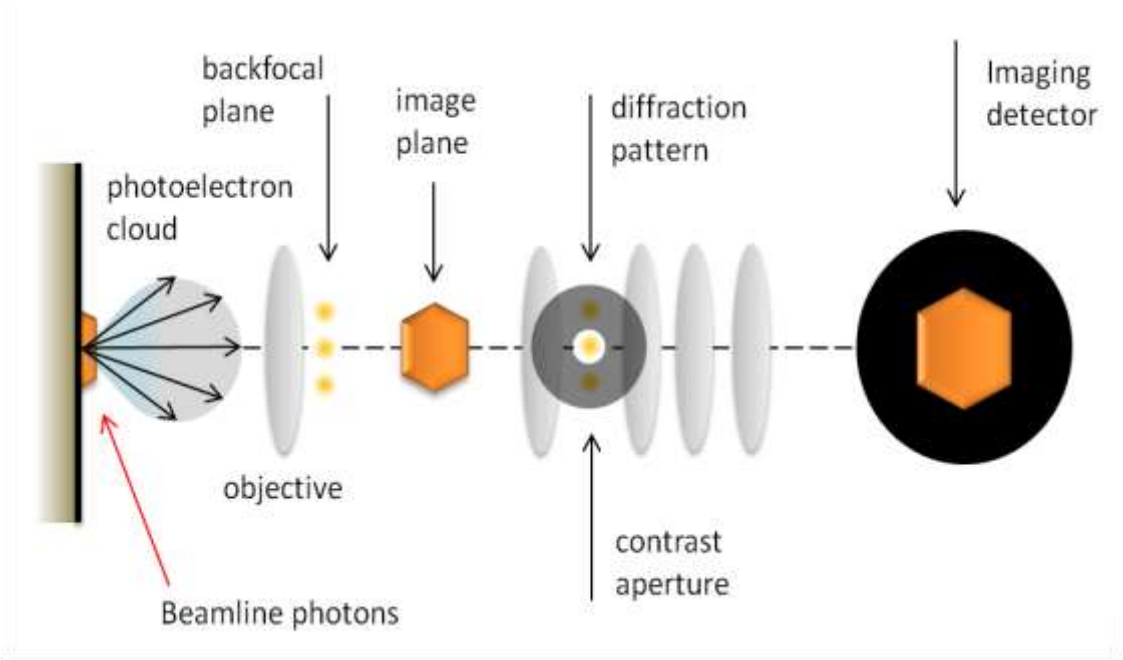
Outline

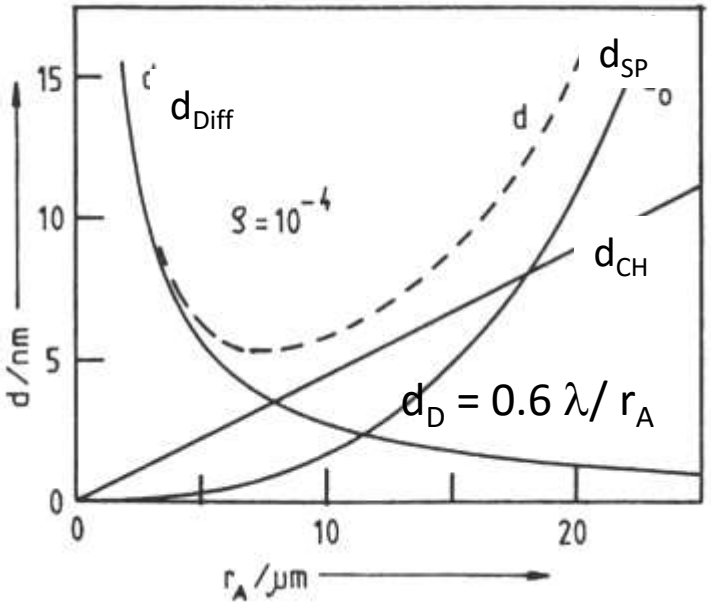
- Synchrotron radiation and x-ray spectro-microscopy: basics
- Cathode lens microscopy: methods
- Applications
  - Chemical imaging of micro-structured materials
  - Graphene research.
  - Magnetism
  - Time-resolved XPEEM

Cathode lens microscopy methods

PEEM, LEEM, SPELEEM, AC-PEEM/LEEM

PEEM basics





$$d = \sqrt{d_{SP}^2 + d_{CH}^2 + d_D^2}$$

PEEM is a full-field technique. The microscope images a restricted portion of the specimen area illuminated by x-ray beam. Photoemitted electrons are collected at the same time by the optics setup, which produces a magnified image of the surface. The key element of the microscope is the objective lens, also known as cathode or immersion lens, of which the sample is part

The different types of PEEM measurements

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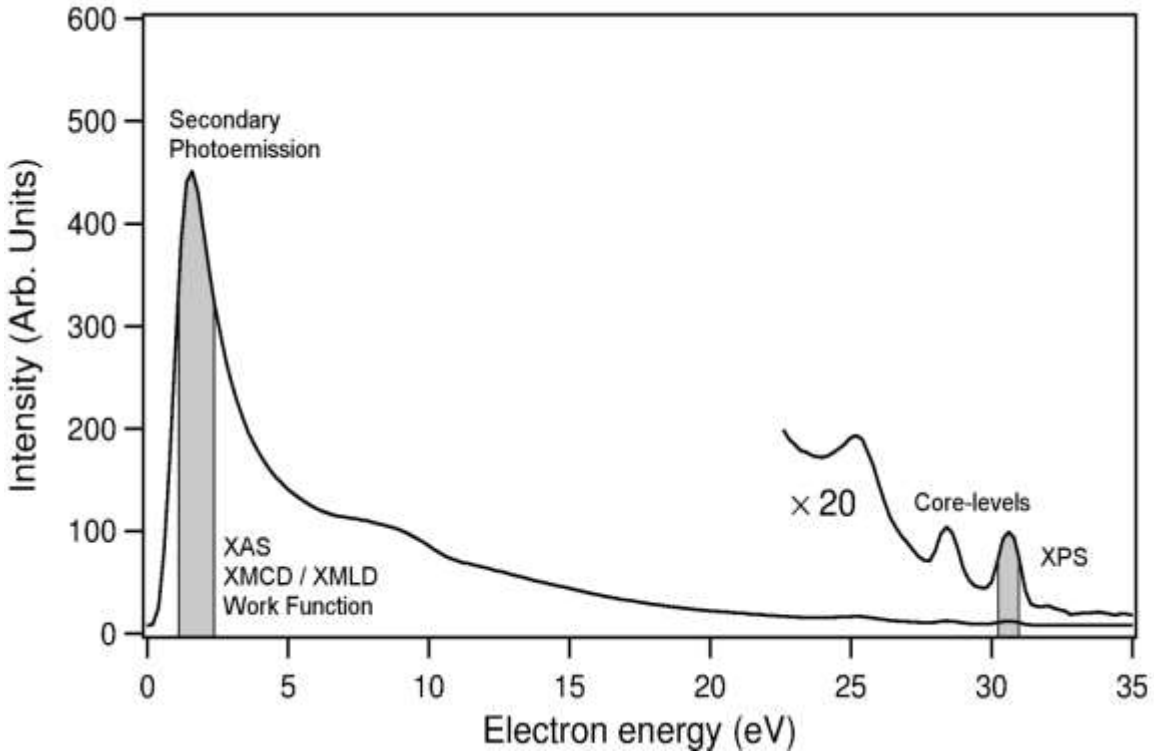
PEEM	Probe	Measurement
• threshold microscopy	Hg lamp	photoelectrons
• Laterally resolved XPS, micro-spectroscopy	X-ray	core levels or VB ph.el.
• Laterally resolved UPS, microprobe ARUPS /ARPES	X-rays, He lamp	VB photoelectrons
• Auger Spectroscopy	X-ray, or electrons	secondary electrons
• XAS-PEEM (XMC/LD-PEEM)	X rays	secondary electrons



Require energy filter

Simple PEEM instruments

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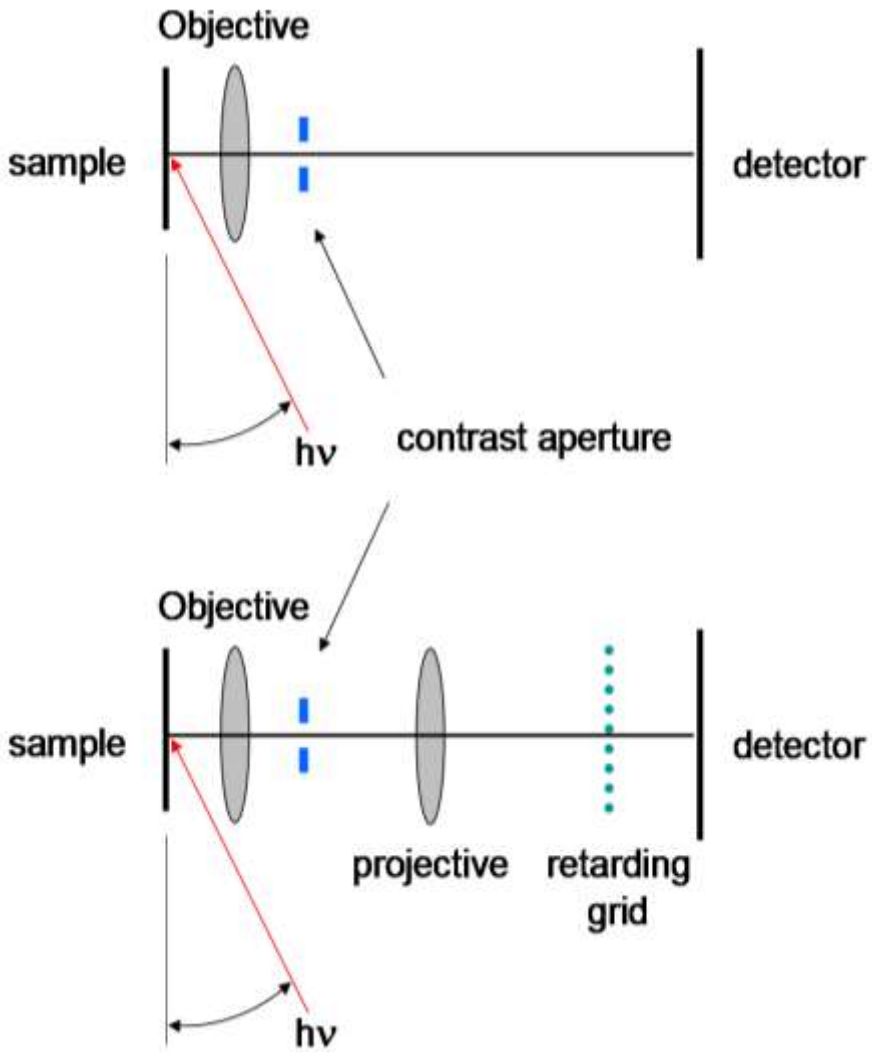

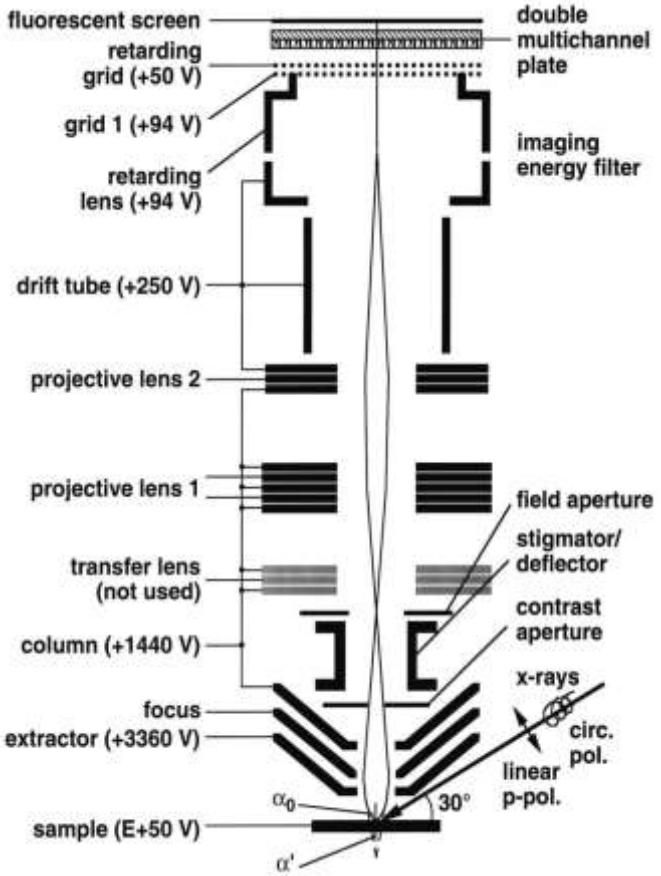

PEEM instrments with energy filter: NanoESCA

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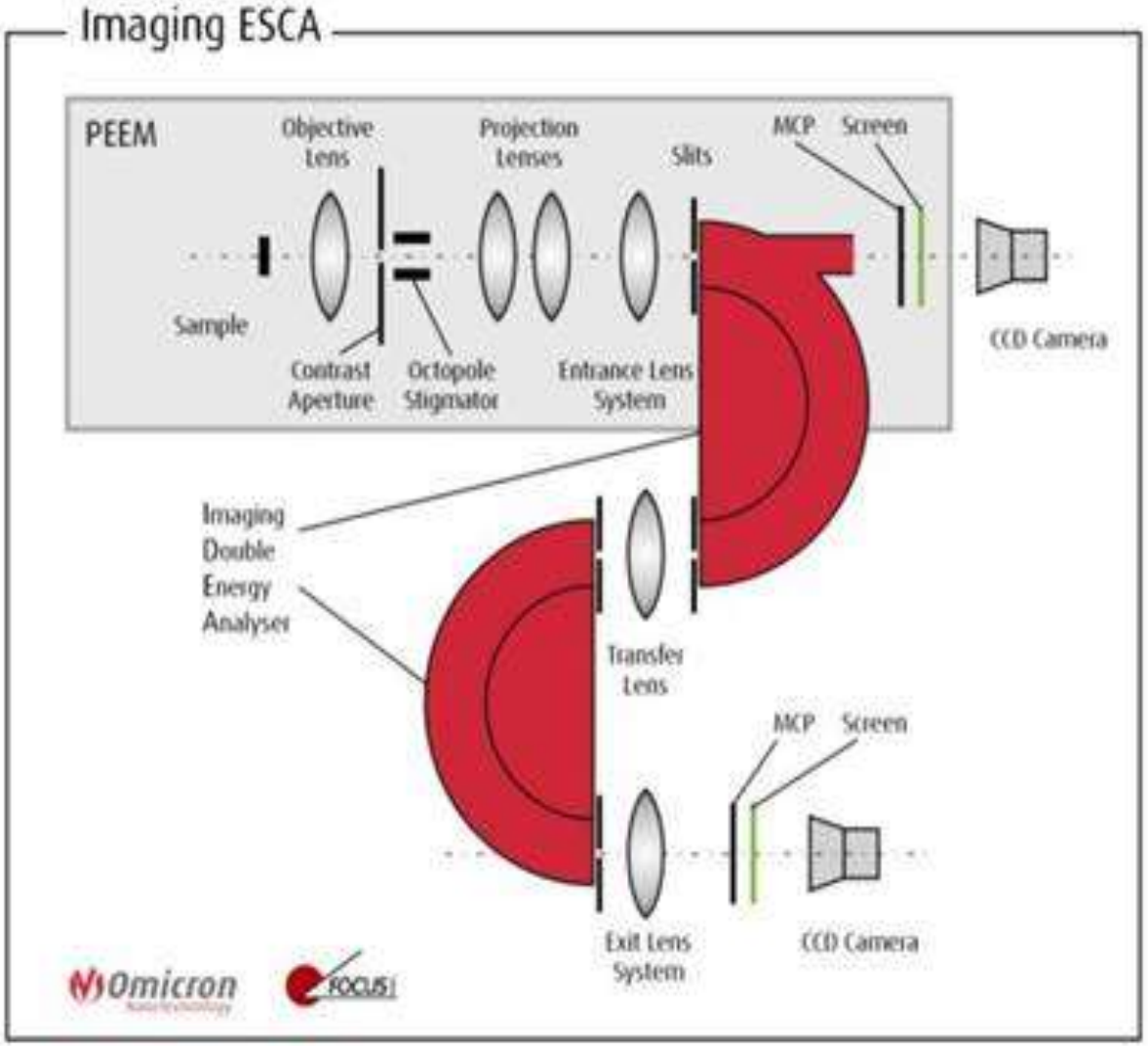

Low energy electron microscopy (LEEM)

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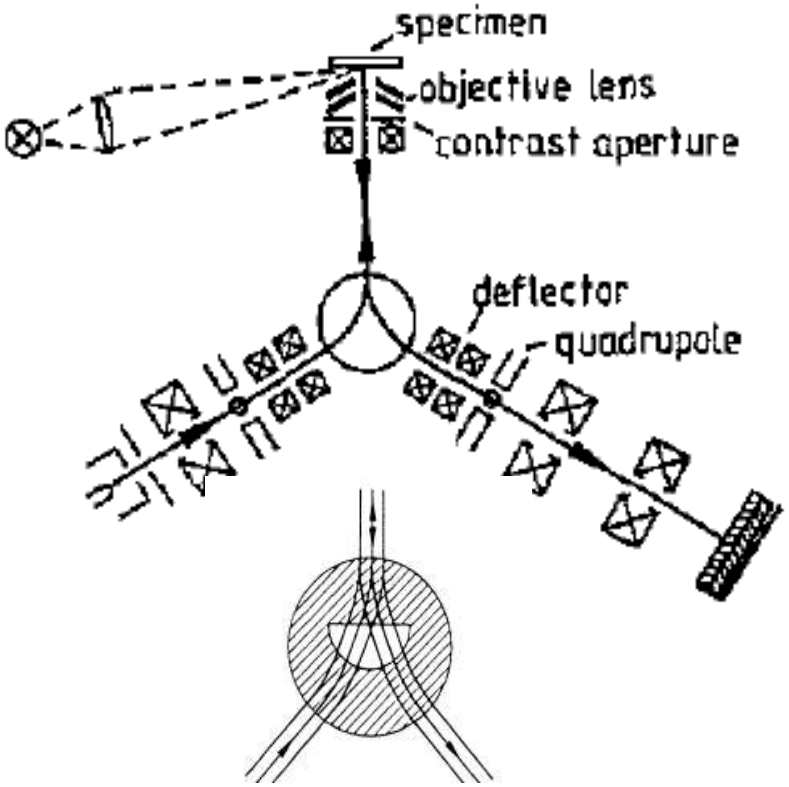
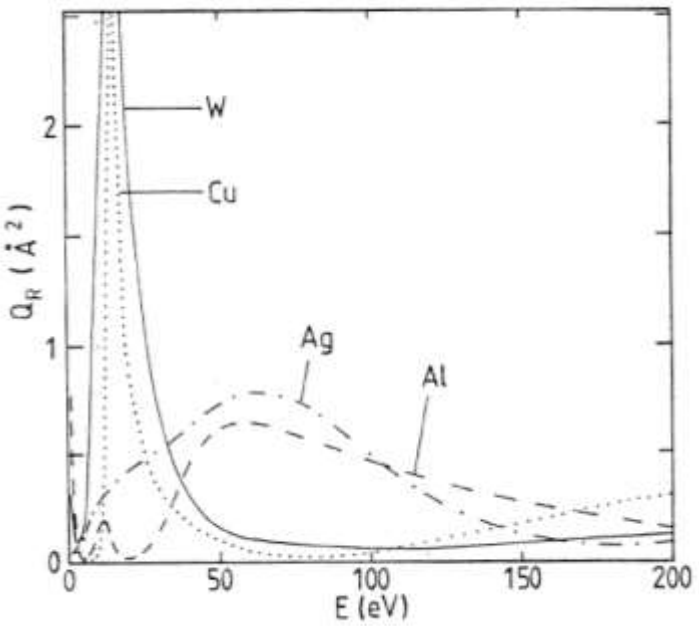


Backscattering cross section



E. Bauer, Rep. Prog. Phys. 57 (1994) 895-938.

- LEEM probes surfaces with low energy electrons, using the elastically backscattered beam for imaging.
- Direct imaging and diffraction imaging modes

- High structure sensitivity
- High surface sensitivity
- Video rate: reconstructions, growth, step dynamics, self-organization

Imaging dynamic processes in LEEM

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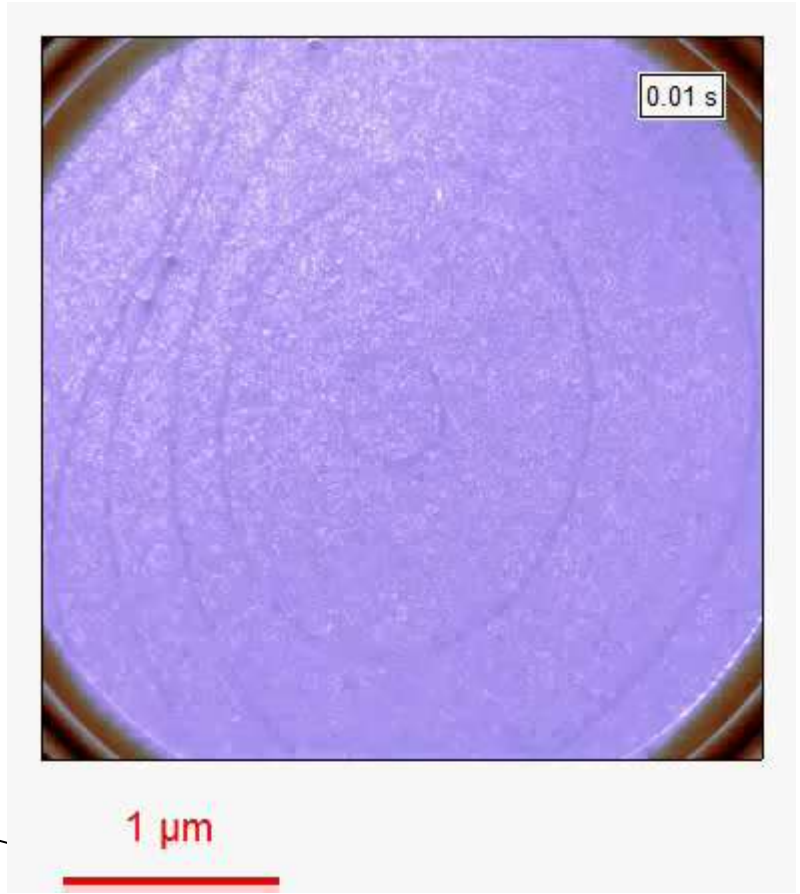
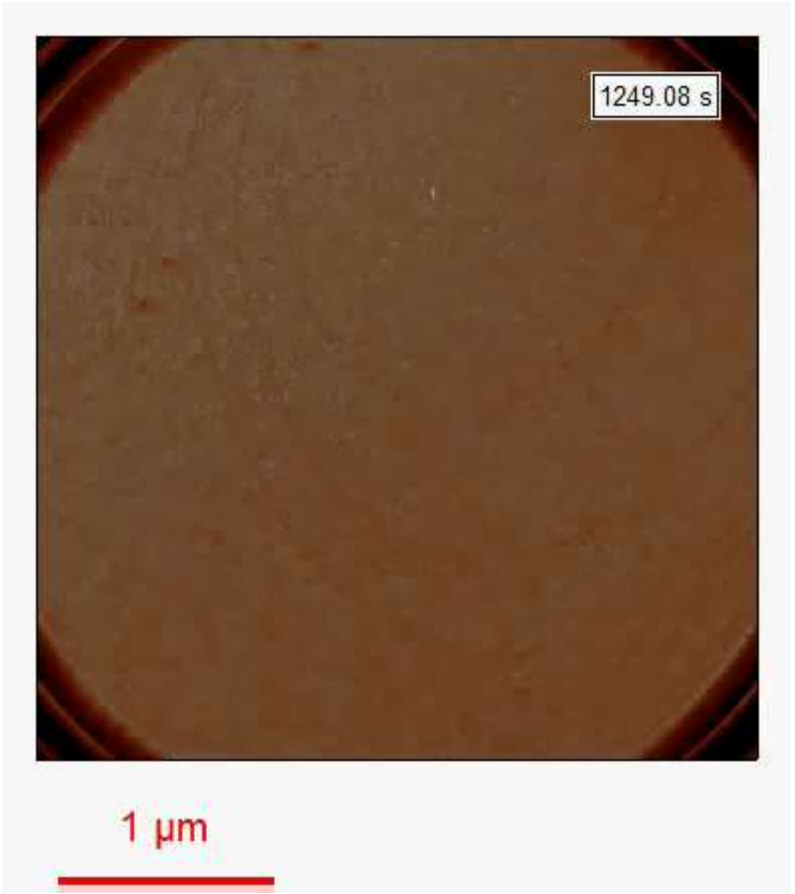
540 < T < 750 C





Ni growth on W(110): step flow and completion of ps ML

Ni growth on W(110): formation of a striped phase above 1 ps ML Ni

Image contrast in LEEM

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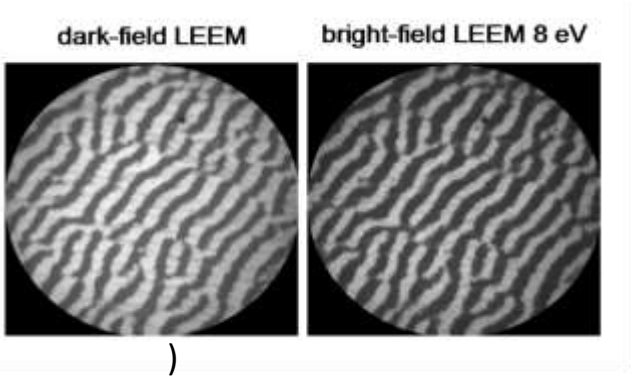
Different contrast mechanisms are available for strucutre characterization

