Cathode Lens Microscopy
LEEM, XPEEM and Applications
part1: Methods
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Why do we need spectromicroscopy?

- 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

Magnetism

Biology

DOI: 10.1103/PhysRevLett.86.5088

DOI: 10.1103/PhysRevLett.87.247201

PRL 98, 268102 (2007)
Outline

• Synchrotron radiation methods
• X-ray spectro-microscopy:
  – Cathode lens microscopy instrumentation
  – XPEEM/LEEM
• Applications
  – Chemical imaging of micro-structured materials
    Graphene research.
  – Biology
  – Magnetic imaging
  – Time-resolved
Why does microscopy need SR?

- **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)

\[ J = f(h\nu, \varepsilon, \Theta, \Phi; E^e_{kin}, \sigma, \theta_e, \varphi_e) \]
X-ray Photoelectron Spectroscopy

The absorption of a photon ionizes the system, exciting one of the electrons into a free state in the continuum. The transition probability from the initial state to the final is proportional to:

\[ \tau_{ik} \propto 4\pi^2 \alpha \hbar \omega \left| \langle \psi_i | \hat{e} \cdot \hat{r} | e^{jkr} \rangle \right|^2 \delta(E_i + \hbar \omega - \frac{\hbar^2 k^2}{2m}) \]

We measure the energy distribution of the photoelectrons emitted from the specimen.

\[ E_k = h\nu - E_B - \Phi \]

\( E_B \) is the binding energy of the initial state. \( E_B \) is a unique fingerprint that allows determining the composition and chemical state of the specimen surface. This is the founding principle of ESCA and XPS (K. Siegbahn’s Nobel prize).

**Main features:** Elemental and chemical sensitivity (surface core level shifts), sensitivity to the electronic structure, sensitivity to local structure (micro-XPD), highest surface sensitivity.
X-ray absorption spectroscopy basics

\[ \mu = 4 \pi^2 \alpha \hbar \omega \sum_k \left| \langle \psi_k | \hat{\mathbf{E}} \cdot \hat{\mathbf{r}} | \psi_c \rangle \right|^2 \delta(e_k - e_c - \hbar \omega) \]

Energy dependent absorption of x-rays! Resonances arise from transitions from core levels into unoccupied valence states via excitation processes occurring during the filling of the core hole.

- Elemental sensitivity.
- Chemical sensitivity
- Electronic charge
  - valence state,
  - bond orientation

We measure:
- Absorption through the material
- Secondary electron yield
- Escape depth of low energy electrons gives access to buried layers

https://www-ssrl.slac.stanford.edu/stohr/xmcd.htm
By measuring secondary Electrons we probe thin films and buried interfaces to a maximum depth of several nm. This is the case of X-ray absorption spectroscopy and its variants (NEXAFS, XMCD, XMLD).

By measuring Photoelectrons emitted from core levels or the valence band (XPS, ARPES, UPS, ARUPS) we achieve sensitivity to the topmost surface layers, especially when the K. E. Is in the range 50 to 150 eV.
Choosing the best photon energy for the experiment is of crucial importance to maximize surface / elemental sensitivity as well as obtaining favourable acquisition times.

Graphene / Ru(0001)

Yeh and Lindau, Atomic Data and Nuclear Data Tables 32, I-1 55 (1985)
The two main approaches of x-ray microscopy

**X-ray photoemission electron microscopy (XPEEM)**

- Direct imaging, parallel detection
- Lateral resolution determined by electron optics: aberration correction nowadays possible with resolution < 2nm
- Combination with LEEM/LEED
- Intermediate spectroscopic ability
- \( P_{\text{max}} < 5 \times 10^{-5} \) mbar
- Flat surfaces

**Scanning photoemission electron microscopy (SPEM)**

- Scanning: sequential indirect imaging
- Lateral resolution determined by X-ray (diffractive) optics: 20-30 nm.
- Combination with TXM
- Excellent spectroscopic ability
- High pressure variants do exist
- Rough surfaces
Microscopies and chemical sensitivity

- NMR
- IR
- SIMS (destructive)
- μ-XAS, XPS, XPEEM, SPEM
- SEM TEM
- STM, AFM

Spatial resolution:
- 100μm
- 1μm
- 10nm
- 1Å

Chemical sensitivity:
Cathode lens microscopy methods

PEEM, LEEM, SPELEEM, AC-PEEM/LEEM
PEEM basics

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.