SURFACE STRUCTURE



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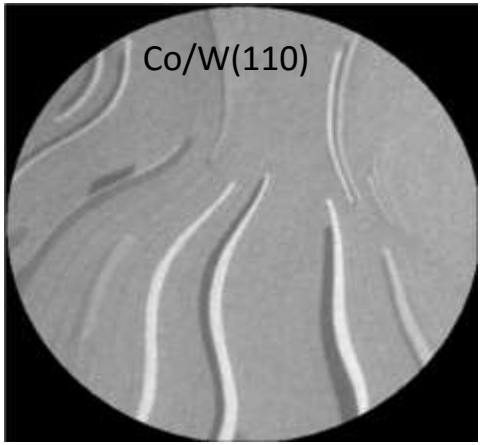
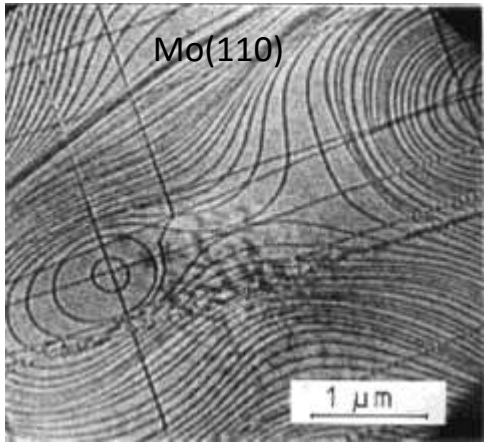
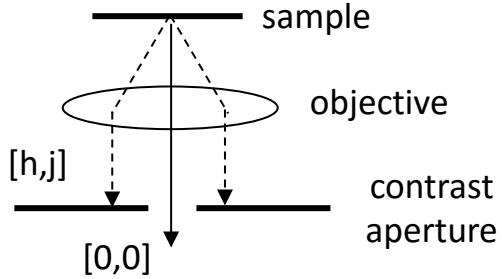
FILM THICKNESS



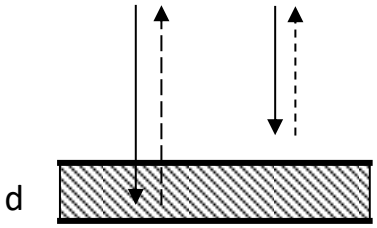
STEP MORPHOLOGY



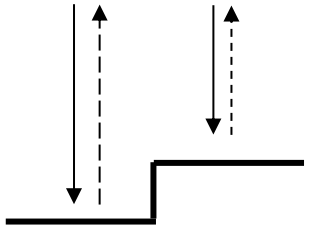
diffraction contrast



quantum size contrast



geometric phase contrast



SPELEEM = LEEM + PEEM

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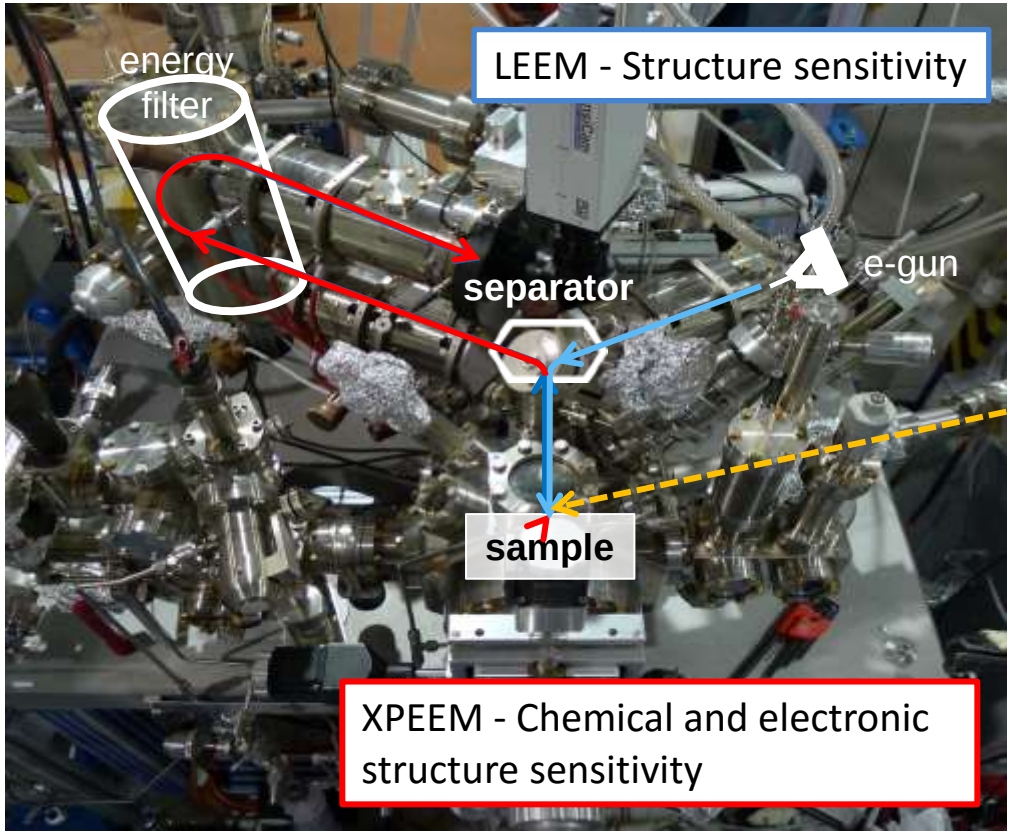
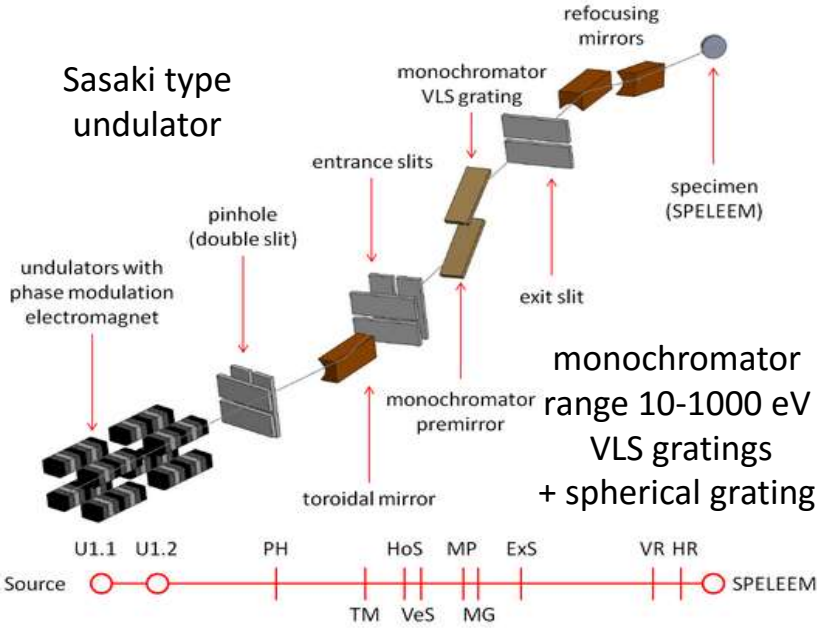


The Nanospectroscopy beamline@Elettra

Flux on the sample: 10^{13}ph/sec (microspot)
intermediate energy resolution.



Applications:
characterization of materials at microscopic level, magnetic imaging of micro-structures
Imaging of dynamical processes

A. Locatelli, L. Aballe, T.O. Menteş, M. Kiskinova, E. Bauer, Surf. Interface Anal. 38, 1554-1557 (2006)

T. O. Menteş, G. Zamborlini, A. Sala, A. Locatelli; Beilstein J. Nanotechnol. 5, 1873–1886 (2014)

SPELEEM many methods analysis

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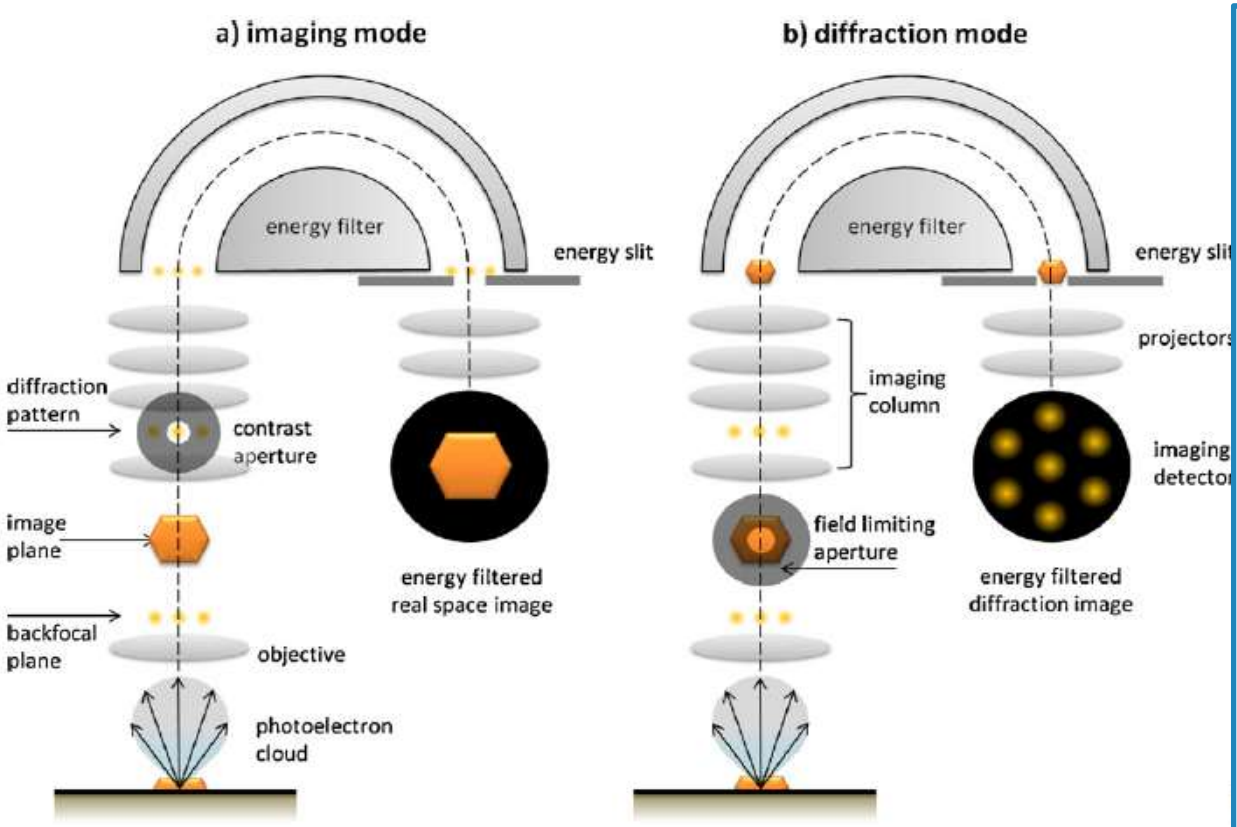
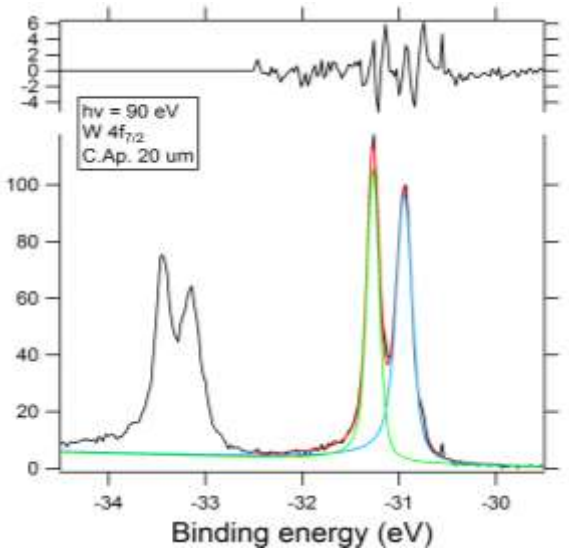
Spectroscopic imaging
XAS-PEEM / XPEEM / LEEM

microprobe-diffraction
ARPES / LEED

microprobe-spectroscopy
XPS





T. O. Menteş et al.
Beilstein J. Nanotechnol. 5, 1873–1886 (2014).

energy resolution
µXPS : 0.11 eV

spatial resolution
LEEM : 10 nm
XPEEM : 25 nm

energy resolution
XPEEM : 0.3 eV

Limited: to 2 microns in dia.
angular resolution
transfer width: 0.01 $Å^{-1}$

SPELEEM summary

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Performance: lateral resolution in imaging: 10nm (LEEM)
30 nm (XPEEM)
energy resolution: 0.3 eV (0.1 eV muXPS)

Key feature: multi-method instrument to the study of surfaces and interfaces offering *imaging* and *diffraction* techniques.

Probe: *low energy e-* (0-500 eV) ⟷ structure sensitivity
soft X-rays (50-1000 eV) ⟷ chemical state, magnetic state, electronic struct.

Applications: *characterization* of materials at microscopic level
magnetic imaging of microstrucutres
dynamical processes

Correction of spherical and chromatic aberrations

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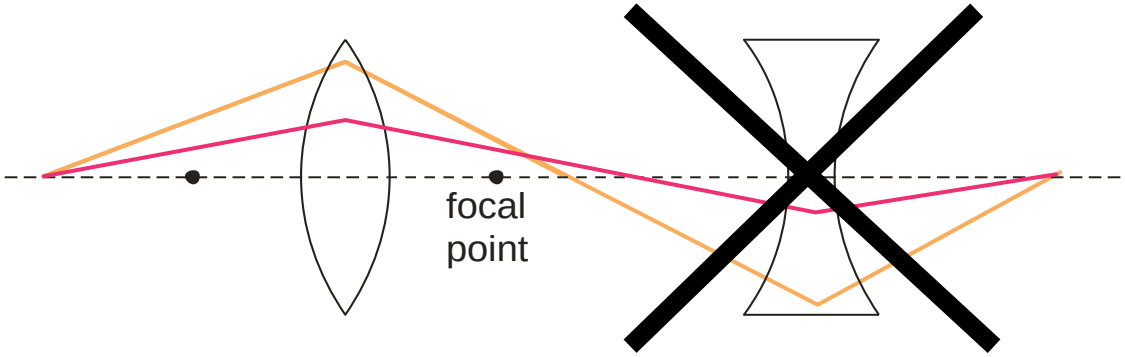
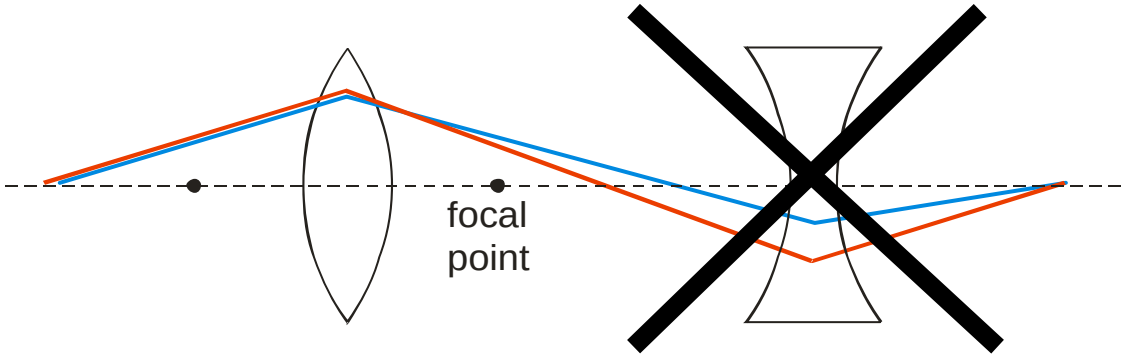
Electron optics

Round **convex** lenses

Round **concave** lenses

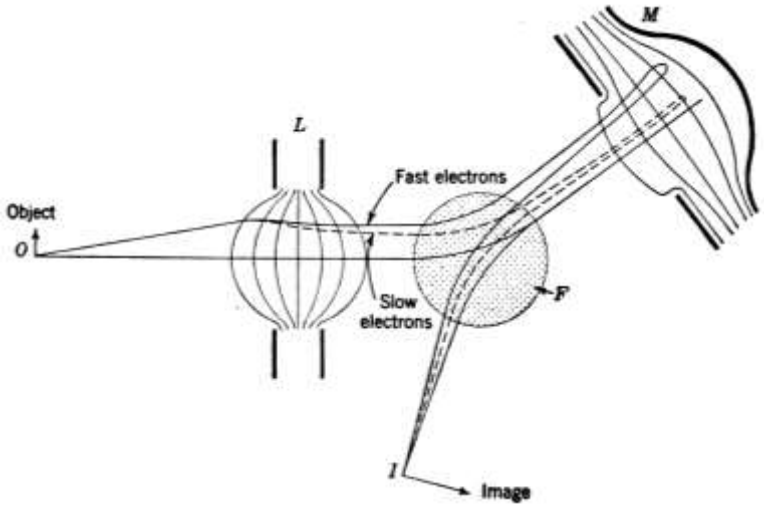


Spherical aberration



Chromatic aberration

Electron Mirror



V.K. Zworykin et al, Electron Optics and the Electron Microscope, John Wiley, New York 1945

The SMART AC microscope: calculation

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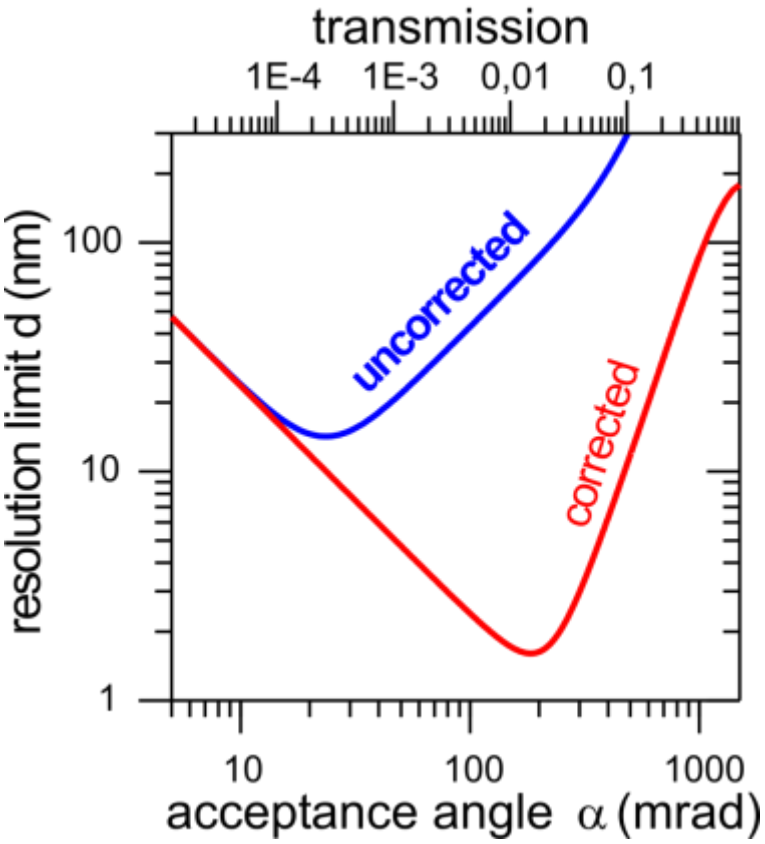
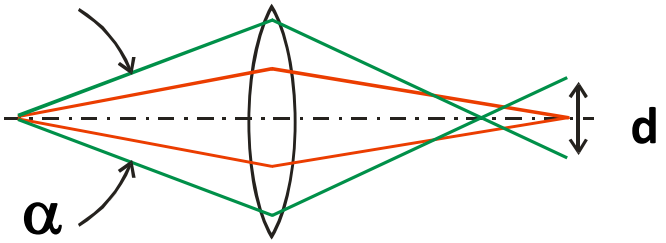
Simultaneous improvement in
Transmission and Resolution!!!



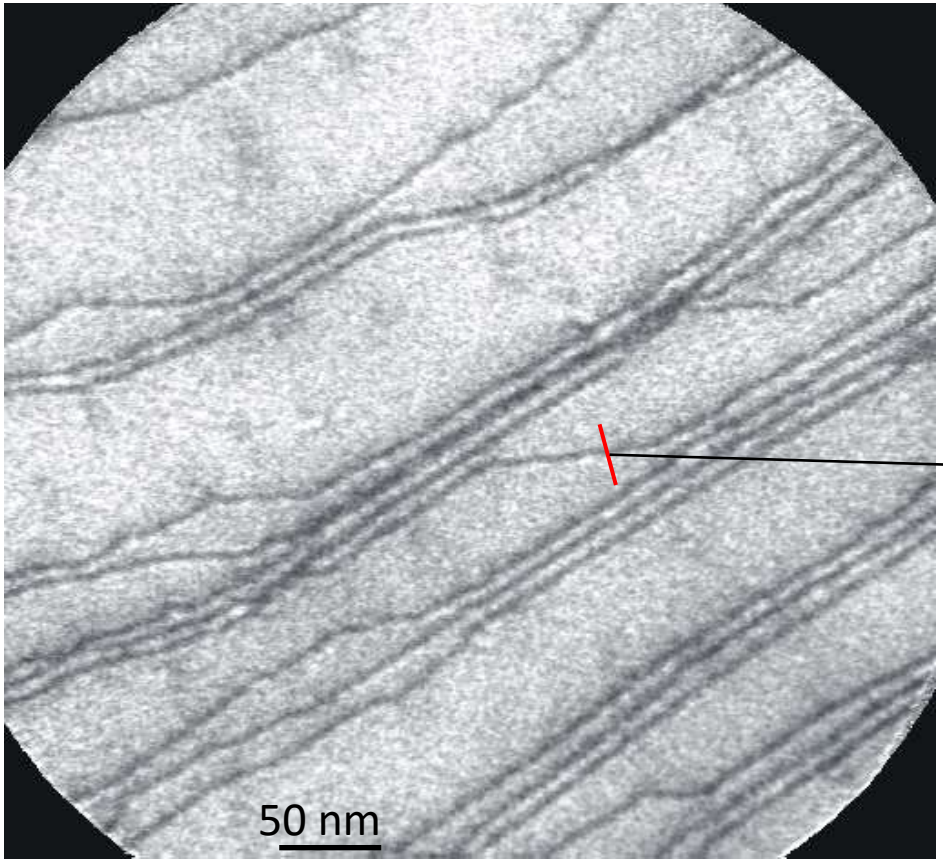


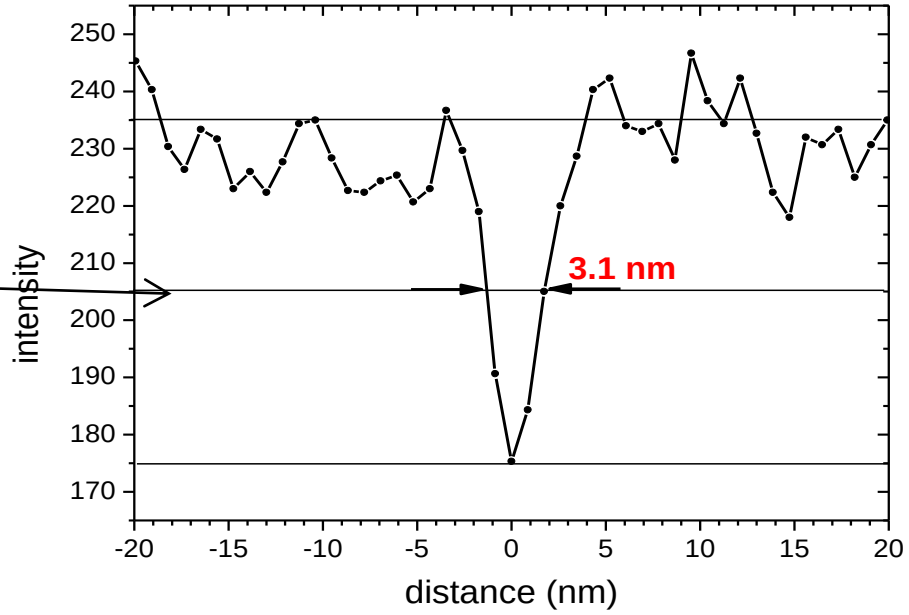
Resolution limit	without correction	with correction
Spherical	$\alpha^3 + \ldots$	α^5
Chromatic	$\Delta E\ \alpha + \ldots$	$\Delta E\ \alpha^2 + \Delta E^2\ \alpha$
Diffraction	$1/\alpha$	$1/\alpha$

D. Preikszas, H. Rose, J. Electr. Micr. 1 (1997) 1
Th. Schmidt, D. Preikszas, H. Rose et al., Surf.Rev.Lett 9 (2002) 223

First results of the SMART microscope @BESSY

Atomic steps on Au(111),
LEEM 16 eV, FoV = 444 nm x 444 nm
(18.09.06)





Courtesy of Th. Schmidt et al.; 5th Int. Conf. LEEM/PEEM, Himeji, 15.-19. Oct. 2006

Lateral resolution limitations: space charge

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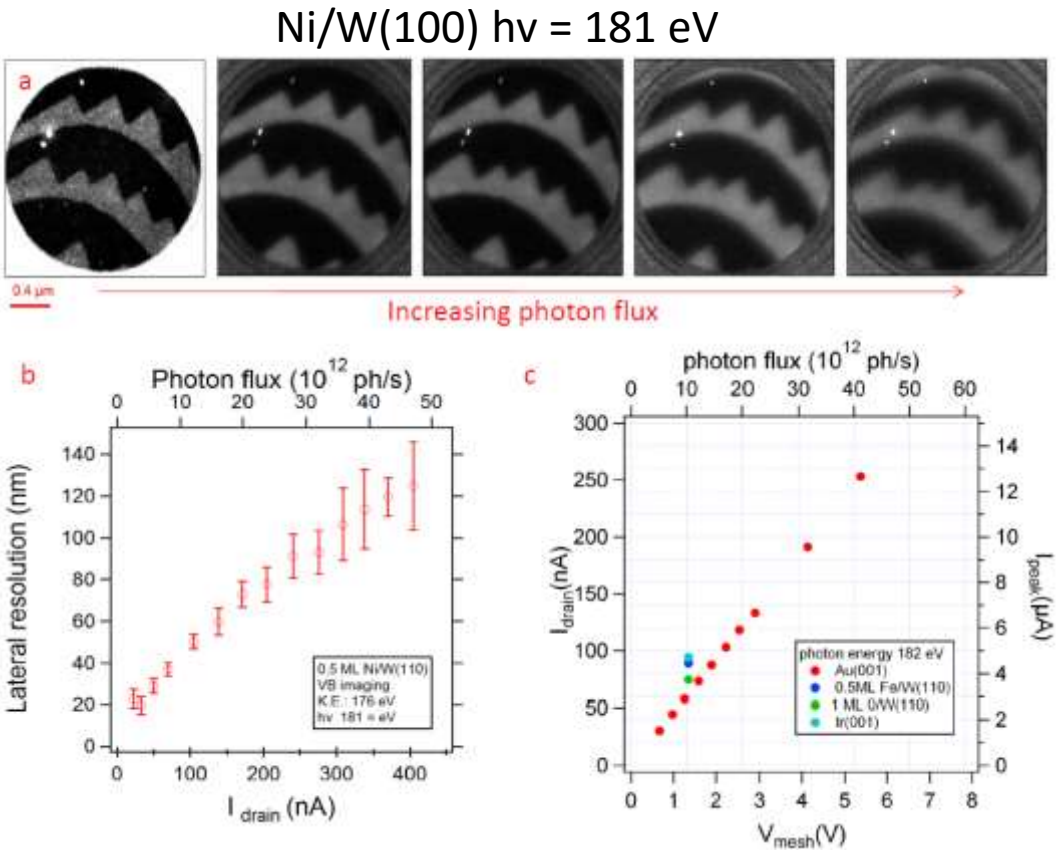


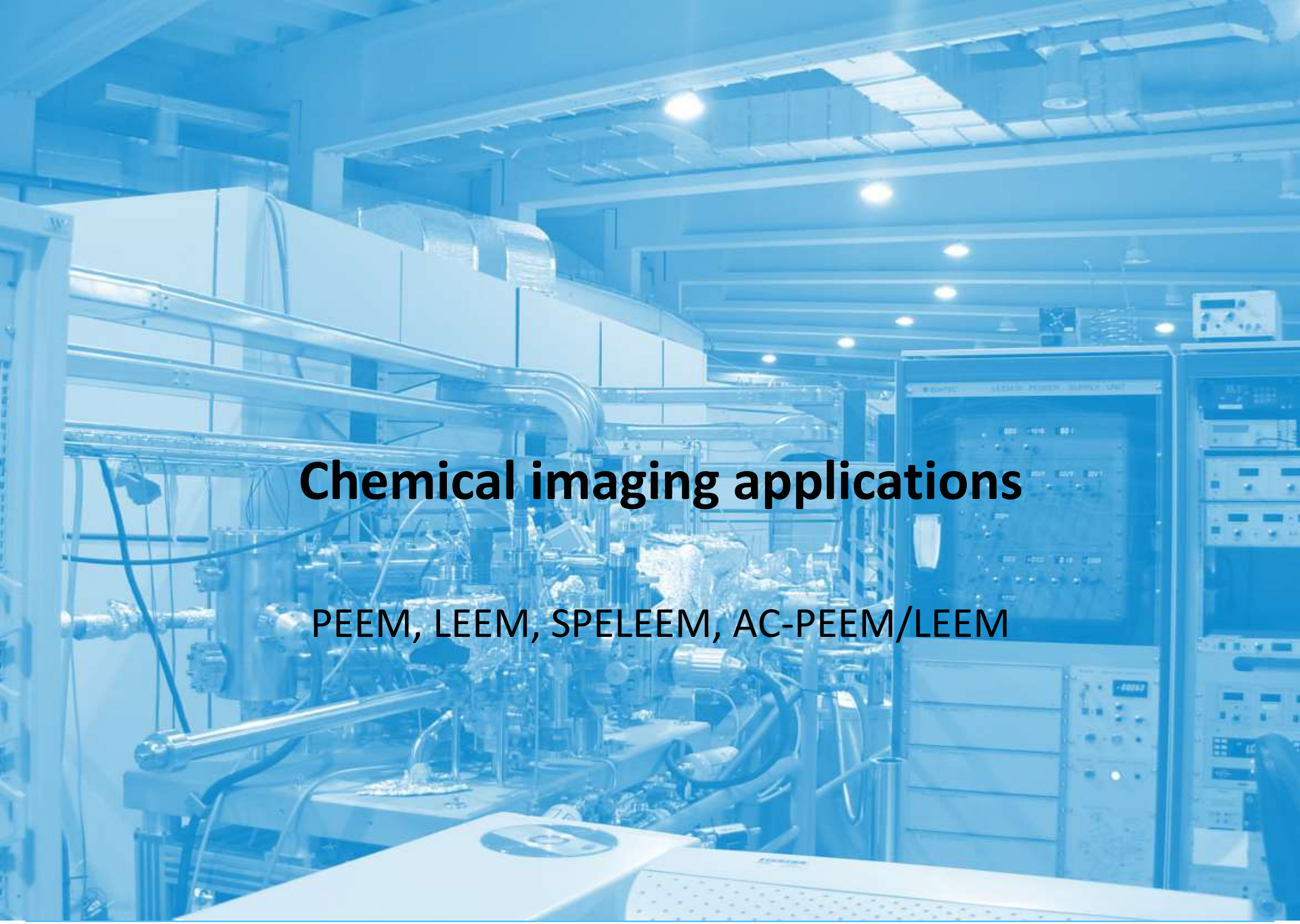
photocurrent estimate for SPELEEM@Elettra; Au/W(110)

- 440 bunches
  rev. frequency: 1.157 MHz
  bunch length: 42 ps (2GeV)
- 1 10^{13} ph./s on sample =
  = 20000 ph./bunch
- Total photoionization yield: about 2% photons result in a photoemission event
- $I_{peak} \approx 400\ e^-/\ 42$ ps
  ≈ 1.5µA vs 20 nA (LEEM)

13 pA/µm^2 versus 20 nA/µm^2

1. Image blur can be observed with SR but only under very high photon fluxes. Must Keep into account in beamline design. No space charge in LEEM
2. Both the lateral and energy resolution are strongly degraded by Boersch and Loeffler effects occurring in the first part of optical path.

Ultramicroscopy **111**, 1447 (2011).



Chemical imaging applications

PEEM, LEEM, SPELEEM, AC-PEEM/LEEM

$Au/TiO_2(110)$: controlling growth by vacancies

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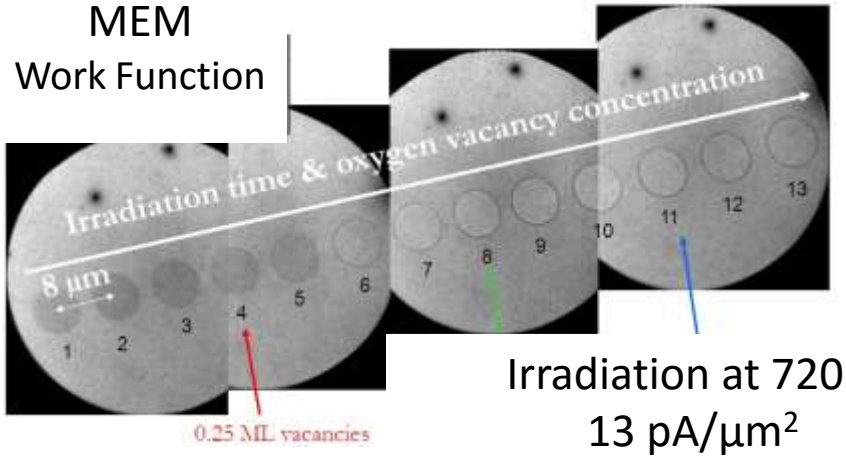
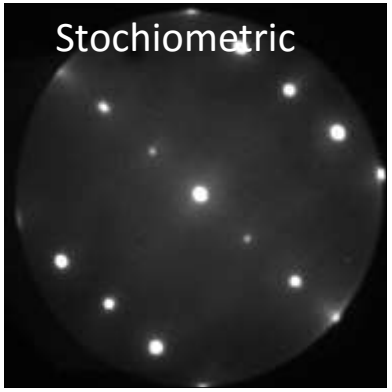
Creation of ordered oxygen vacancies

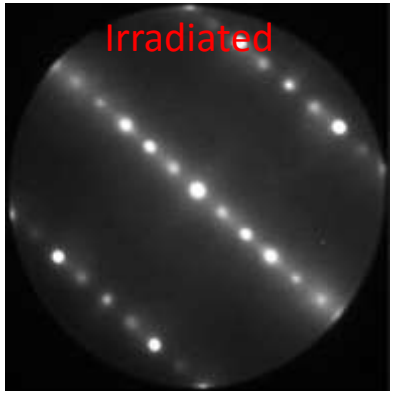
MEM
Work Function



Irradiation at 720 K
13 pA/μm²

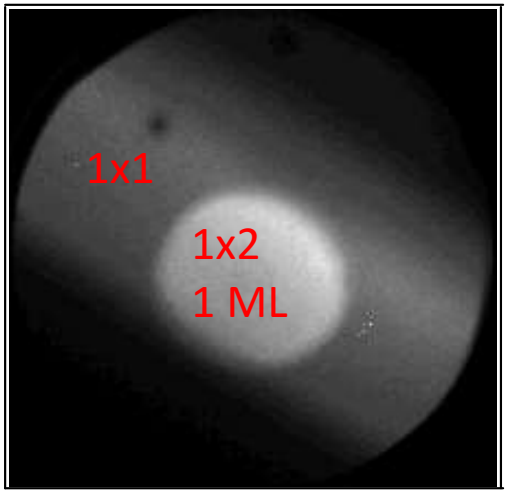


(1x1)



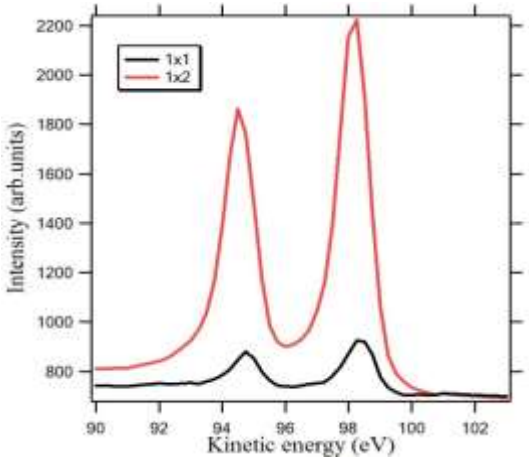
(1x2)

Au growth on $TiO_2(110)$



XPEEM
@ Au 4f

μ-LE
struc



μ-XPS

Surface Oxygen on Ag : *e-beam "Lithography"*

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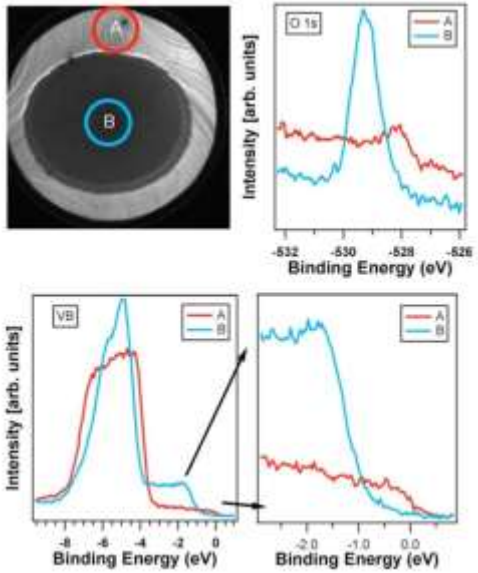
Full oxidation of Ag using NO_2 does not occur:

$$NO_2 \rightarrow NO_{ad} + O_{ad}$$

Instead: e-beam (60 eV) stimulated desorption of NO_{ad} works at RT!

Low T: NO_{ad} stays, prevents oxidation.

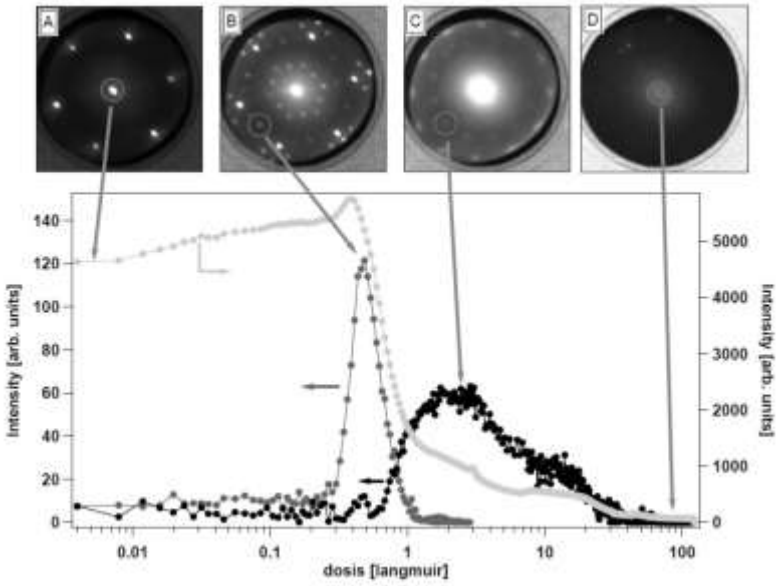
High T: NO_{ad} desorbs, but Ag_2O unstable.



A: metallic Ag
B: Ag_2O

S. Günther *et al.*, *App. Phys. Lett.* 93, 233117 (2008).

LEED reveals path towards Ag_2O under e-beam



S. Günther *et al.*, *Chem. Phys. Chem.* 2010.

Thickness dependent reactivity in Mg

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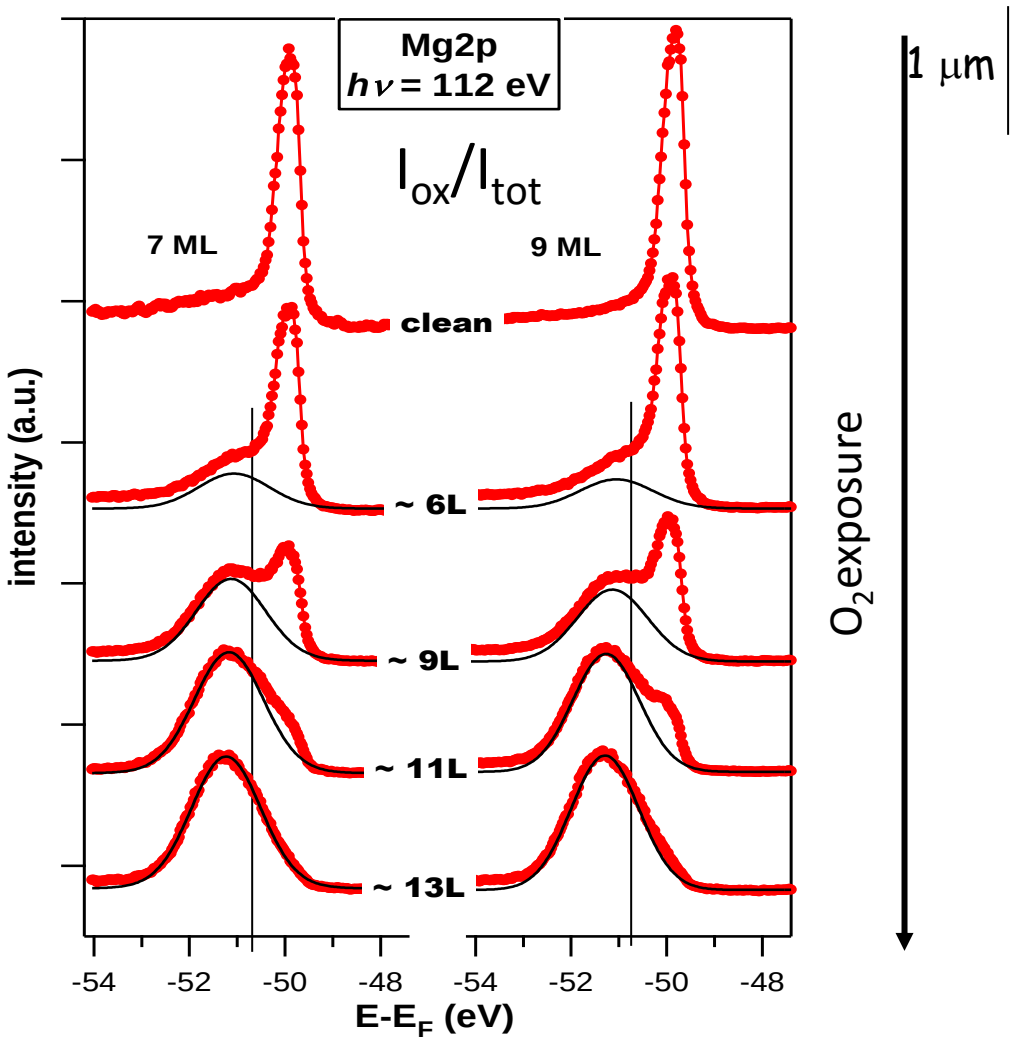
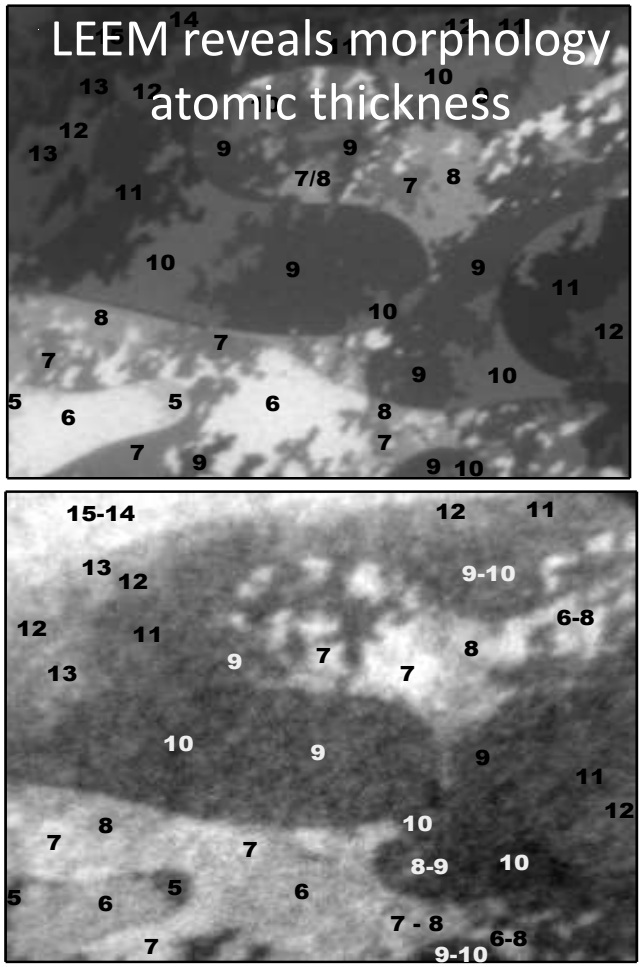


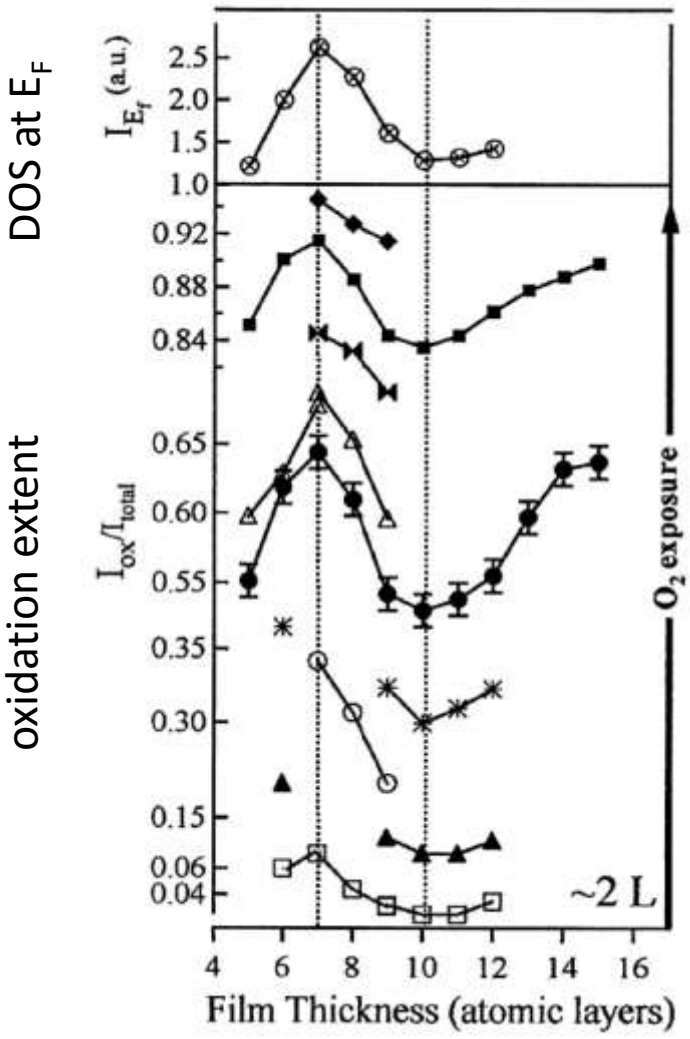


Oxide component reveals chemistry!

L. Aballe *et al.*, Phys. Rev. Lett. **93**, 196103 (2004)

Oxidation of Mg film and QWR

Elettra Sincrotrone Trieste



FACTS

- ✓ Strong variations in the oxidation extent are correleted to thickness and to the density of states at E_F
- ✓ XPEEM is a powerful technique for correlating chemistry and electronic structure information

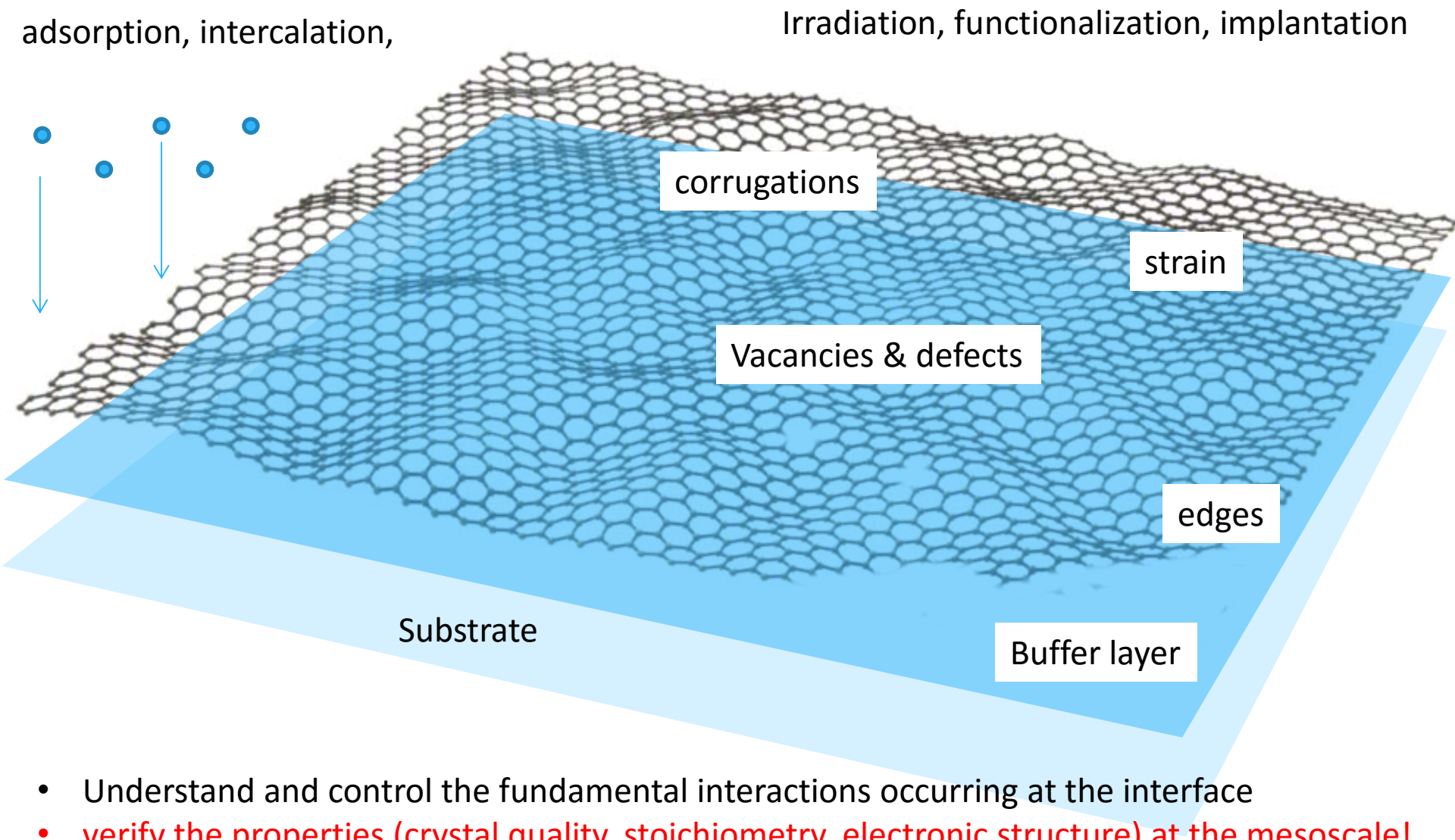
SIGNIFICANCE OF THE EXPERIMENTS

- ✓ Control on film thickness enables modifying the molecule-surface interaction
- ✓ Theoretical explanation: Decay length of QWS into vacuum is critical: it reproduces peak of reactivity in experimental data. See Binggeli and M. Altarelli, Phys.Rev.Lett. 96, 036805 (2005)

L. Aballe *et al.*, Phys. Rev. Lett. 93, 196103 (2004)

XPEEM studies of the metal-graphene interface

Elettra Sincrotrone Trieste

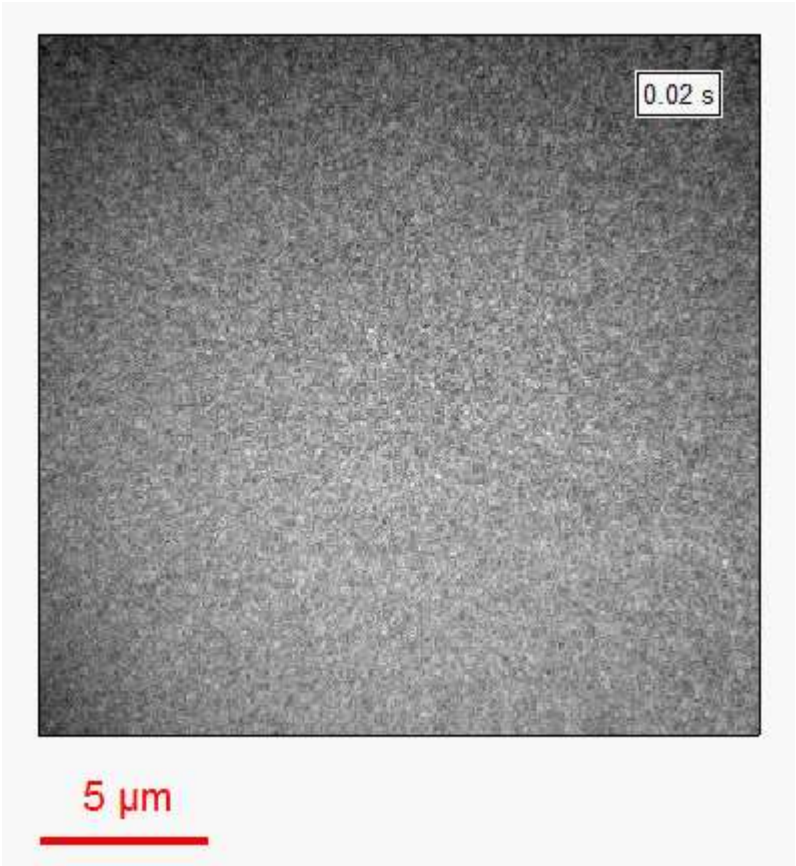


- Understand and control the fundamental interactions occurring at the interface
- verify the properties (crystal quality, stoichiometry, electronic structure) at the mesoscale!