- Direct imaging, parallel detection
- Lateral resolution determined by electron optics: with AC, few nm possible
- Elemental sensitivity (XAS)
- Spectroscopic ability (energy filter)
- $P_{\text{max}} < 5 \cdot 10^{-5}$ mbar
Cathode lens operation principle

1. In emission microscopy $\theta$ (emission angle) is large. Electron lenses can accept only small $\theta$ because of large chromatic and spherical aberrations.

2. Solution of problem: accelerate electrons to high energy before lens → Immersion objective lens or cathode lens

   - $n \sin \theta = \text{const}$
   - $n \sim \sqrt{E}$
   - $\theta \rightarrow \alpha$
   - $\sin \alpha / \sin \alpha_0 = \sqrt{E_0/E}$

Example for $E = 20000$ eV:

<table>
<thead>
<tr>
<th>$E_0$</th>
<th>2 eV</th>
<th>200 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ for $\alpha_0 = 45^\circ$</td>
<td>0.4°</td>
<td>4.5°</td>
</tr>
</tbody>
</table>

3. The aberrations of the objective lens and the contrast aperture size determine the lateral resolution:

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

$$d_D = 0.6 \frac{\lambda}{r_A}$$
The different types of PEEM measurements

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

Require energy filter
Low energy electron microscopy (LEEM)

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

Backscattering cross section


- High structure sensitivity
- High surface sensitivity
- Video rate: reconstructions, growth, step dynamics, self-organization
Image contrast in LEEM

Different contrast mechanisms are available for structure characterization

SURFACE STRUCTURE

FILM THICKNESS

STEP MORPHOLOGY

diffraction contrast

quantum size contrast

geometric phase contrast

sample

objective

closest aperture

Co/W(110)

Mo(110)
SPELEEM = LEEM + PEEM

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

The Nanospectroscopy beamline@Elettra
Flux on the sample: $10^{13}$ph/sec (microspot) intermediate energy resolution.

Sasaki type undulator

monochromator range 10-1000 eV
VLS gratings + spherical grating


SPELEEM many methods analysis

Spectroscopic imaging
XAS-PEEM / XPEEM / LEEM

Microprobe-diffraction
ARPES / LEED

Microprobe-spectroscopy
XPS

Spatial resolution
LEEM: 10 nm
XPEEM: 25 nm

Energy resolution
XPEEM: 0.3 eV

Angular resolution
XPEEM: 0.01 Å⁻¹

Limited: to 2 microns in dia.

Transfer width: 0.01 Å⁻¹
SPELEEM many methods analysis

**Spectroscopic imaging**
- XAS-PEEM / XPEEM / LEEM

**microprobe-diffraction**
- ARPES / LEED

**microprobe-spectroscopy**
- XPS

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**Spatial resolution**
- LEEM: 10 nm
- XPEEM: 25 nm

**Energy resolution**
- LEEM: 0.3 eV
- XPEEM: 0.3 eV
- XPS: 0.11 eV

**Angular resolution**
- XPEEM: 0.01 Å⁻¹

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energy resolution
μXPS: 0.11 eV
SPELEEM summary

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 microstructures
dynamical processes
I will focus on Surfaces, interfaces and thin films
Part 2: XPEEM Applications: Imaging the Chemical and Electronic Structure

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Thickness dependent reactivity in Mg

Oxidation of Mg film and quantum well states

**FACTS**

- Strong variations in the oxidation extent are correlated 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)

The complexity of the metal-graphene interface

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

- Effect of substrate’s symmetry
  - The complex structure of g/Ir(100)
- Buffers
  - Au Intercalation
  - Carbides in graphene on Ni(111)
- Irradiation/implantation
  - Low energy N+ ion irradiation of g/Ir(111)
  - [Irradiation with noble gases of g/Ir(100)]
graphene growth on Ir(001)