High temperatrue graphene growth on Ir(100)

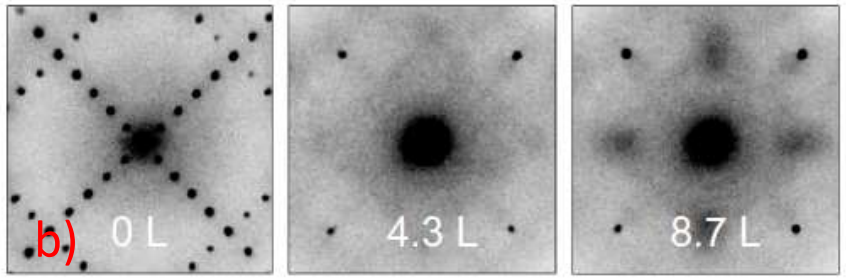
Elettra Sincrotrone Trieste

LEEM imaging

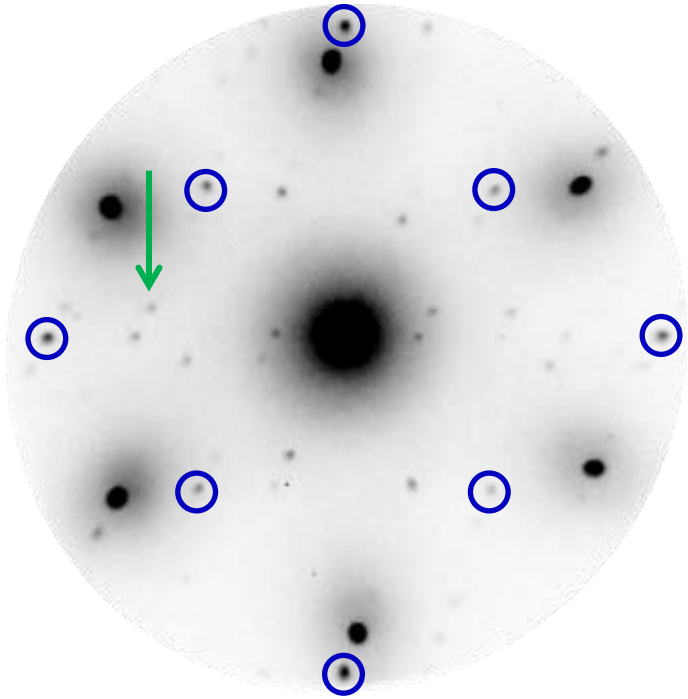


T > 800 C;P=2·10^{-8} mbar ethylene

microprobe-LEED: Ir

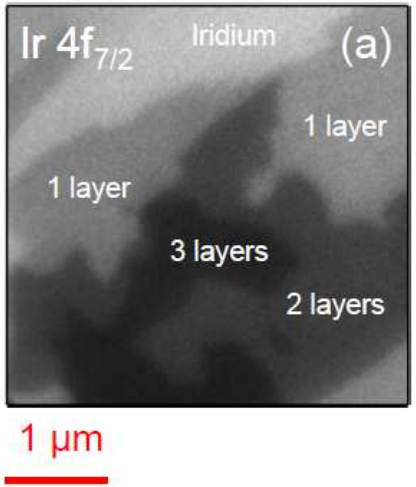


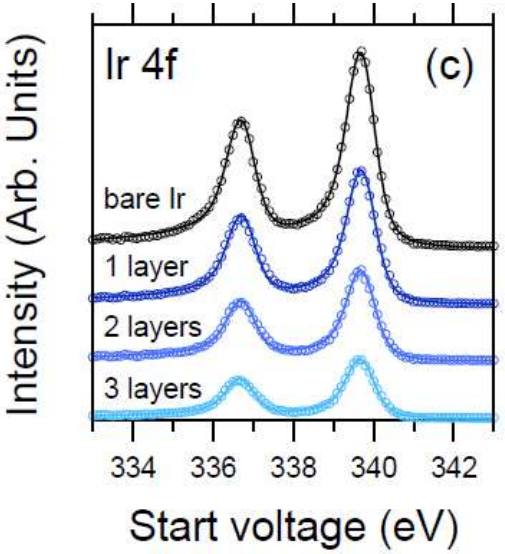
microprobe-LEED: graphene

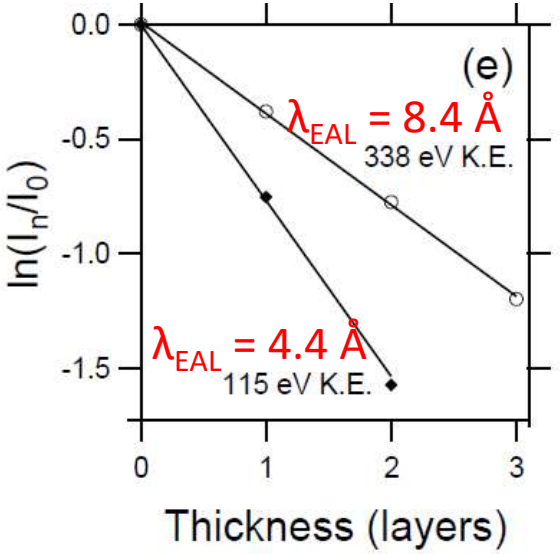


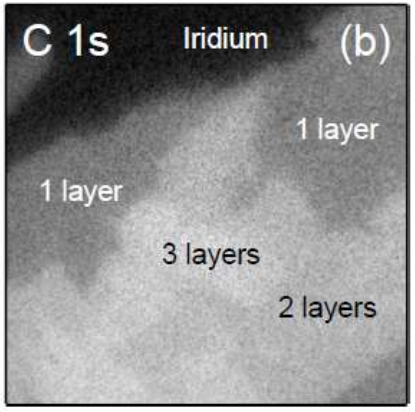
Graphene thickness determination

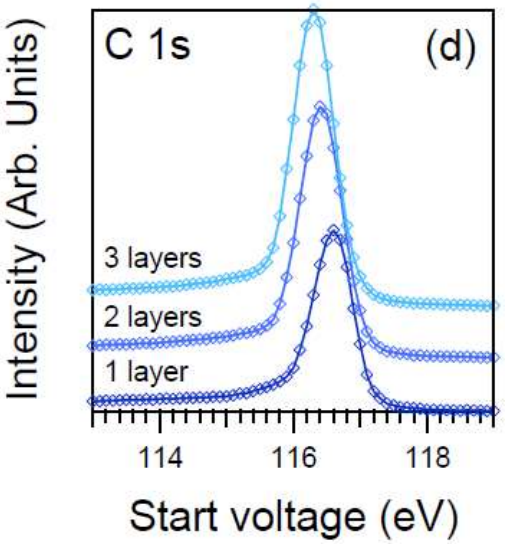
Elettra Sincrotrone Trieste

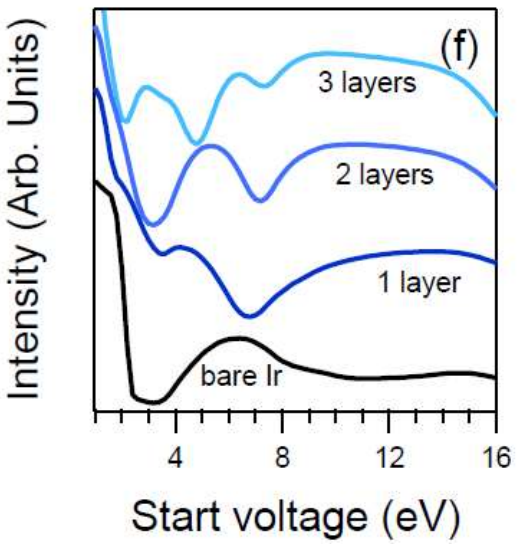










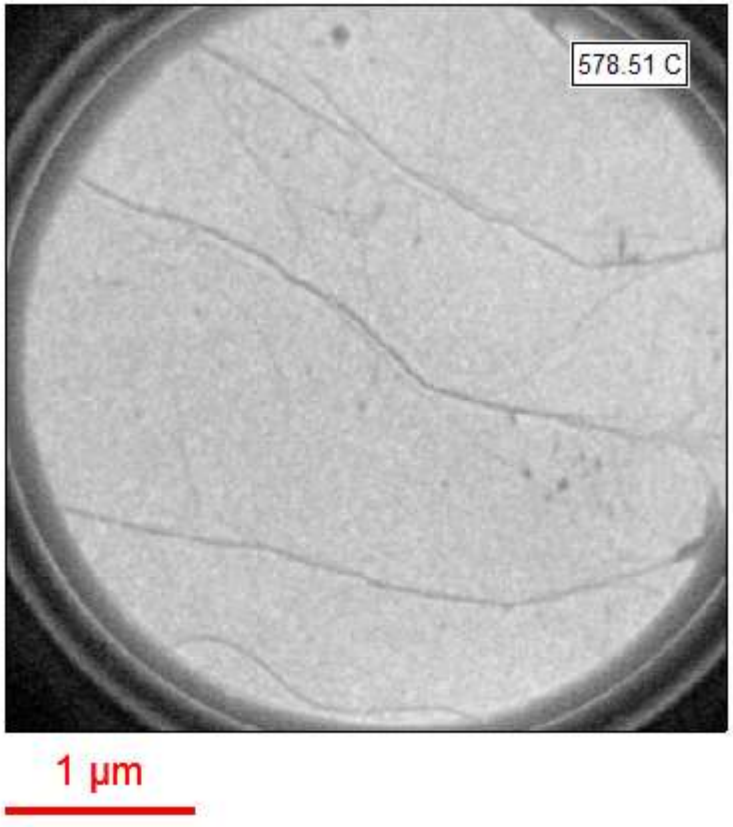


Growth on Ir(100) at 760°C: formation of multilayers

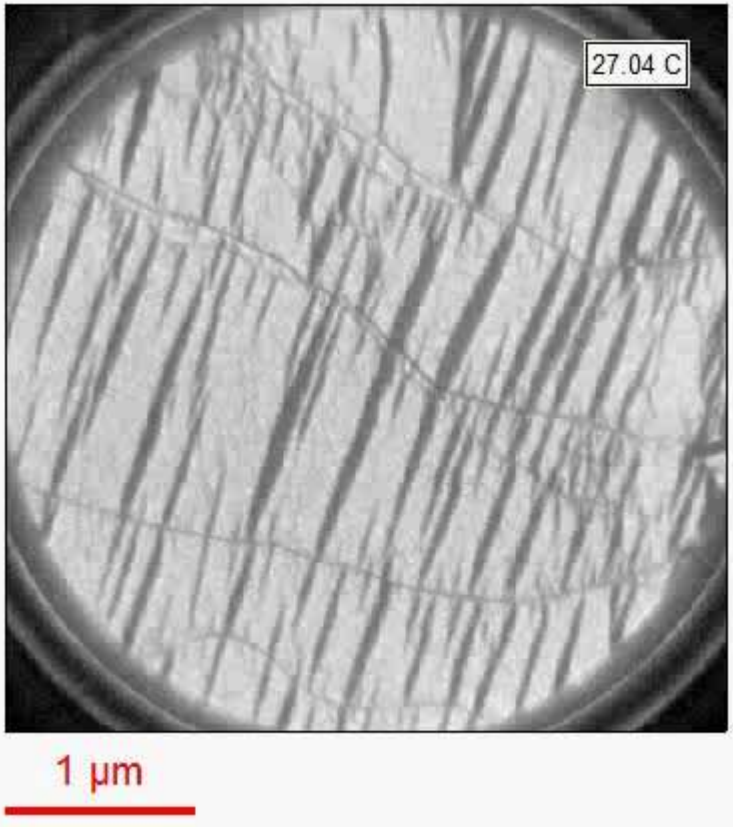
Reversible graphene phase transformation

Elettra Sincrotrone Trieste

Upon cooling a new graphene phase nucleates (dark stripes)



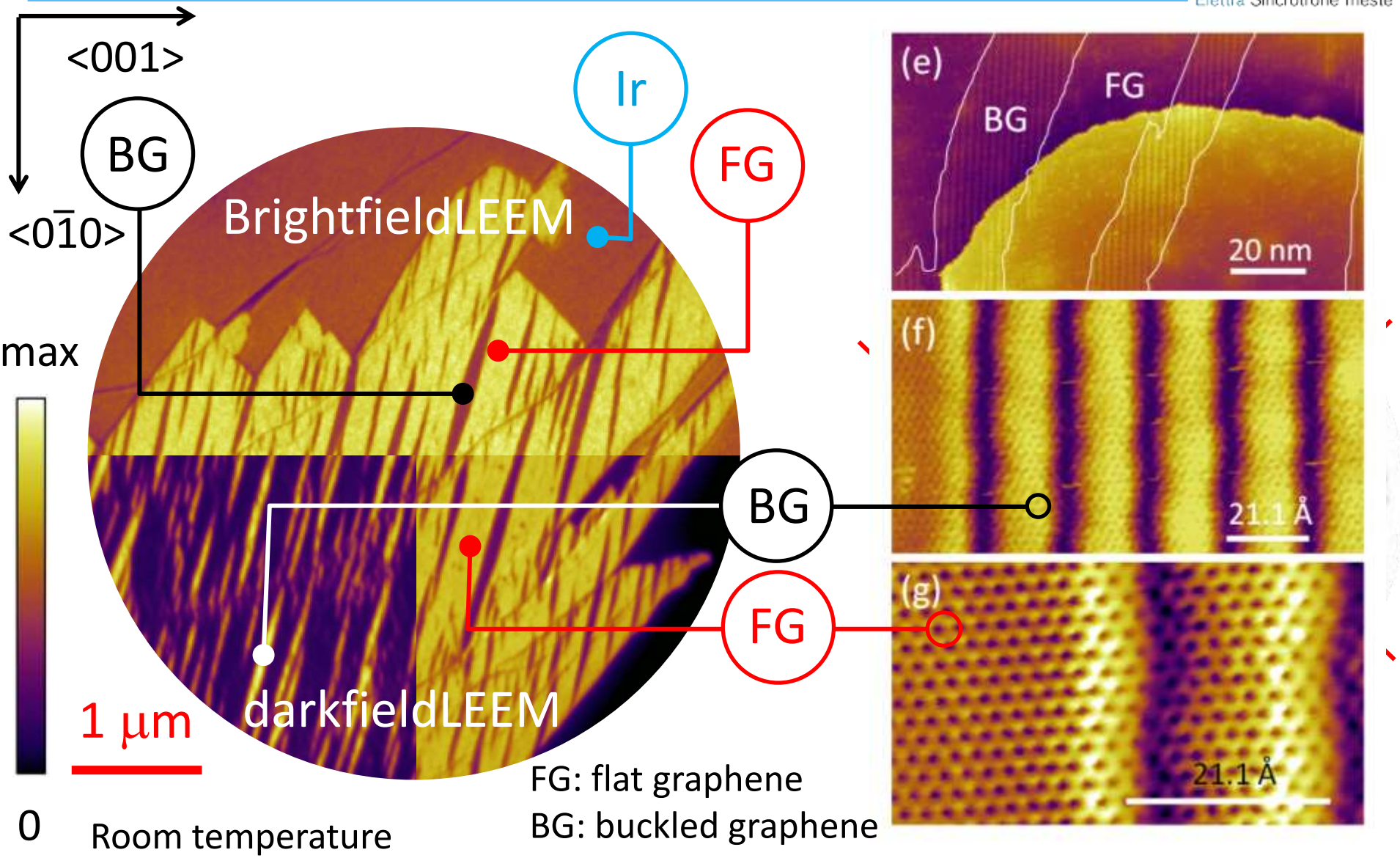
The stripes disappear upon annealing to high temperature.



LEEM, Fov 4 µm, S.V. 13 eV

Graphene/Ir(100): strucutre of FG and BG

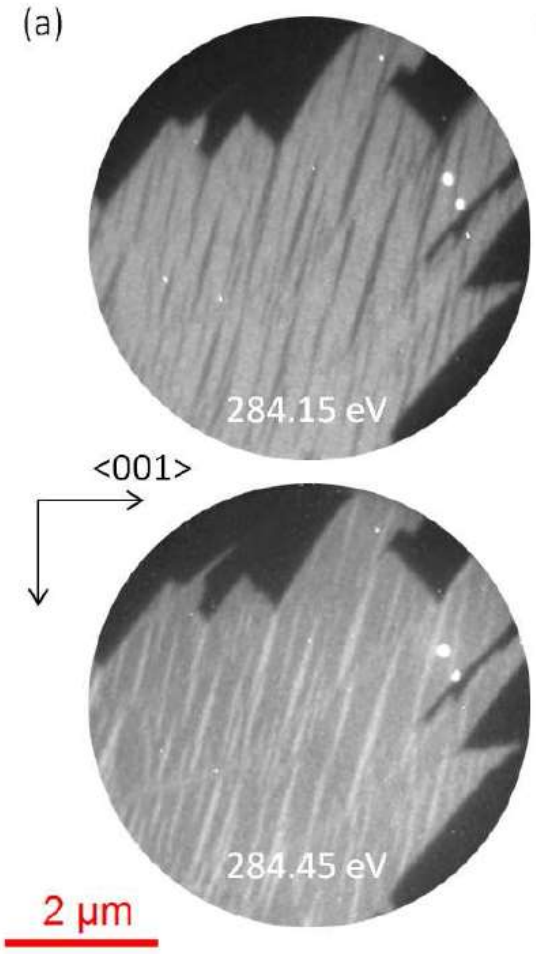
Elettra Sincrotrone Trieste

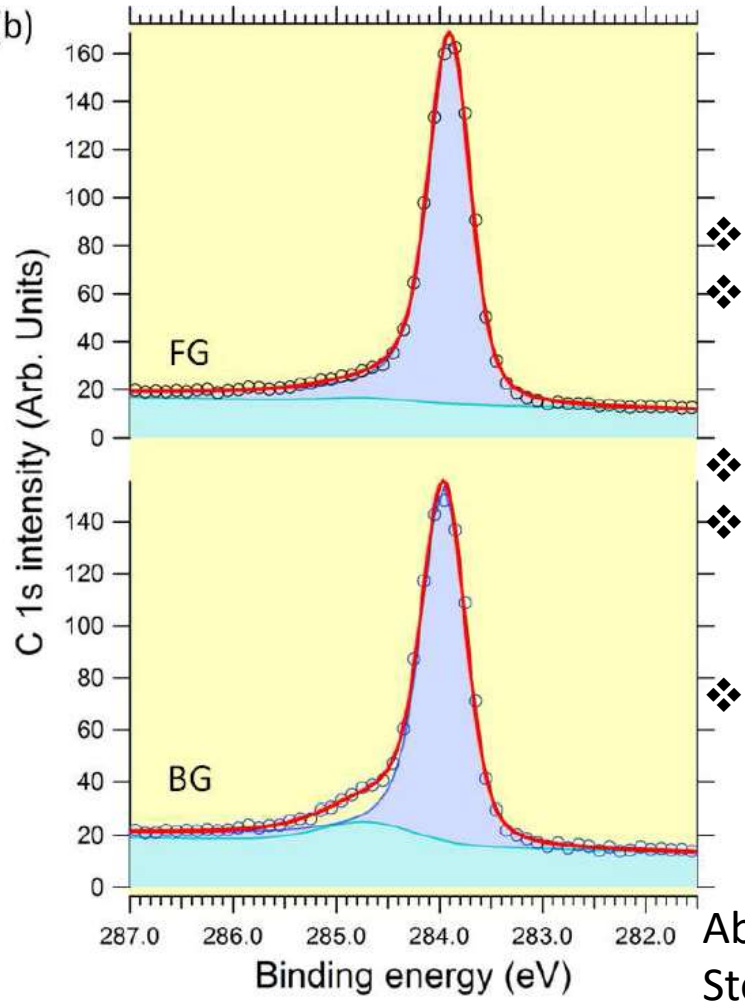


Buckled graphene unit cell by ab-initio

Elettra Sincrotrone Trieste

buckled graphene unit cell





Buckled Graphene

Exceptionally large buckling

GGA:

- Min Ir-C distance of 1.9 Å
- Max Ir-C distance of 4.0 Å

DFT-D:

- Min Ir-C distance of 2.1 Å
- Max Ir-C distance of 3.7 Å

- 18 atoms over 160 (i.e. 11%) are **chemisorbed**, the others are physisorbed

Ab-inito calculations by N. Stojic, N. Binggeli, ICTP;

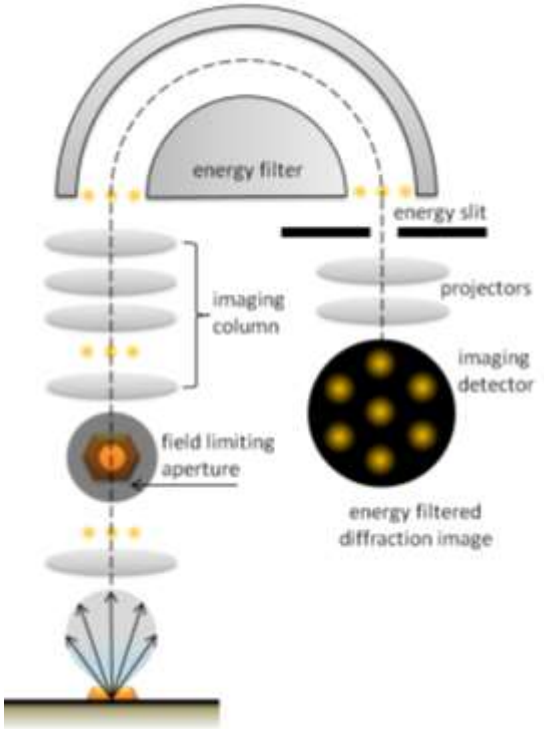
Buckled graphene shows regular one-dimensional ripples with periodicity of 2.1nm.

Electronic structure: graphene doping

Elettra Sincrotrone Trieste

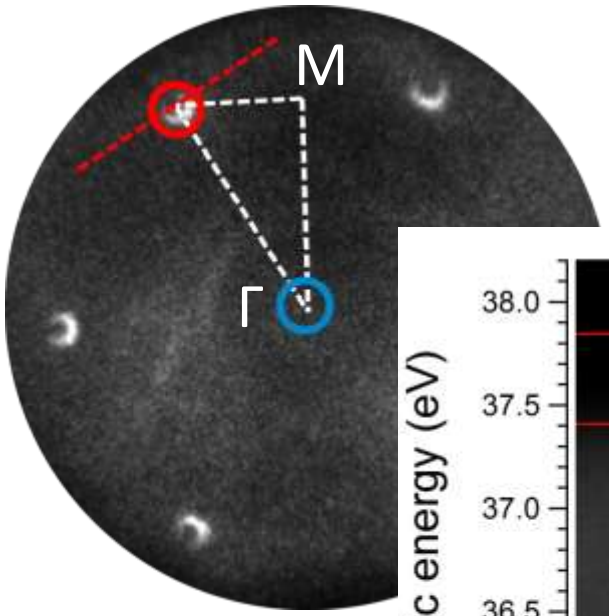
microprobe diffraction cannot resolve FG and BG!

Diffraction Imaging



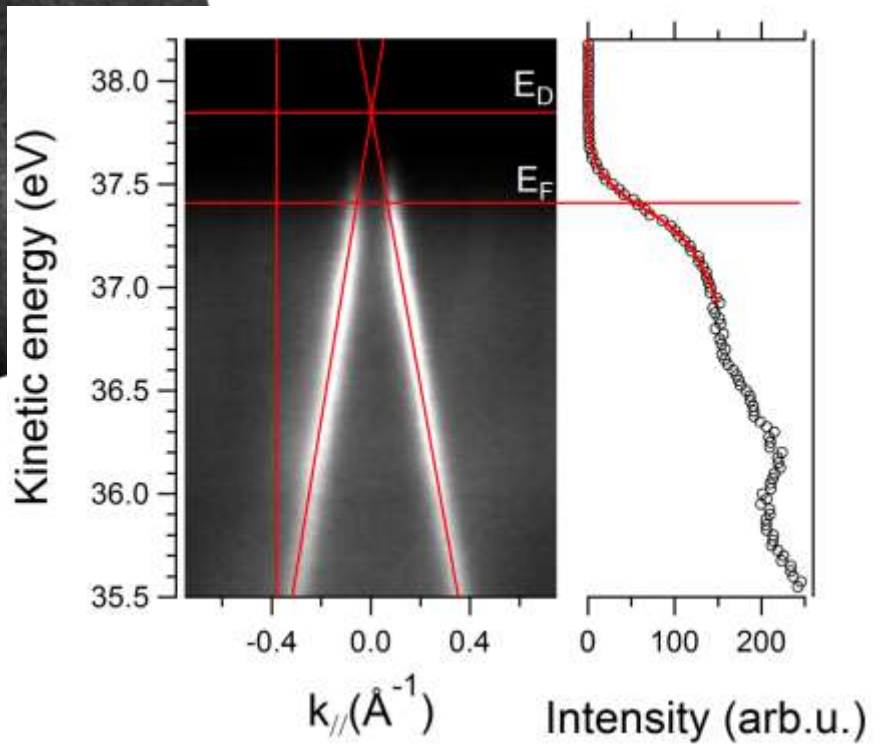
Microprobe measurements limited to 2 um in dia.

μ – ARPES



P-type doping

E_D = 0.42 eV

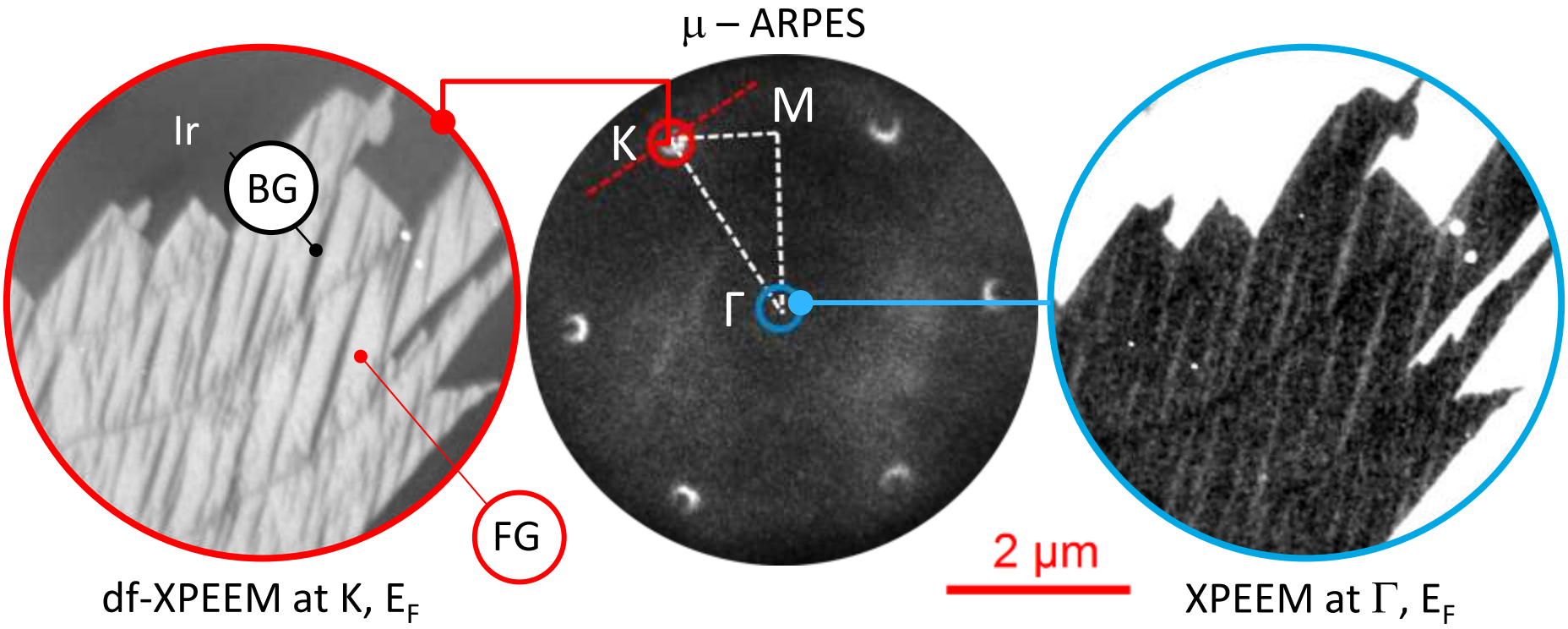


A. Locatelli et al; ACS Nano, ACS Nano, 7, 6955–6963 (2013)

Electronic structure - experiment

Elettra Sincrotrone Trieste

Issues: what is the difference in electronic structure between FG and BG?
do they both show the same Dirac-like dispersion?

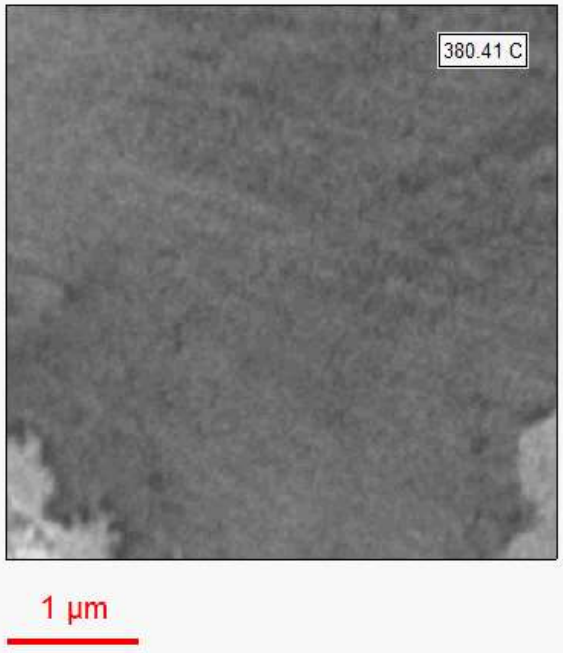


- emission from the π band at K allows quantifying local DOS of FG and BG phases.
- DF-PEEM images at E_F clearly indicate that **only FG** shows high DOS at K.
- much reduced DOS and contrast inversion at Γ→ BG hybridization and metallicity.
- Microprobe-ARPES data are thus representative of the FG phase, not the BG one!

Carbides formation/dissolution under rot. Graphene/Ni(111)

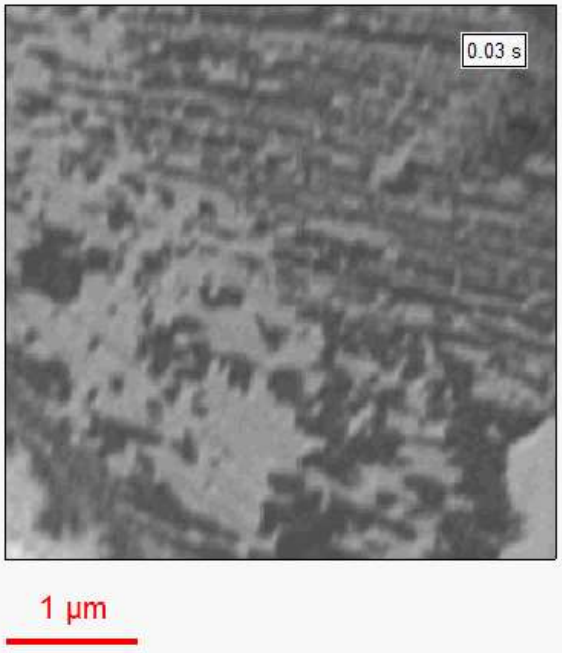
Elettra Sincrotrone Trieste

1: carbide nucleation



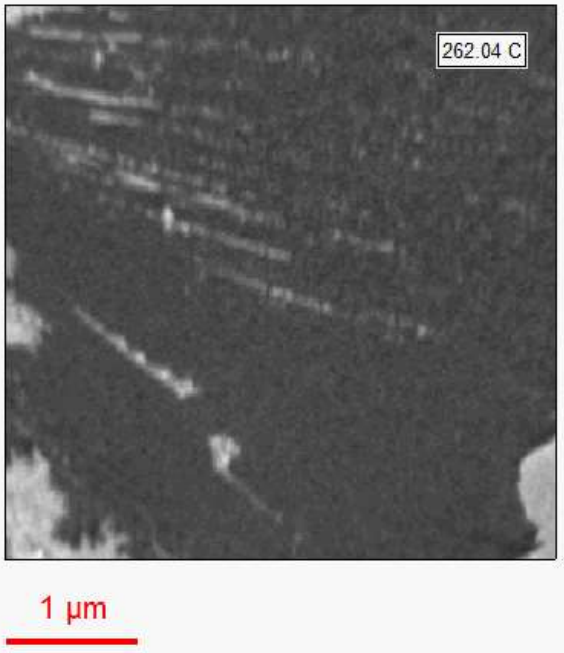
The Ni-carbide nucleates under rotated graphene, T < 340°C
Patera et al., ACS Nano 7, 7901 (2013)

2: carbide growth



A uniform layer of Ni-carbide is formed below graphene in about two hours

3: carbide growth

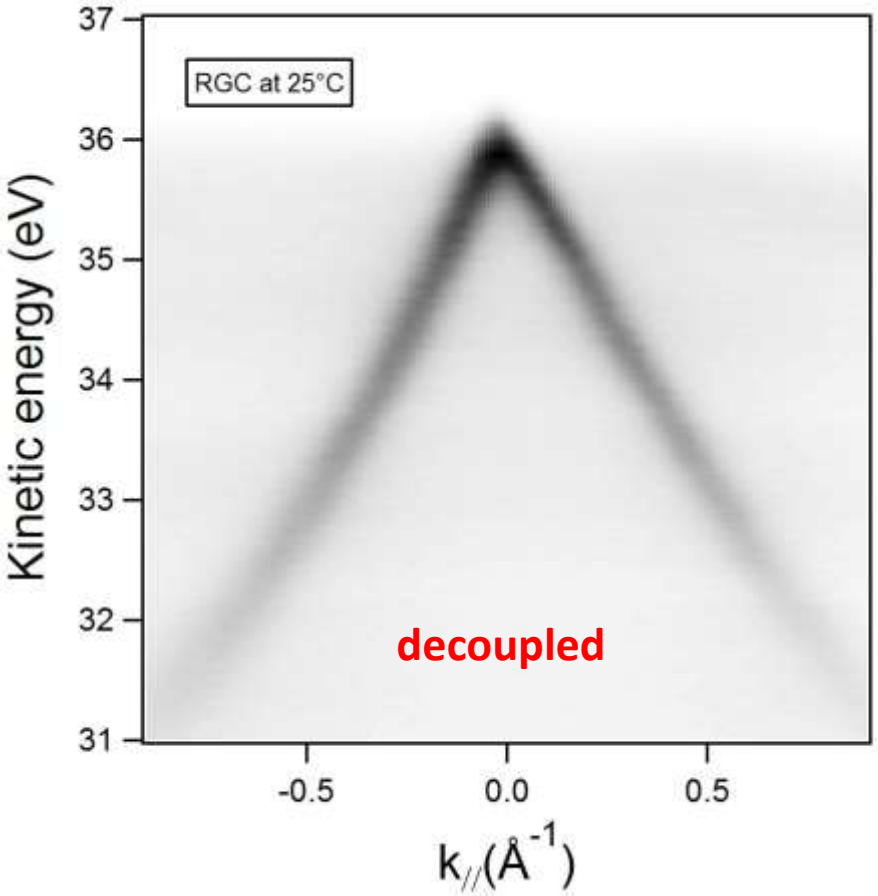


The carbide is dissolved into the bulk at about 360°C. The process is repeatable!

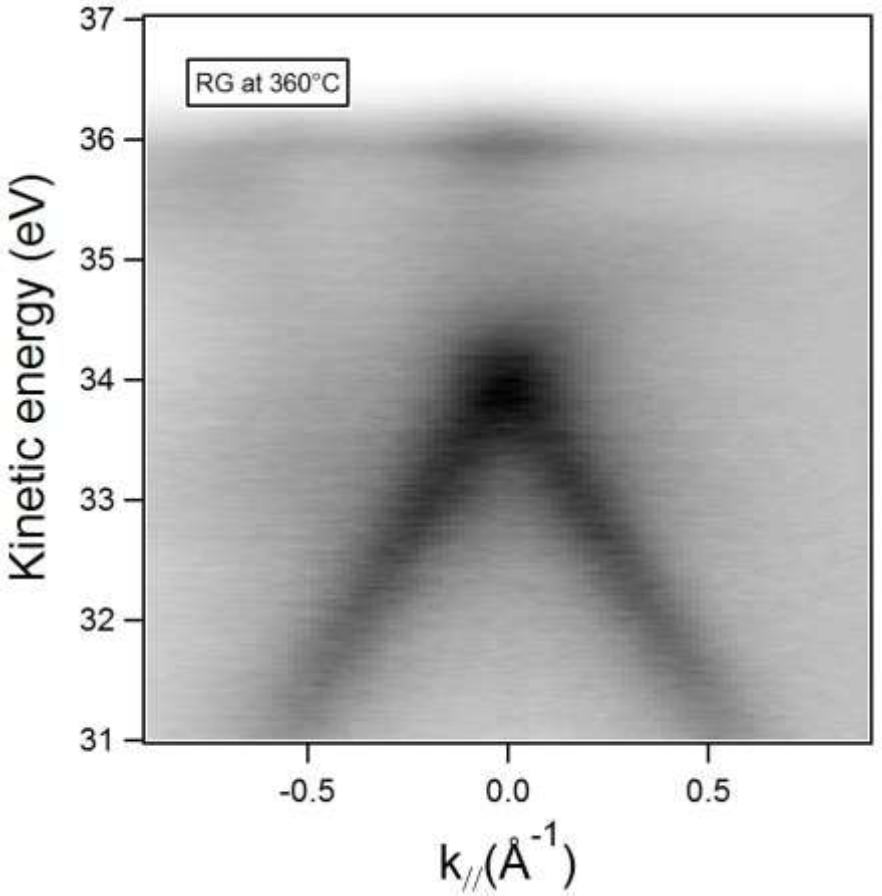
All movies: LEEM FoV 6 um, electron energy: 11 eV

Electronic structure is by μ-ARPES

Elettra Sincrotrone Trieste



Rotated graphene with Ni-carbide underneath at room temperature; There's no double layer



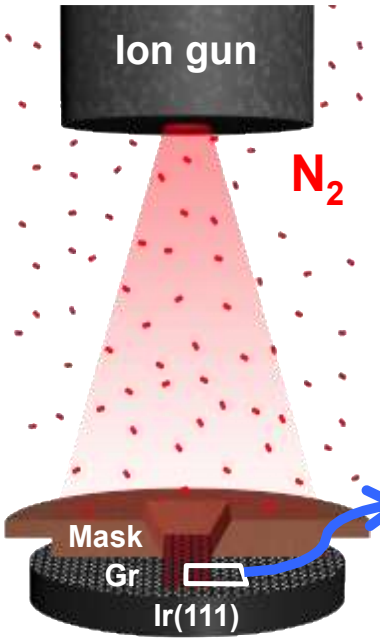
Rotated graphene without Ni-carbide underneath at 365°C

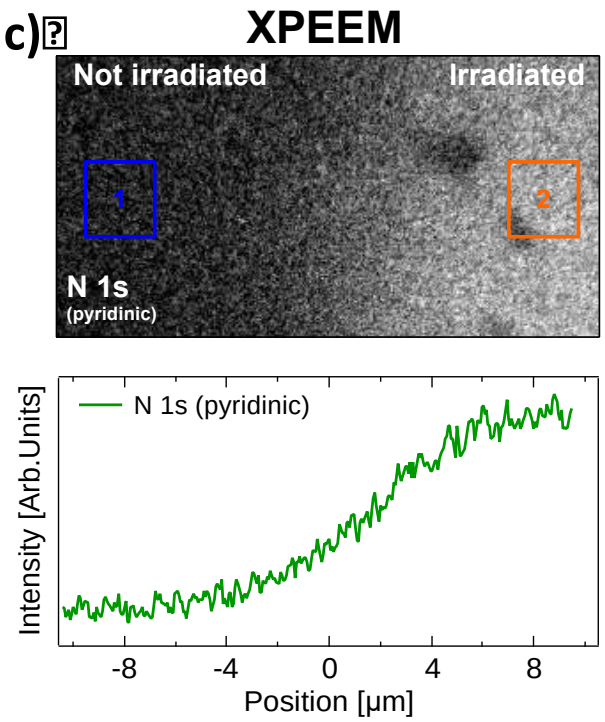
Ion irradiation of graphene:

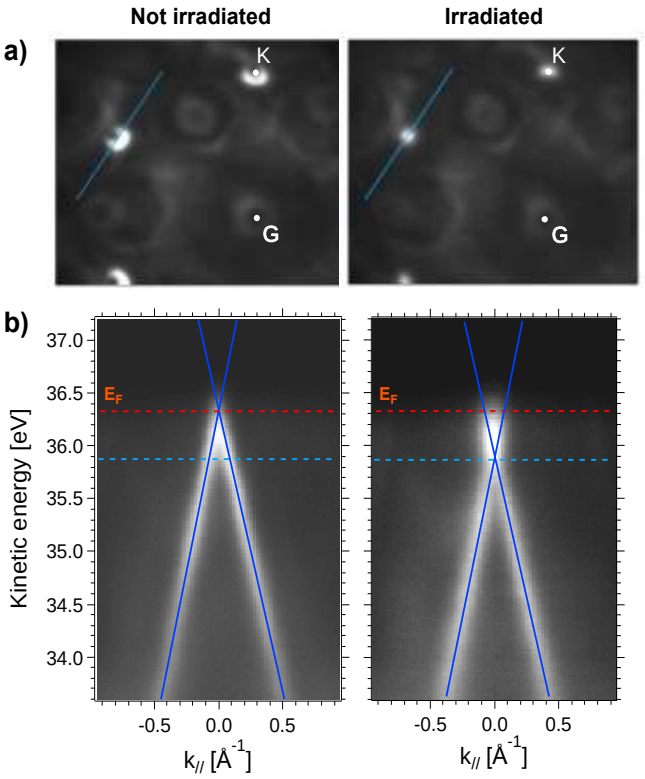
- **Substitutional implantation:**
  - Local doping by low energy ion irradiation
- **Ar nanobubbles ripening under graphene**
  - Strain engineering! [C. Lee et al., Science 321, 385 (2008)]
  - Anvil cells (high pressure) [Xuan Lim et al., Nat. Comm. 4, 1556 (2013)
  - Exhotic magnetic properties [N. Levy et al. Science 329, 544 (2010)]

2D heterojunction by low energy N_2^+ irradiation

Elettra Sincrotrone Trieste







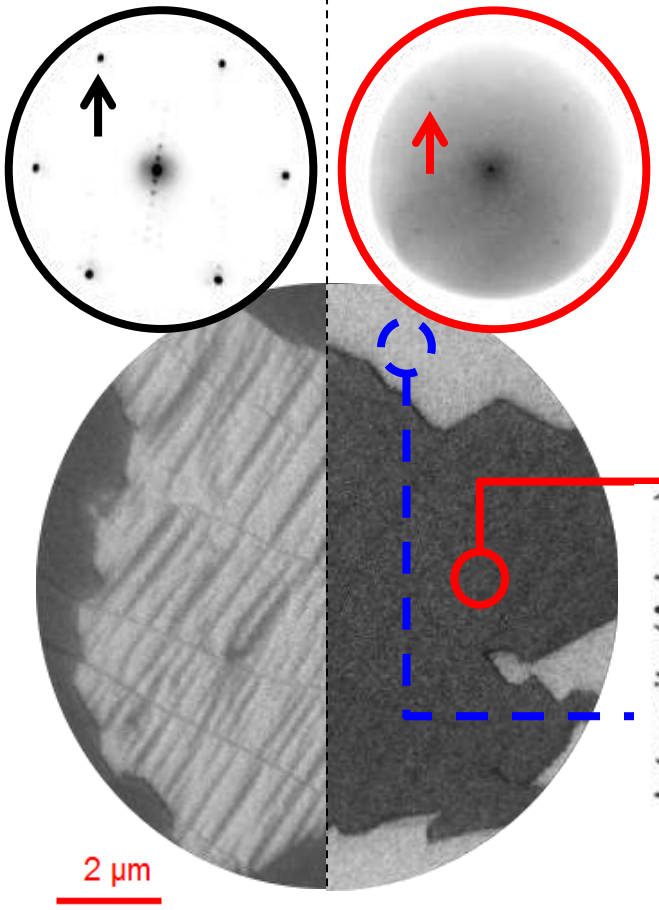
- Small damage to graphene lattice;
- Thermal stability: graphitic: stable above 700°C; pyridinic stable up to 400°C;
- Boundary also stable upon annealing (no migration/loss)
- Negative doping → formation of doping patterns

Morphology of Ar⁺ irradiated graphene/Ir(100)

Elettra Sincrotrone Trieste

(a) LEED

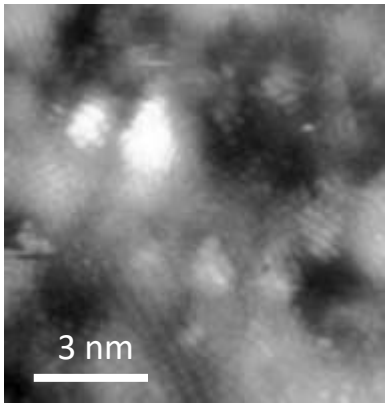
before irradiation | after irradiation



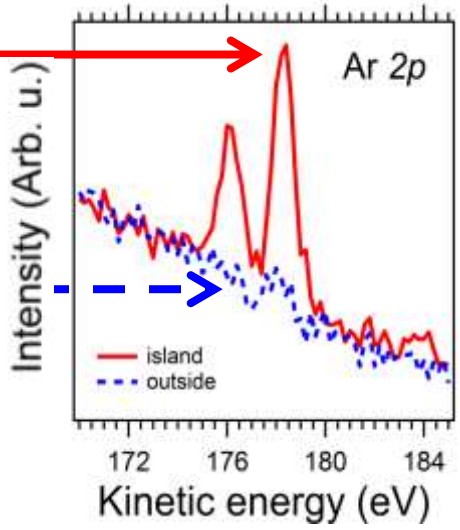
LEEM 12 eV

Irradiation with 0.5keV Ar⁺ 7 s

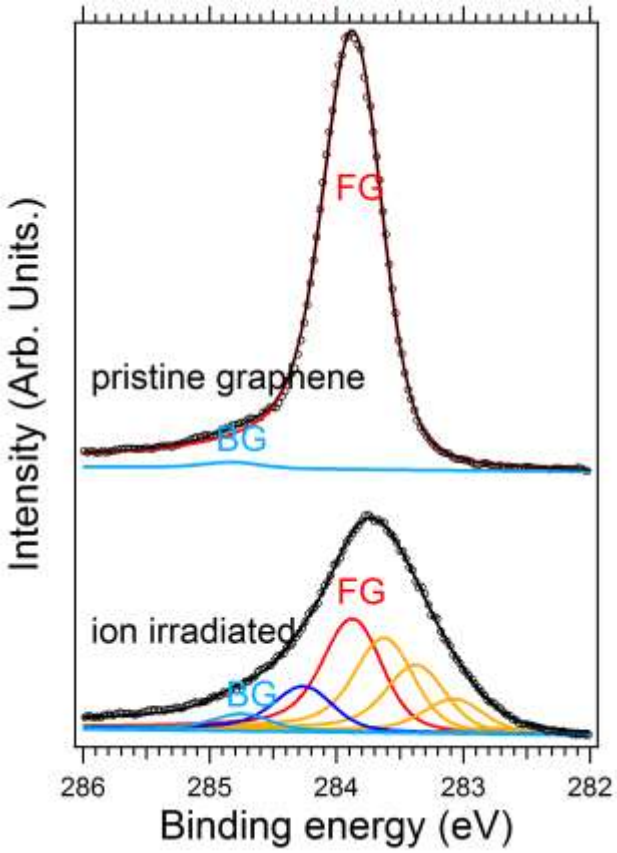
(b) STM



(c) XPEEM



Rough morphology, but …
graphene is <u>continuous</u>
average height 0.15 nm!