Growth $600^\circ C < T < 670^\circ C_b$

$P_{C_2H_4} = 2 \cdot 10^{-8}$ mbar

growth at $T > 800^\circ C$

microprobe-LEED: graphene

A. Locatelli, G. Zamborlini, T.O. Menteş; Carbon 74, 237–248 (2014);
Reversible phase transformation in graphene

Upon cooling a new graphene phase nucleates (dark stripes)

The stripes disappear upon annealing to high temperature.
Graphene/Ir(100): structure of FG and BG

FG: flat graphene
BG: buckled graphene

Room temperature

0 1 μm

Brightfield LEEM
Darkfield LEEM

<001>  <010>
Buckled graphene unit cell by ab-initio

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

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

Diffraction Imaging

µ-ARPES at $E_F$

measurements limited to 2 um in dia.

$E_D = 0.42$ eV
Different character of FG and BG

μ-ARPES at $E_F$

FG: high DOS at $K \rightarrow$ Dirac cones intact

BG: hybridized, metallic-like DOS

Image intensity proportional to local DOS!
Decoupling graphene from substrate:

- [Intercalated Au/g/Ir(100)]
- Switchable formation of carbides in g/Ni(111)
Identifying crystal grains in graphene/Ni(111)

- Rotated graphene (+17)
- Epitaxial graphene
- Rotated graphene (-17)

Formation/dissolution of carbides under rg/Ni(111)

1: carbide nucleation

The Ni-carbide nucleates exclusively under rotated graphene, starting at temperatures below 340°C.

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 μm, electron energy: 11 eV
Coupling-decoupling is revealed by µ-ARPES

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
Nitrogen-ion irradiated gr/Ir(111)

Nonirradiated

Irradiated

LEEM - 4 eV

Slit: 1 mm wide
100 eV N ions
@2·10⁻⁵ mbar
0.14 uA on sample

A. Sala et al., Small 11(44), 5927-5931 (2015)
Nitrogen-ion irradiated gr/Ir(111)

Nonirradiated

Irradiated

LEEM - 4 eV
Slit: 1 mm wide
100 eV N ions
@2·10⁻⁵ mbar
0.14 uA on sample

XPEEM N 1s - 400.5 eV
hv = 500 eV

M. Scardamaglia et al., Carbon 73 (2014), 371-381
A. Sala et al., Small 11(44), 5927-5931 (2015)
Nitrogen-ion irradiated gr/Ir(111)

Not irradiated

Irradiated

Slit: 1 mm wide

100 eV N ions @ 2·10⁻⁵ mbar

0.14 uA on sample
Applications of XAS in biology: biomineralization

- Bio-mineralization resulting from microbial activity
- X-PEEM images of (A) non mineralized fibrils from the cloudy water above the biofilm (scale bar, 5 um)
- (B) mineralized filaments and a sheath from the biofilm (scale bar, 1 um); (bottom)
- X-PEEM Fe L-edge XANES spectra of the FeOOH mineralized looped filament shown in (B), compared with iron oxyhydroxide standards, arranged (bottom to top) in order of decreasing crystallinity.

Contrast is observed between adjacent individual nacre tablets, arising because different tablets have different crystal orientations with respect to the radiation’s polarization vector. The 290.3 eV peak corresponds to the C 1s $\rightarrow$ $P_{i*}$ transition of the CO bond. Synchrotron radiation is linearly polarized in the orbit plane. Under such illumination, the intensity of the peak depends on the crystallographic orientation of each nacre tablet with respect to the polarization. This was the first observation of x-ray linear dichroism in a bio-mineral.

Part 3: XPEEM applications: magnetic imaging

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The change in landscape is hereby not exclusively scientific, but also reflects the magnetism related industrial application portfolio. Specifically, Hard Disk Drive technology, which still dominates digital storage and will continue to do so for many years, if not decades, has now limited its footprint in the scientific and research community, whereas significantly growing interest in magnetism and magnetic materials in relation to energy applications is noticeable, and other technological fields are emerging as well. Also, more and more work is occurring in which complex topologies of magnetically ordered states are being explored, hereby aiming at a technological utilization of the very theoretical concepts that were recognized by the 2016 Nobel Prize in Physics.
Topics in Magnetism (i): materials