Evolution upon annealing: STM and μ-XPS

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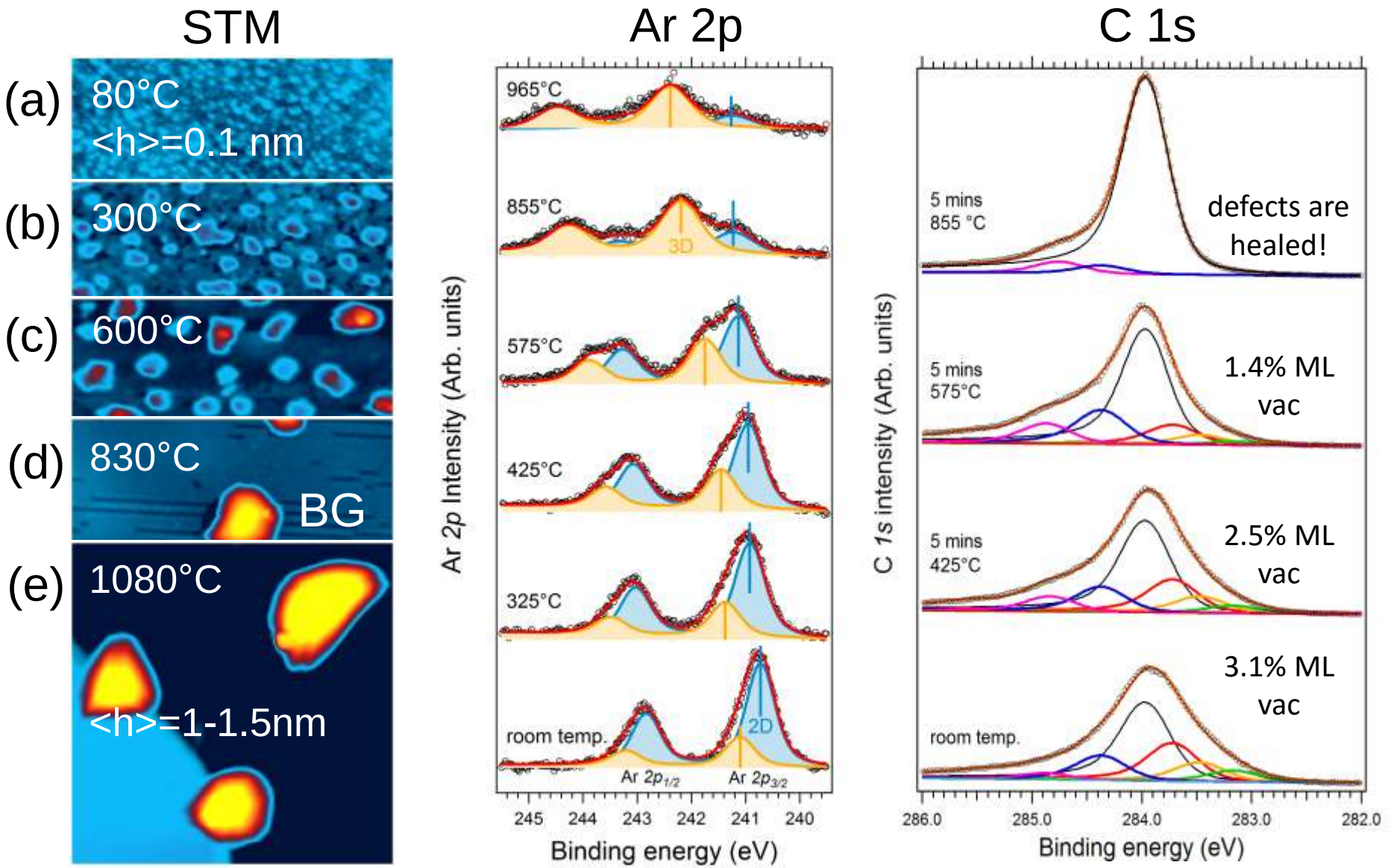
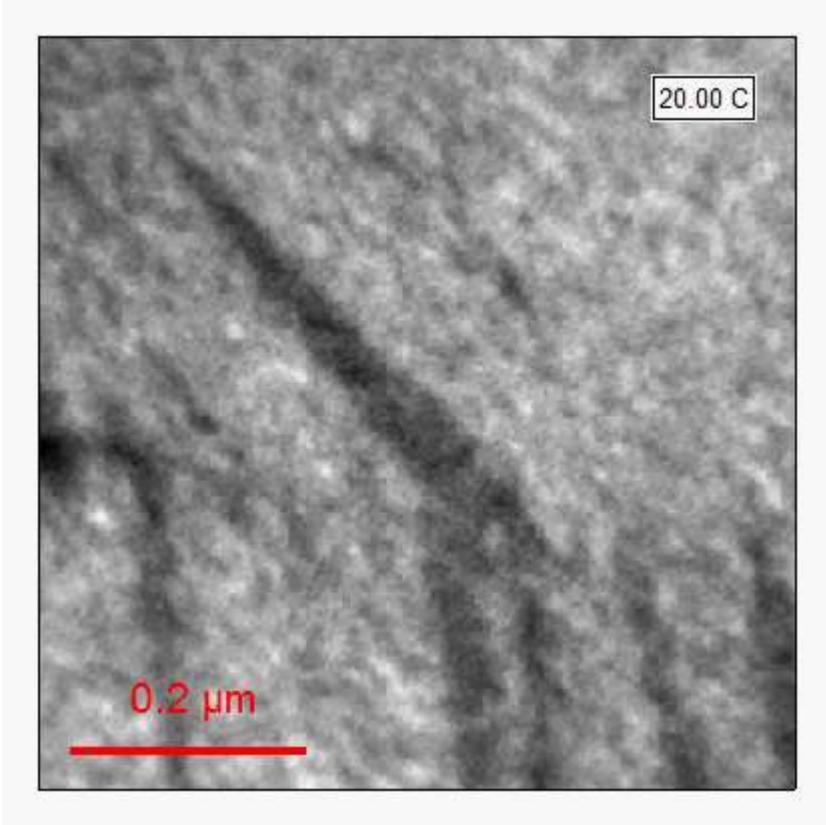


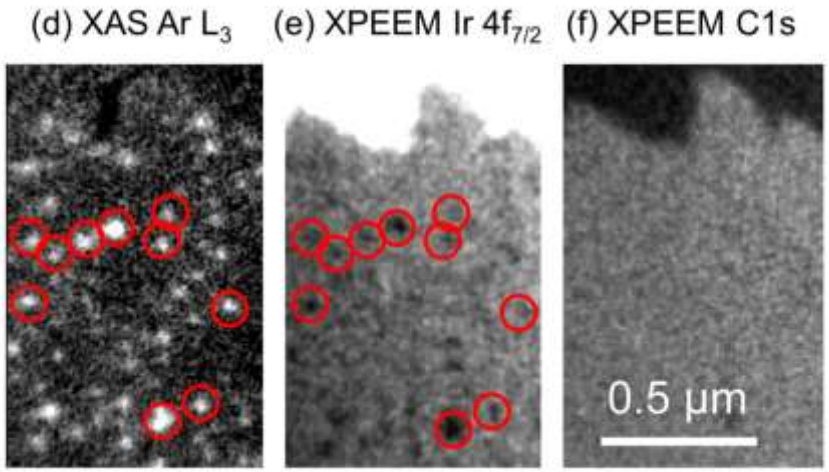
Irradiation with 0.1keV Ar^+ 150 s and 5 min annealing; The XPS data were acquired at RT

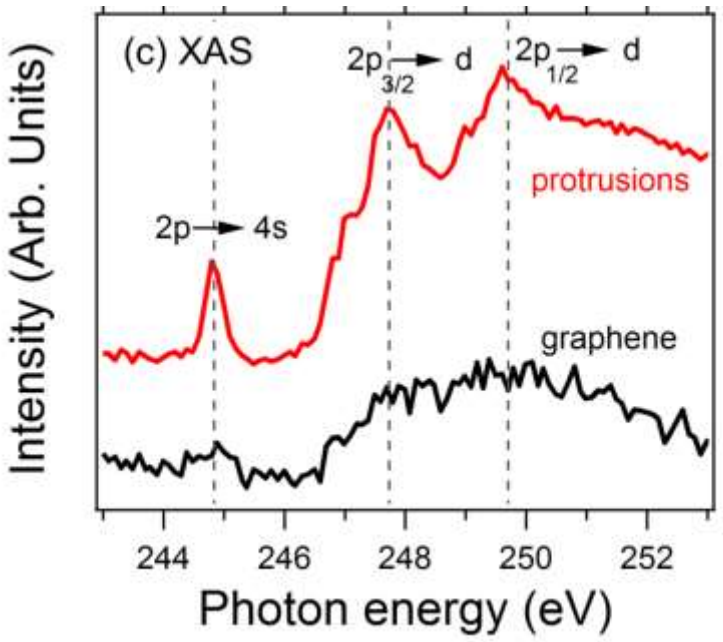
LEEM & XPEEM formation of Ar nanobubbles

Elettra Sincrotrone Trieste

LEEM movie 12 eV







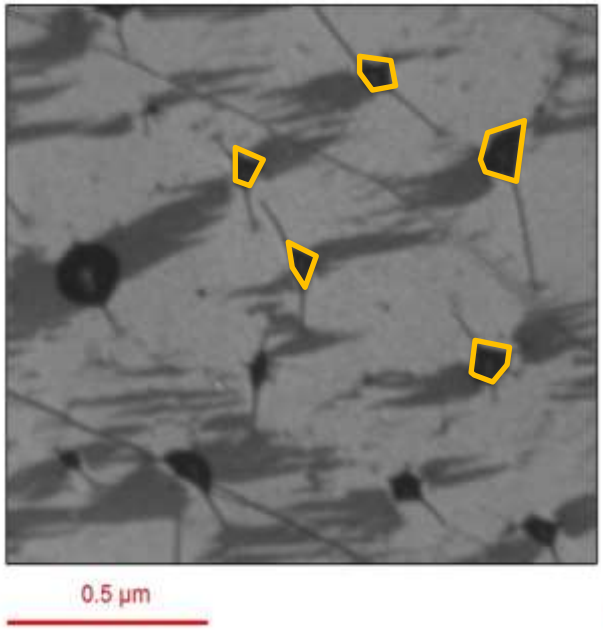
G. Zamborlini et al., *Nano Lett.*, 2015, 15 (9), pp 6162–616

NB formation for g/Ne/Ir(100)

Elettra Sincrotrone Trieste

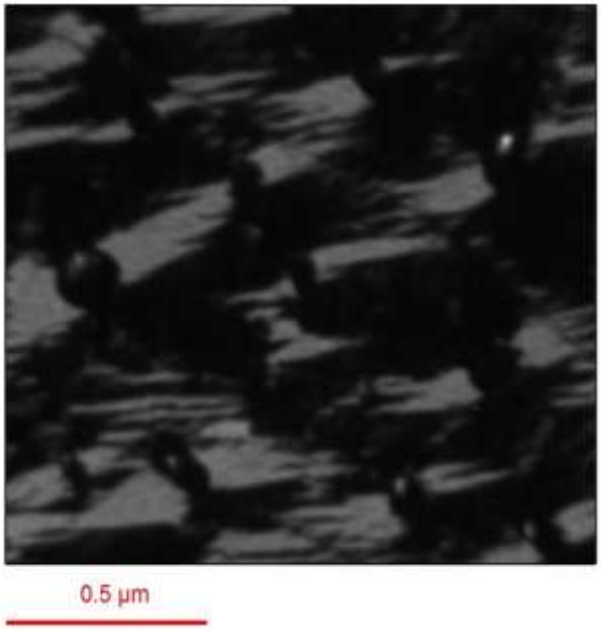
100 eV Ne+ ion irradiation was followed by 5 min annealing to 650 °C and subsequent cooling to RT

bright-field LEEM 12 eV

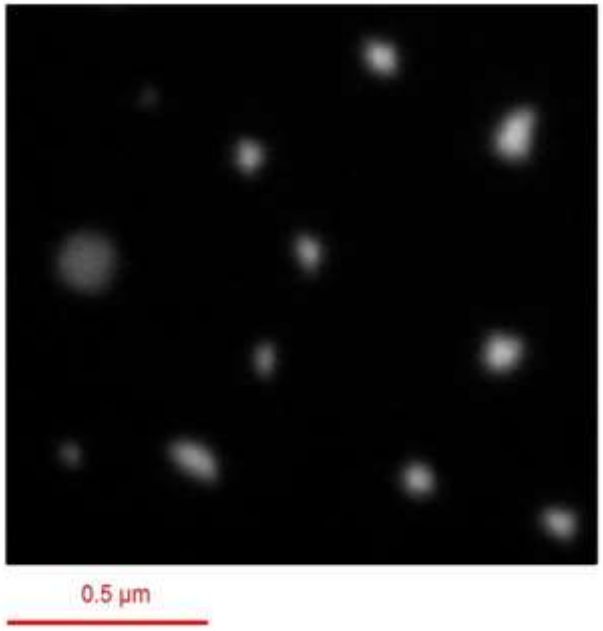


- Wrinkles surround the larger particles
- At RT, bubbles have a polygonal shape → solid?

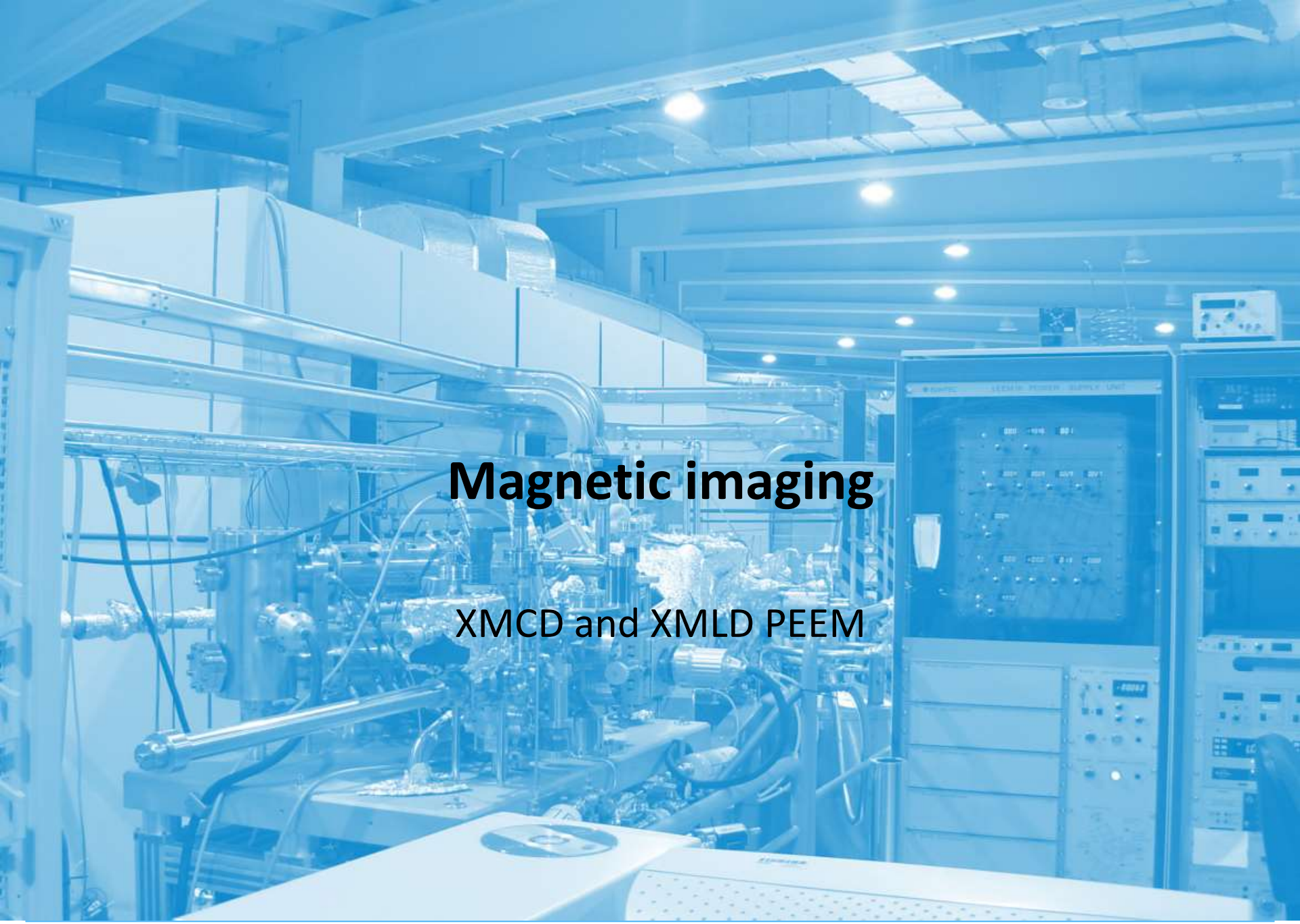
dark-field LEEM BG phase



XPEEM imaging Ne 2p



- elemental composition below graphene!
- XPS from individual particles
- Shift to high BE for large clusters

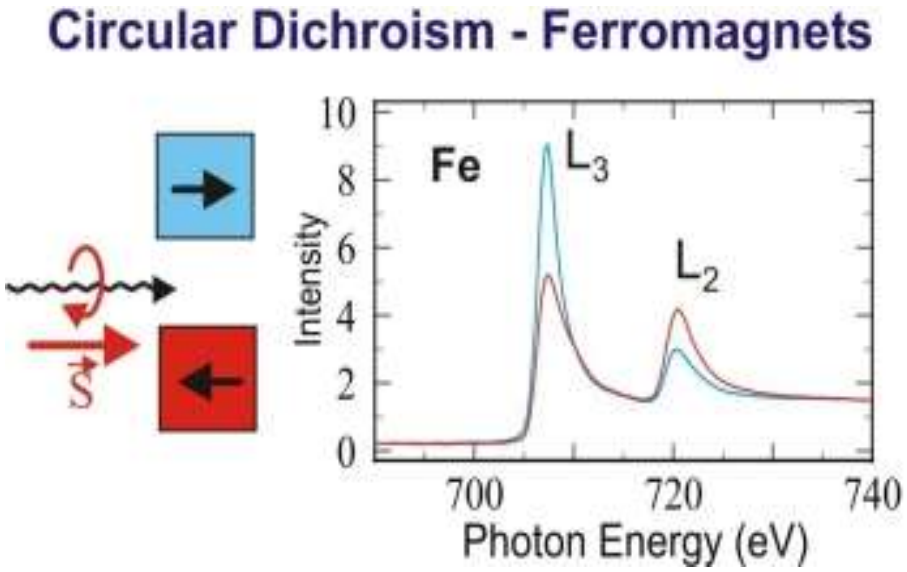


Magnetic imaging

XMCD and XMLD PEEM

Magnetic imaging: XMCD

Elettra Sincrotrone Trieste

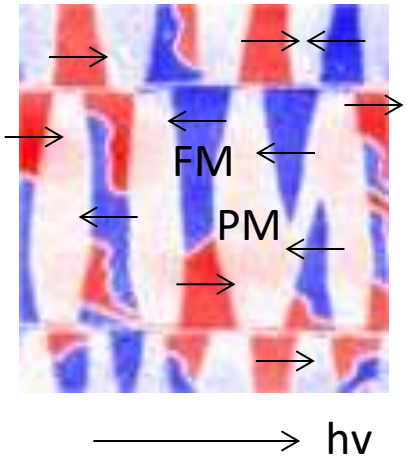


X-ray magnetic circular dichroism (XMCD) is the dependence of *x-ray absorption* on the relative orientation of the local magnetization and the polarization vector of the circularly polarized light

✓Element sensitive technique

✓ Secondary imaging with PEEM determine large probing depth (10 nm), buried interfaces.

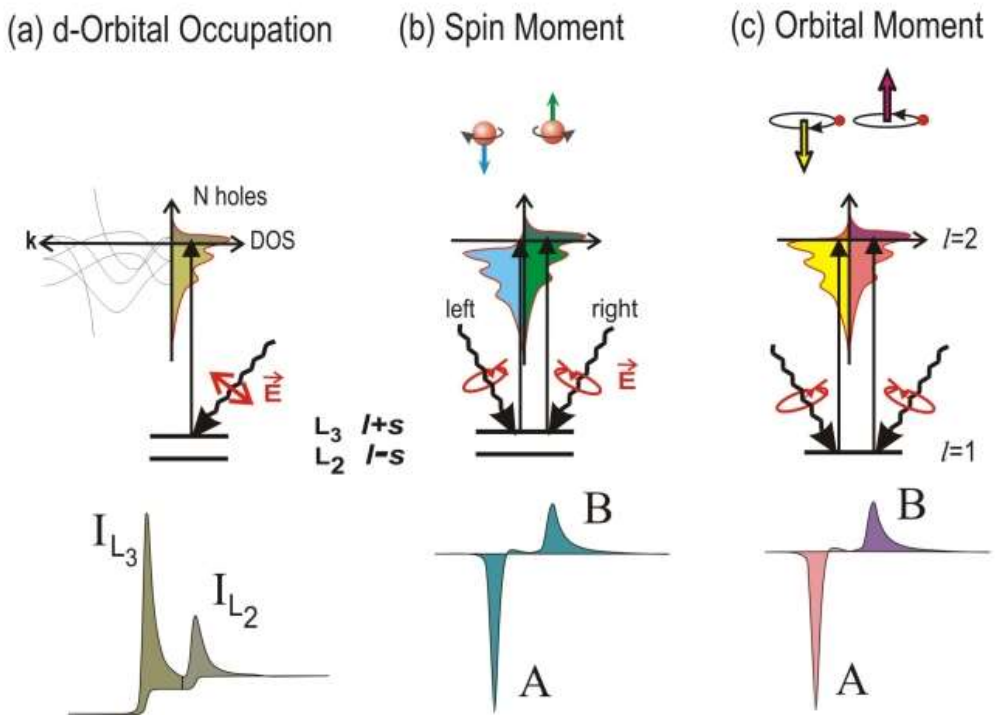
MnAs/GaAs



Magnetic domain imaging

At resonance, the secondary electron yield is proportional to the dot product between the magnetization direction and the photon helicity vector, which is parallel or anti-parallel to the beam propagation direction

XMCD principles



- We **PROBE** 3d elements by exciting 2p into unfilled 3d states
- Dominant channel: 2p → 3d
- White line intensity of the L3 and L2 resonances with the number N of empty d states (holes).

- By using circularly polarized radiation, the angular momentum of the photon can be transferred in part to the spin through the spin-orbit coupling. Photoelectrons with opposite spins are created in the cases of left and right handed polarization. Spin polarization is opposite also for $p_{3/2}$ (L_3) and $p_{1/2}$ (L2) levels.
- The spin-split valence shell is thus a detector for the spin of the excited photoelectron. The size of the dichroism effect scales like cosθ, where θ is the angle between the photon spin and the magnetization direction.
- **Refs: IBM. J . Res. Develop. 42, 73 (1998) and J. Magn. Magn. Mater. 200, 470 (1999).**

XMCD image algebra

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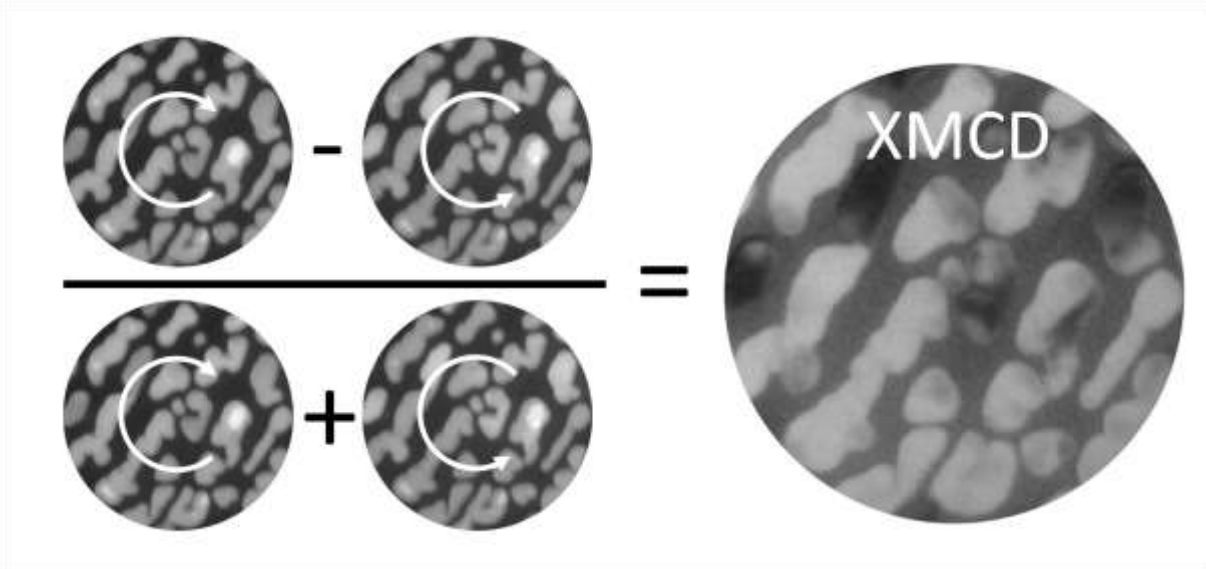
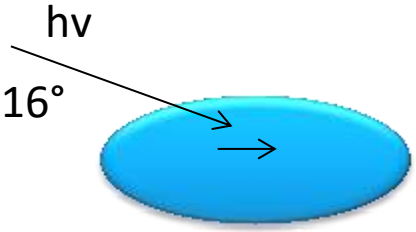
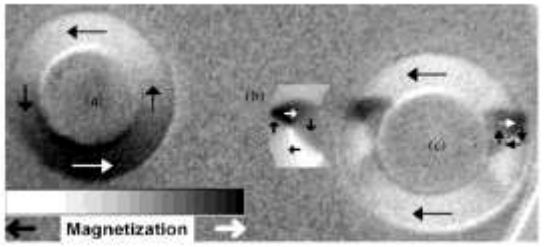
The size of the dichroism effect scales like cosθ, where θ is the angle between the photon spin and the magnetization direction. Hence the maximum dichroism effect (typically 20%) is observed if the photon spin and the magnetization directions are parallel and anti-parallel. Sum rules allows measuring orbital and spin moments



Geometry



the illumination geometry,
→ *in plane* component of M



XMCD movies

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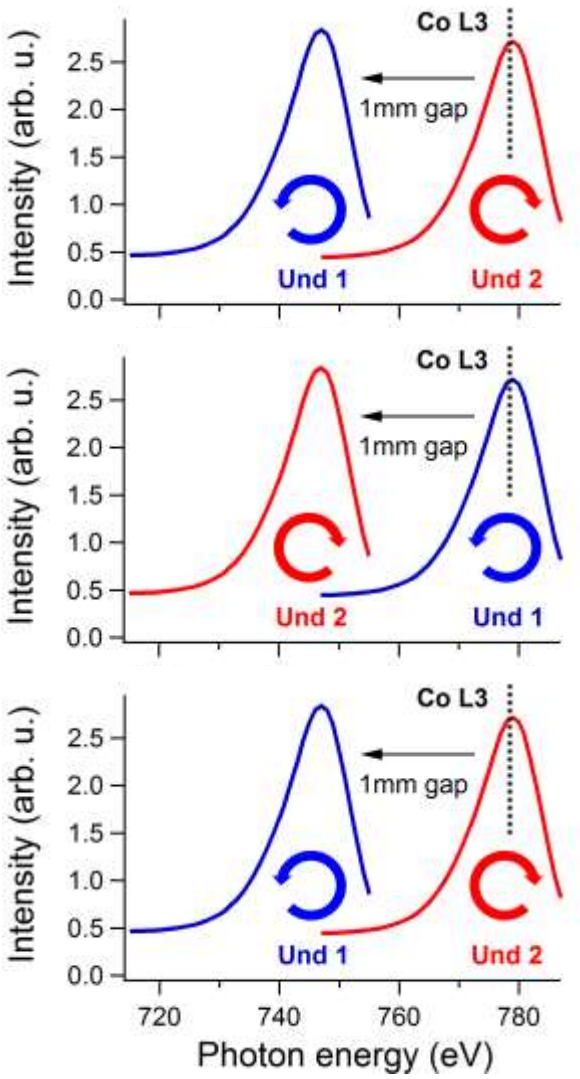
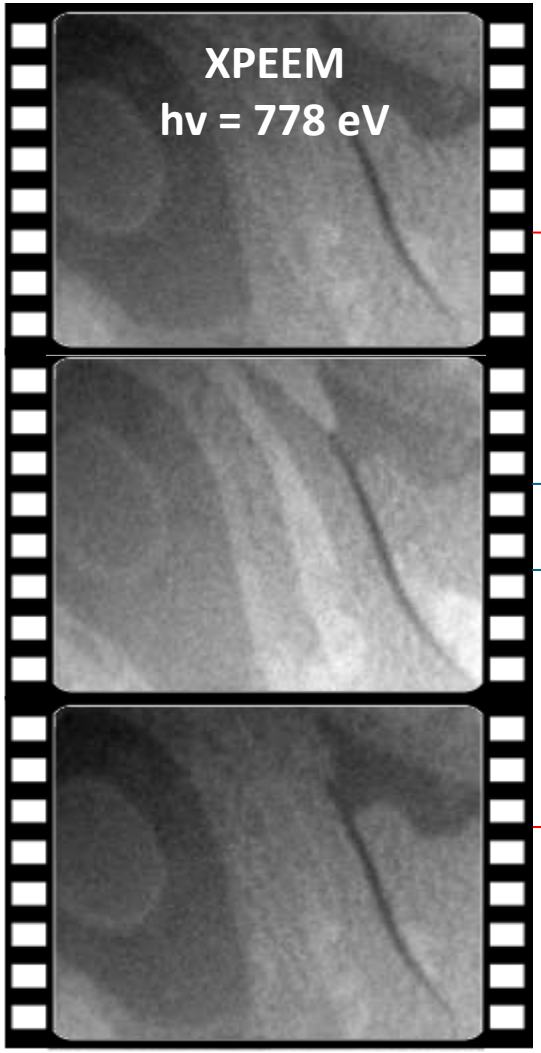
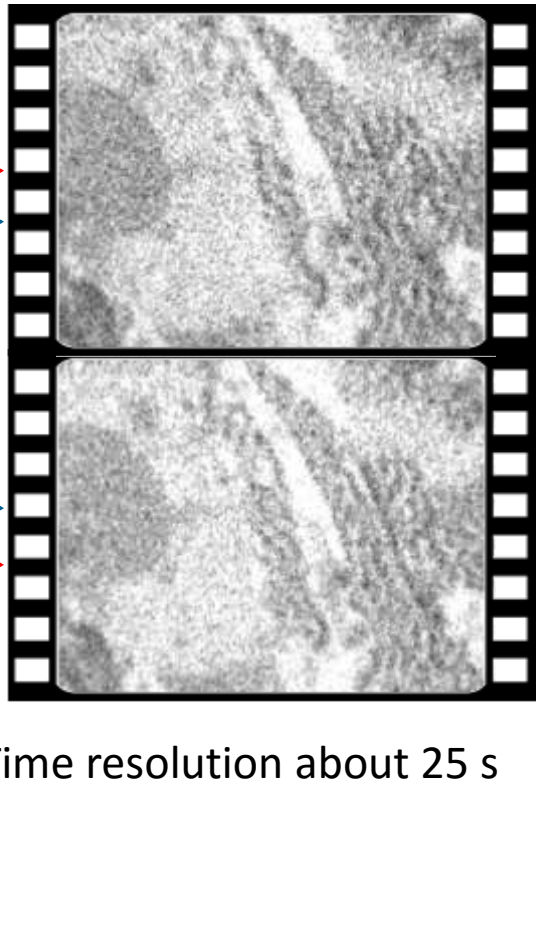
Beamline settings





FoV 6 um; 12 sec/frame

$$I^{XMCD} = \frac{I^- - I^+}{I^- + I^+}$$



Time resolution about 25 s

XMCD movie of a spin reorientation transition

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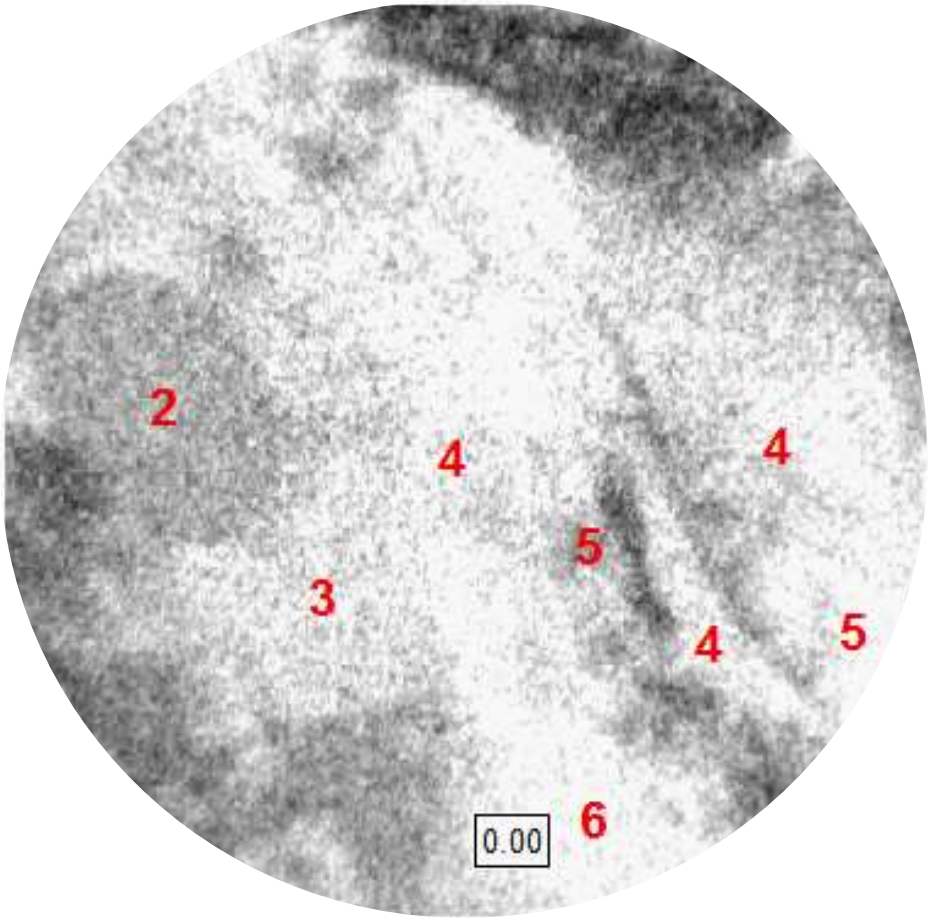
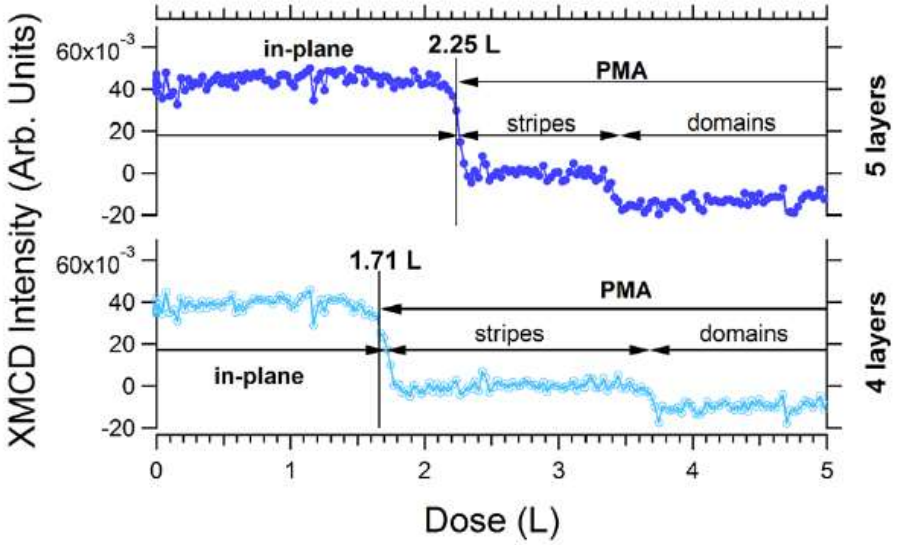
XMCD movie @ Co L_3 edge in $P_{CO}=2\cdot10^{-9}$ mbar; frame acquisition 12 s, FoV 6 µm



4 atomic layers Co more reactive than 5 & 3



Different layers have different period
Unstable domain structure
Period changes with CO dose

Examples of XMCD-PEEM applications

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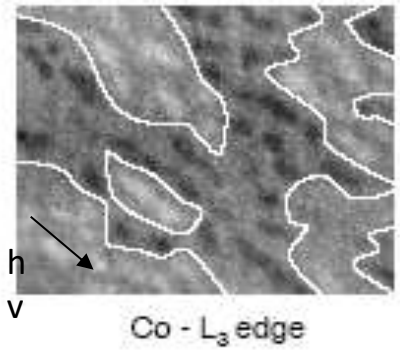
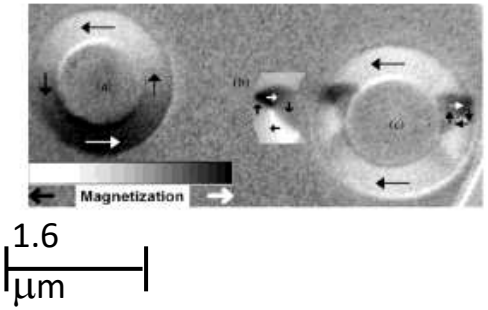
MAGNETIC STATE using XMCD & XMLD

Co nanodots on Si-Ge

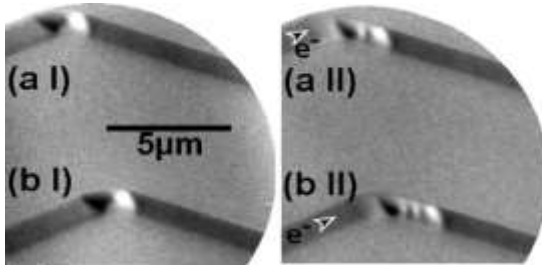


A. Mulders et al, Phys. Rev. B 71, 214422 (2005).

patterned structures

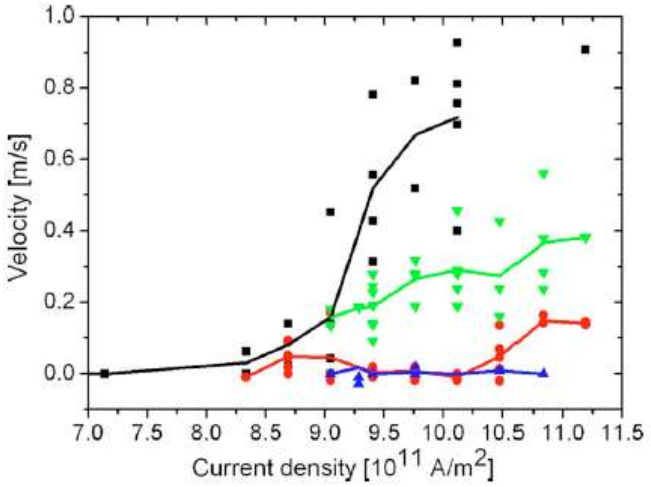


pulse injection



M. Klaeui et al, PRL , PRB 2003 - 2010

domain wall motion induced by spin currents



Laufemberg et al, APL 88, 232507(2006).

Magnetic imaging basics: XMLD

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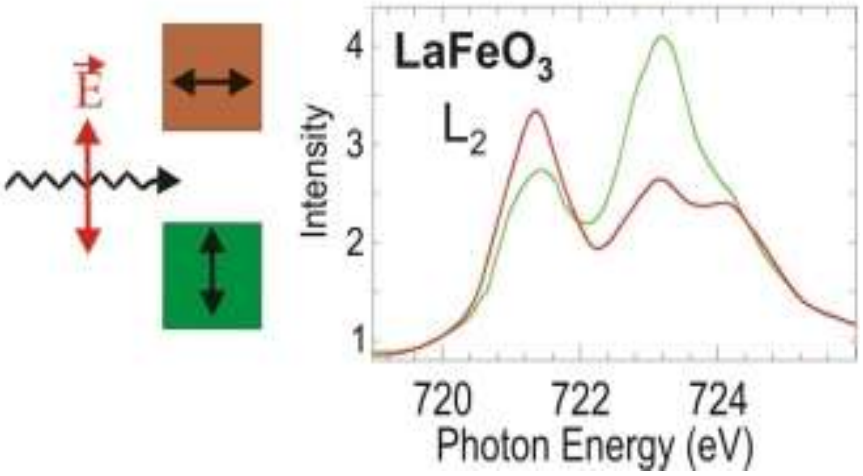
Linear Dichroism - Antiferromagnets



In the presence of spin order the spin-orbit coupling leads to preferential charge order relative to the spin direction, which is exploited to determine the spin axis in antiferromagnetic systems.

✓Element sensitive technique

✓ Secondary imaging with PEEM determine large probing depth (10 nm), buried interfaces.

✓Applied in AFM systems (oxides such as NiO)

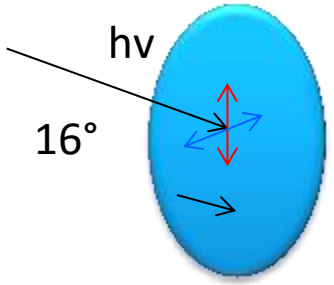
Absorption intensity at resonance

$$I(\vartheta,\theta,T) = a + b(3\cos^2\vartheta - 1)\langle Q_{zz}\rangle$$

$$+ c(3\cos^2\theta - 1)\langle M^2\rangle_T + d\sum_{i,j}\langle \hat{s}_i \cdot \hat{s}_j\rangle_T$$

1st term: quadrupole moment, i.e.electronic charge (not magnetic!)

2nd term determines XMLD effect; Θ is the angle between E and magnetic axis A; XMLD max for E || A;



Linear vertical and linear horizontal polarization of the photon beam

Applications of XMCD and XMLD

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Direct observation of the alignment of ferromagnetic spins by antiferromagnetic spins

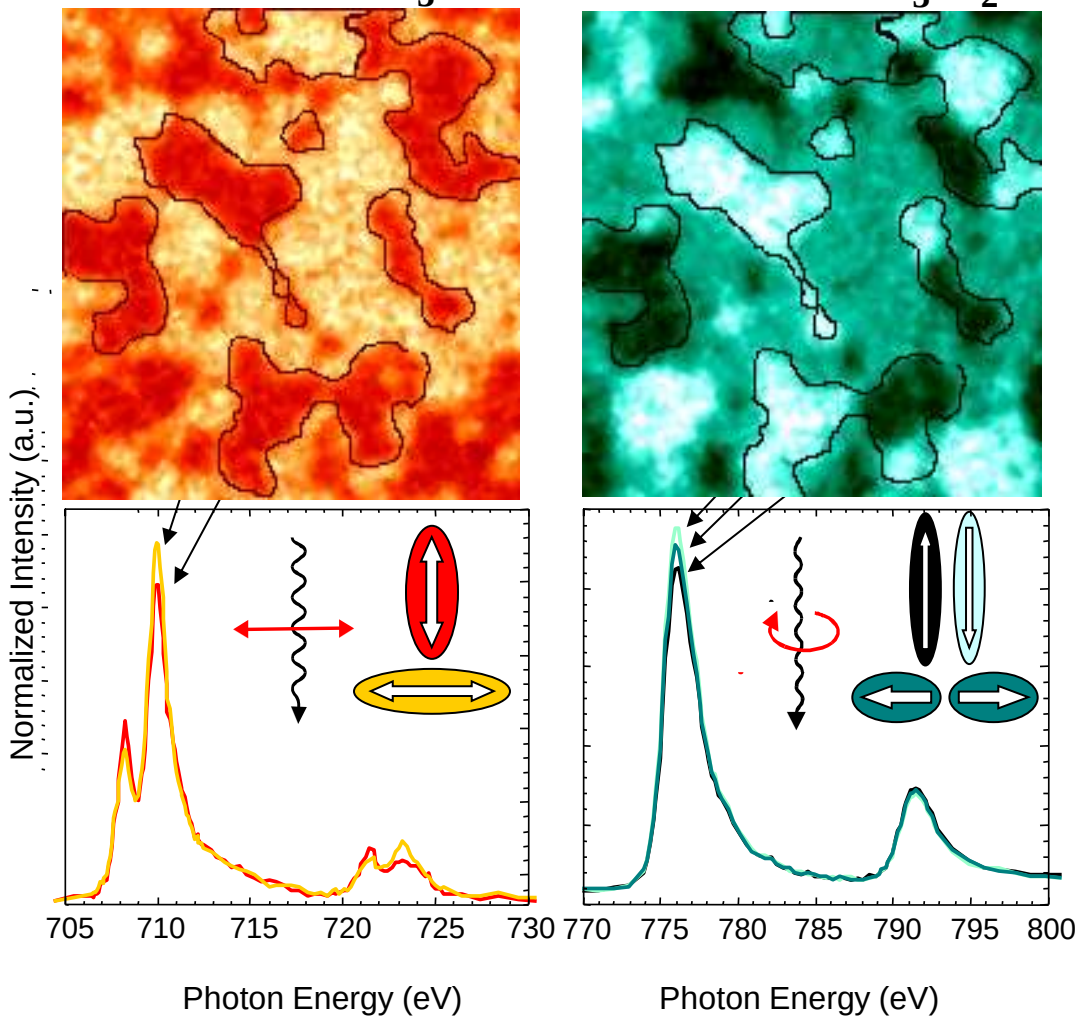
F. Nolting*, A. Scholl*, J. Stöhr†, J. W. Seo‡§, J. Fompeyrine§, H. Siegwart§, J.-P. Locquet§, S. Anders*, J. Lüning†, E. E. Fullerton†, M. F. Toney†, M. R. Scheinfein‖ & H. A. Padmore*

Nature, 405 (2000), 767.

ferromagnet/antiferromagnet
Co/LaFeO3 bilayer
interface exchange coupling
between the two materials

$LaFeO_3$ layer
XMLD Fe L_3

Co layer
XMCD Co L_3/L_2



DW imaging in magnetic wires

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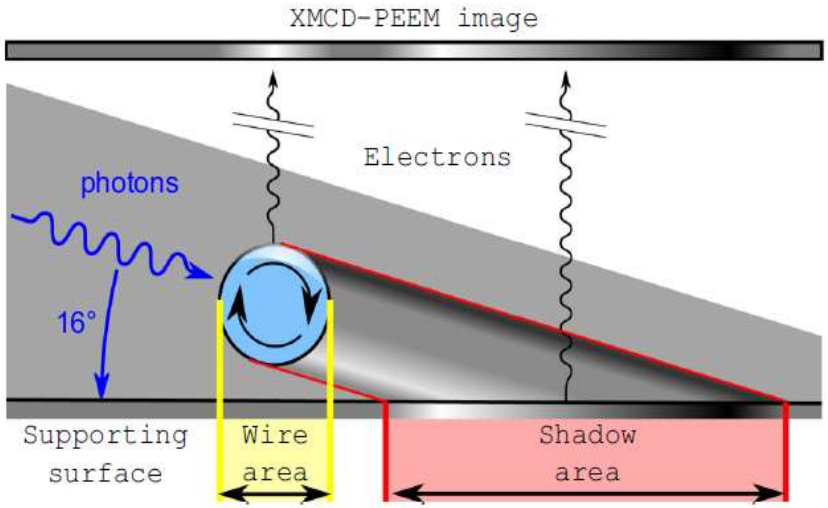
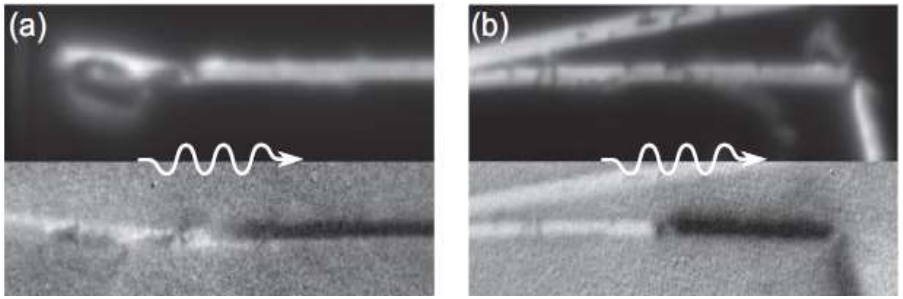
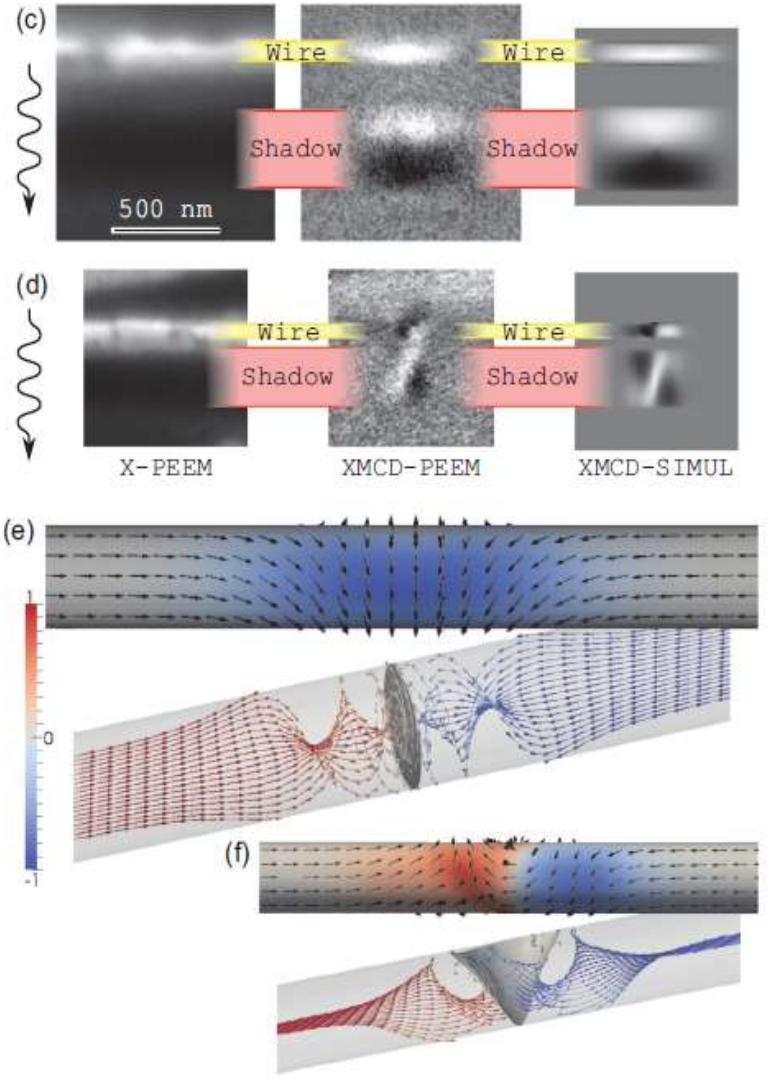
Observation of Bloch-point domain walls in cylindrical magnetic wir







S. Da Col *et al.*, Phys. Rev. B**89**, 180405(R) (2014)

Limited probing depth of XMCD: MnAs/GaAs

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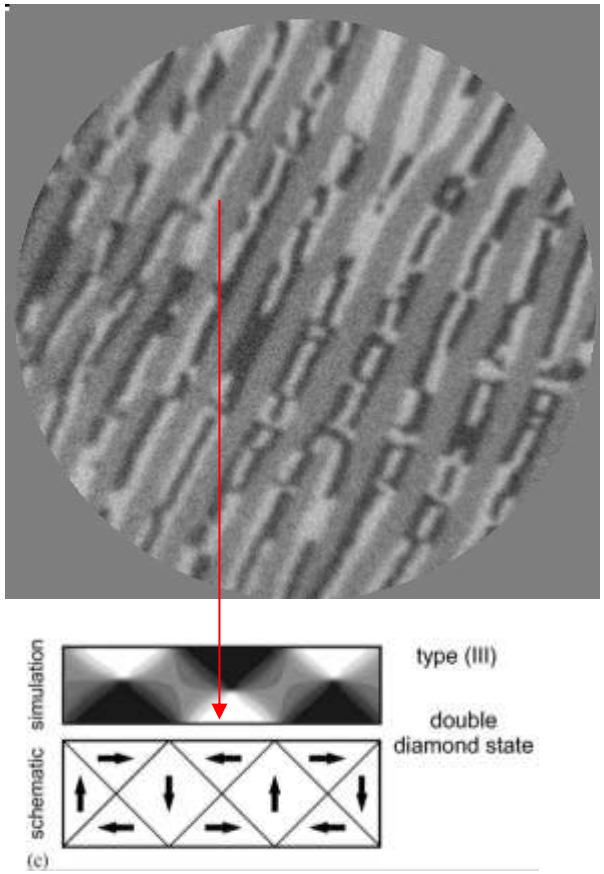
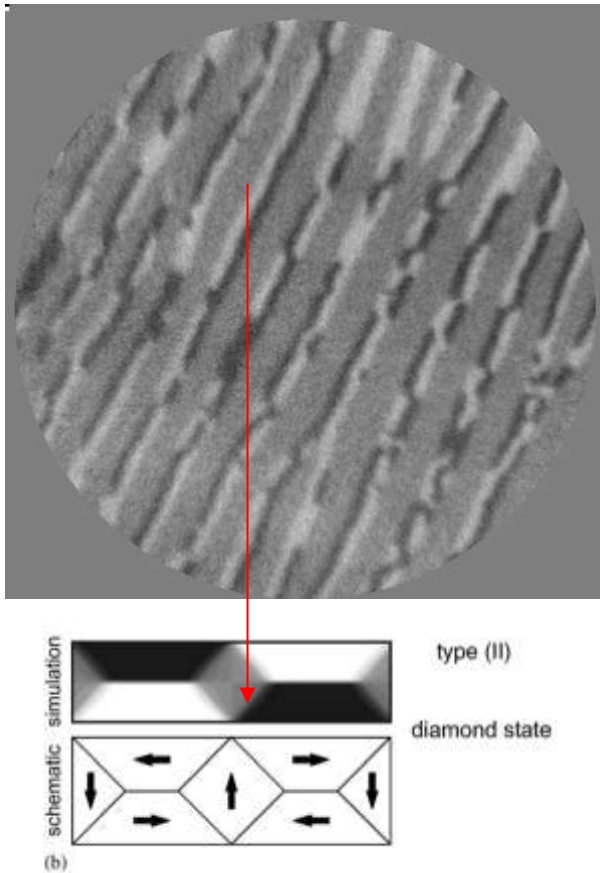
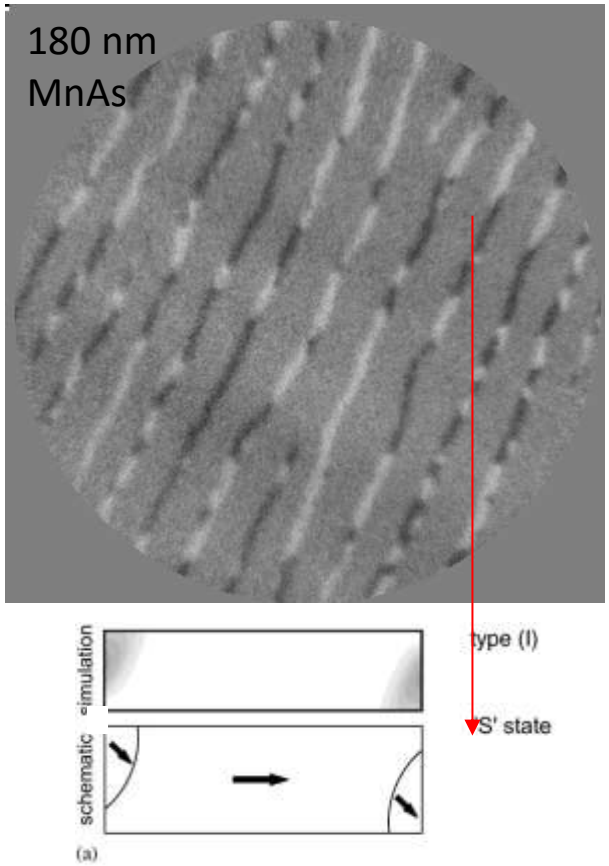
Experiment: Straight walls; Head to head domains

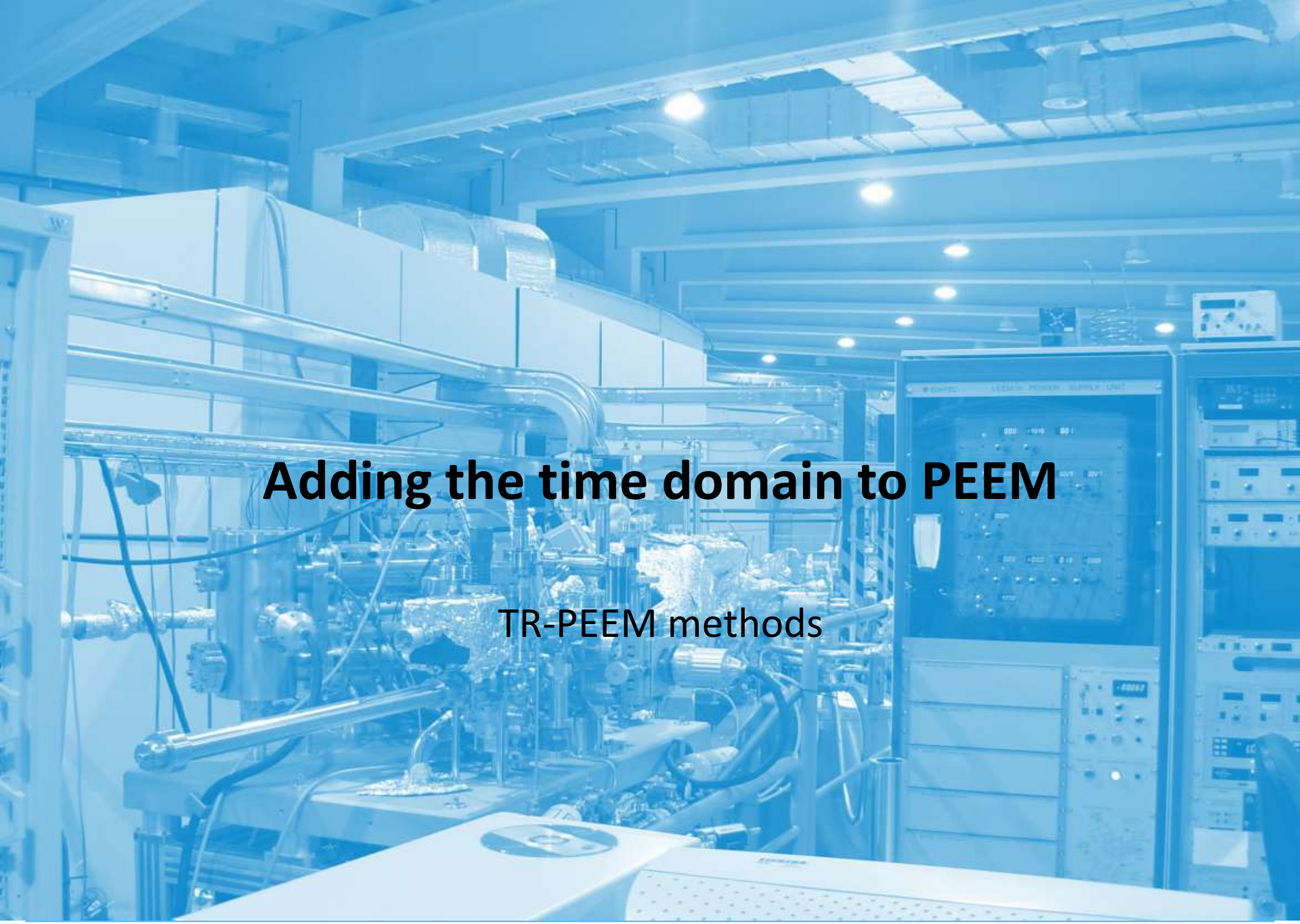






Simulation: Cross sectional cut: diamond state

R. Engel-Herbert et al, J. Magn. Magn. Mater. 305, (2006) 457



Adding the time domain to PEEM

TR-PEEM methods

Time-resolved PEEM: the stroboscopic approach

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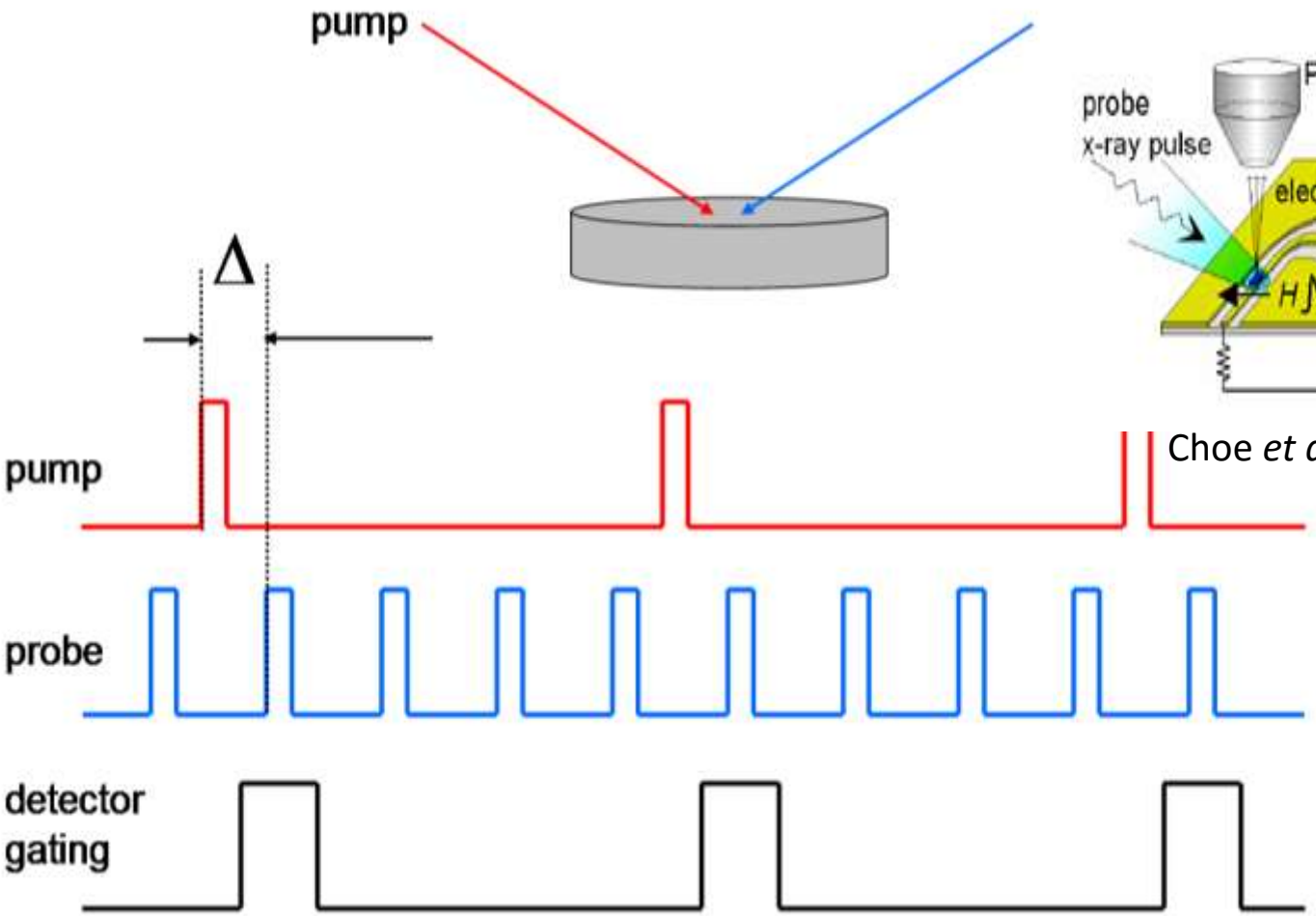
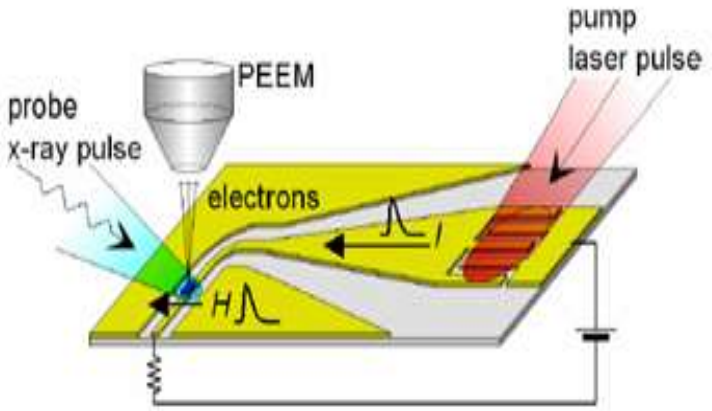
Stroboscopic experiments combine high lateral resolution of PEEM with high time resolution, taking advantage of pulsed nature of synchrotron radiation





Choe *et al.,* Science 304, 420 (2004)

Detector gating for time-resolved XMCD PEEM

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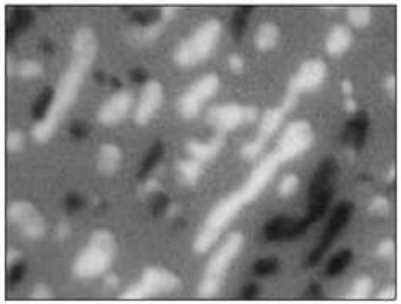
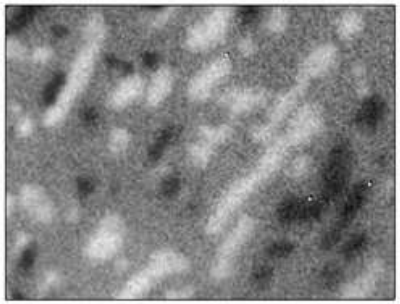
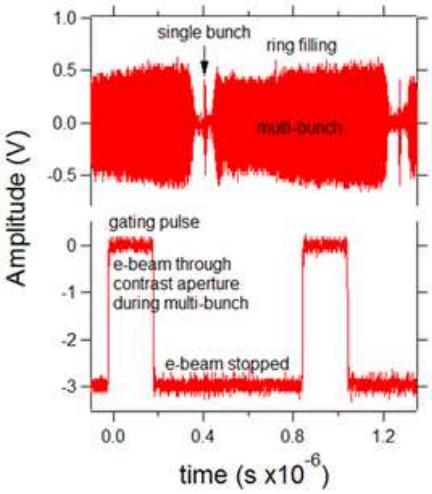


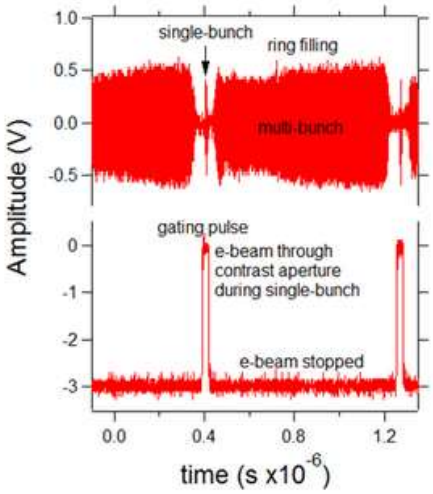
Multi-bunch image
32 images per helicity
Image exposure 4 s
Acquisition time: 5':18"



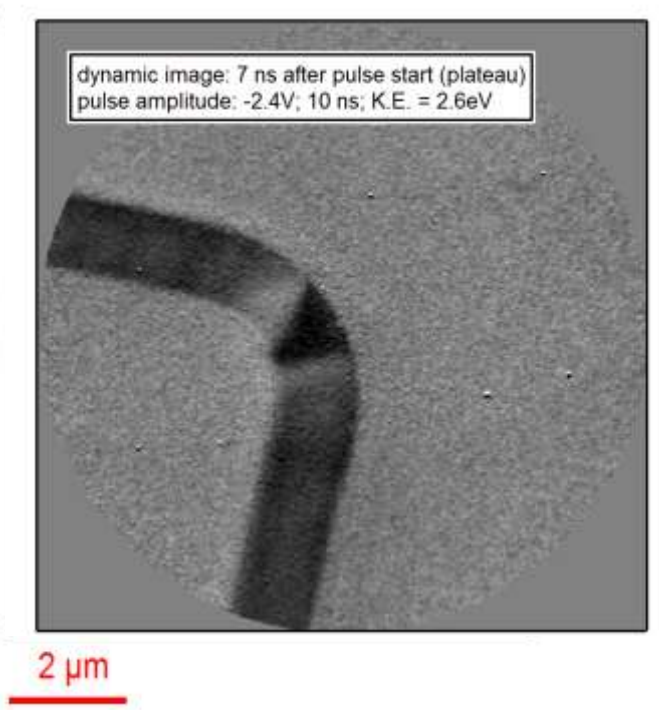
Single bunch image
24 images per helicity
Image exposure 20 s
Acquisition time: 17':40"



pulse width 200 ns



pulse width 30 ns



Current-induced motion of magnetic domain walls in Permalloy (Fe20Ni80) nanostripes, through the spin-transfer torque (STT) effect. Our measurements reveal clear eformations of the domain wall shape

J. Vogel, A. Locatelli *et al.,* in preparation

Magnetic excitations in LFC structures

Elettra Sincrotrone Trieste

Quantitative Analysis of Magnetic Excitations in Landau Flux-Closure Structures Using Synchrotron-Radiation Microscopy

J. Raabe,[1,*] C. Quitmann,[1] C. H. Back,[2] F. Nolting,[1] S. Johnson,[1] and C. Buehler[1]

The time dependent magnetization is described by the phenomenological Landau-Lifshitz-Gilbert equation

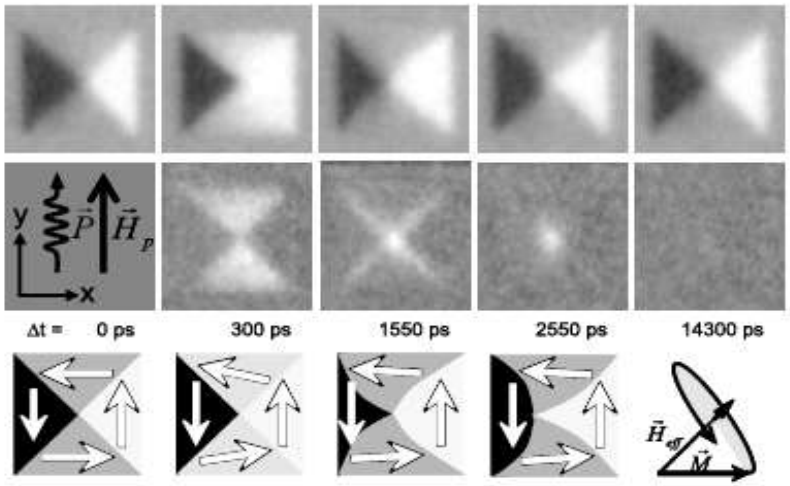
$$\frac{d}{dt}\vec{M} = -\gamma_0 \vec{M} \times \vec{H}_{\text{eff}} + \frac{\alpha}{M}\left(\vec{M} \times \frac{d}{dt}\vec{M}\right).$$

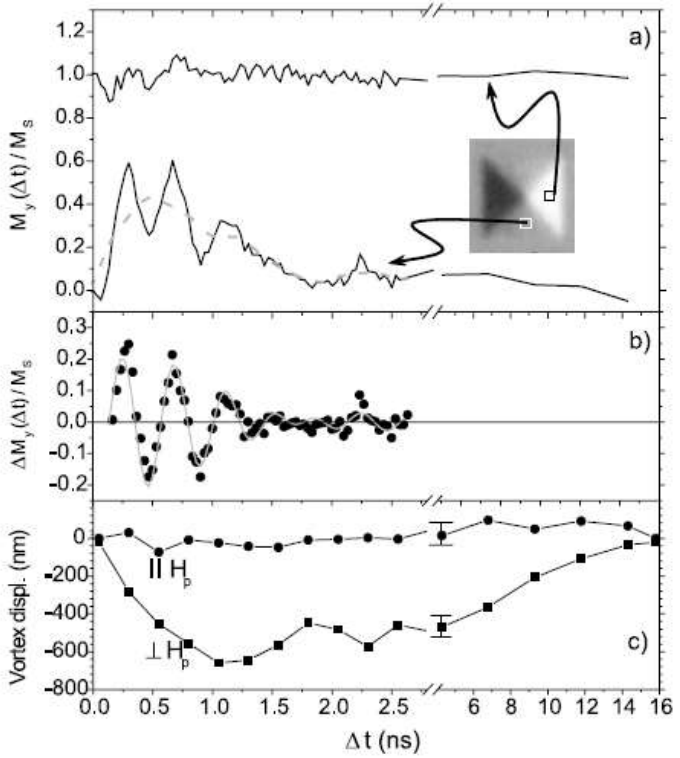
The first term describes the precession of the magnetization $\vec{M}$ about the total effective field $\vec{H}_{\text{eff}}$. The second term describes the relaxation back into the equilibrium state using the dimensionless damping parameter α.

torque $\vec{T} = -\gamma_0 \vec{M} \times \vec{H}_{\text{eff}}$

xmcd

t_i-t_0





Summary

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- XPEEM is a versatile full-field imaging technique. Combined with SR it allows us to implement laterally resolved versions of the most popular x-ray spectroscopies taking advantage of high flux of 3rd generation SR light sources.

- In particular, XAS-PEEM combines element sensitivity with chemical sensitivity (e.g. valence), and, more importantly, magnetic sensitivity. Magnetic imaging has been the most successful application of PEEM (next tutorial lecture!).

- XPEEM or energy-filtered PEEM adds true chemical sensitivity to PEEM. Modern instruments allow to combine chemistry with electronic structure using ARUPS.

- XPEEM can be complemented by LEEM, which adds structure sensitivity and capability to monitor dynamic processes.

- Lateral resolution will approach the nm range as AC instruments become available. Limitations due to space charge are not yet clear

- Novel application field are being approached, such as biology, geology and earth sciences. HAXPES will increase our capabilities to probe buried structures (bulk).

Review work

Elettra Sincrotrone Trieste

Reviews and topical papers on x-ray spectromicroscopy and XPEEM

- S. Guenther, B. Kaulich, L.Gregoratti, M. Kiskinova, *Prog. Surf. Sci.* **70**, 187–260 (2002).
- E. Bauer, *Ultramicroscopy* **119**, 18–23 (2012).
- E. Bauer, *J. Electron. Spectrosc. Relat. Phenom*. (2012): http://dx.doi.org/10.1016/j.elspec.2012.08.001
- G. Margaritondo, *J. Electron. Spectrosc. Relat. Phenom.* **178–179**, 273–291 (2010) .
- A. Locatelli, E. Bauer*, J. Phys.: Condens. Matter* **20**, 093002 (2008) .
- G. Schönhense *et al*., in "*Adv. Imaging Electron Phys*.", vol. **142**, Elsevier, Amsterdam, P. Hawkes (Ed.), 2006, pp. 159–323.
- G. Schönhense*, J. Electron. Spectrosc. Relat. Phenom.* **137–140**, 769 (2004) .
- C.M. Schneider, G. Schönhense, *Rep. Prog. Phys.* **65**, R1785–R1839 (2002) .
- W. Kuch, in "*Magnetism: A Synchrotron Radiation Approach*", Springer, Berlin, E. Beaurepaire et al. (Eds.), 2006, pp. 275–320.
- J. Feng, A. Scholl, in P.W. Hawkes, "*Science of Microscopy*", Springer, New York, J.C.H. Spence (Eds.), 2007, pp. 657–695.
- E. Bauer and Th. Schmidt, in "*High Resolution Imaging and Spectroscopy of Ma-terials*", Springer, Berlin, Heidelberg, F. Ernst and M. Ruehle (Eds.), 2002, pp. 363-390.
- E. Bauer, *J. Electron Spectrosc. Relat. Phenom.* **114-116,** 976-987 (2002).
- E. Bauer, *J. Phys.: Condens. Matter* **13,** 11391-11405 (2001).