• **Novel two dimensional materials**
  – graphene, phosphorene, bismuth chalcogenides and transition metal dichalcogenides (TMDs) could play a key role for spintronics in a wide range of topics
  – Growth, mechanical assembly, self-assembly

• **Novel materials with curved geometry:**
  – asymmetrically sandwiched ultrathin ferromagnetic metals, Heusler alloys, Weyl semimetals, and magnetoelectric materials.
  – Topological structures (chiral, e.g. skyrmions)
Topics in Magnetism (ii): materials

- **Novel materials with curved geometry:**
  - asymmetrically sandwiched ultrathin ferromagnetic metals, Heusler alloys, Weyl semimetals, and magnetoelectric materials.
  - Topological structures (chiral, e.g. skyrmions)
Magnetic imaging methods: an overview

- Imaging the magnetic state of the material, e.g. understanding the magnetic domain structure with nm lateral resolution
- Monitoring its evolution under an external stimulus. This requires both space and time resolution!

- Magneto-optical microscopies (MOKE)
- Magnetic scanning probe microscopies (MFM)
- Magnetic electron microscopies (SEMPA, SPLEEM)

- Magnetic x-ray microscopies (STXM, PEEM)
Magnetic imaging methods: requirements!

- Lateral resolution close to the nm
- Time resolution: from fs to ns
- Sensitivity to buried layers, interfaces
- Ability to quantify magnetic properties!
- in-operando studies:
  
as a function of external parameters, magnetic and electric fields, current pulses, temperature, pressure (under UHV, or in gases)
  Control of strain (magneto-electrics in multiferroic materials)

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6. Advances in magnetic characterization

Peter Fischer

Using electric fields to switch magnetization in multiferroic materials, utilizing pure spin current or at least spin polarized currents in spin-orbitronics, and ultimately all-optical control of magnetism are the most prominent research directions today (section 9). The challenges for characterization are the ability to study with high spatial and temporal resolution, ultimately down to the nm and fs regimes, respectively, and in-operando as a function of applied external parameters, including electric and heat currents, electric and magnetic fields, ultrashort optical pulses, the statics and dynamics of the underlying microscopic spin textures. A detailed, i.e. highly spatial, and temporal resolution characterization of spin textures at buried interfaces and specifically the spin dynamics at such interfaces, or more generally, the behavior of spins in 3D nanoscale systems, is still elusive. Whereas, independently, fundamental
XMCD principles

Sum rules

- intensity of the L$_3$ and L$_2$ goes with empty d states (holes).
- Size of spin and orbital moments


The spin-split valence shell is a detector for the spin of the excited photoelectron.
Magnetic domain imaging by XMCD

• The x-ray absorption depends on the relative orientation of the magnetization and the polarization of circularly polarized light.
• The size of the dichroism effect scales like cos(θ).
• We PROBE 3d elements by exciting 2p into unfilled 3d states.
• Photoelectrons with opposite spins are created in the cases of left and right handed polarization.
• Spin polarization is opposite for p_{3/2} (L_{3}) and p_{1/2} (L_{2}) levels.
XMCD as magnetometry

Experimental Confirmation of the X-Ray Magnetic Circular Dichroism
Sum Rules for Iron and Cobalt

C. T. Chen,¹ Y. U. Idzerda,² H.-J. Lin,¹,* N. V. Smith,¹,† G. Meigs,¹
G. H. Ho,³,* E. Pellegrin,¹ and F. Sette¹,†

SUM RULES

\[ m_{\text{orb}} = -\frac{4}{3} \int_{L_3+L_2} (\mu_+ - \mu_-) d\omega (10 - n_{3d}) , \quad (1) \]

\[ m_{\text{spin}} = -\frac{6 \int_{L_3} (\mu_+ - \mu_-) d\omega - 4 \int_{L_3+L_2} (\mu_+ - \mu_-) d\omega}{\int_{L_3+L_2} (\mu_+ + \mu_-) d\omega} \times (10 - n_{3d}) \left( 1 + \frac{7\langle T_z \rangle}{2 \langle S_z \rangle} \right)^{-1} , \quad (2) \]

\( \langle T_z \rangle \) is the expectation value of the magnetic dipole operator

\( \langle S_z \rangle \) is equal to half of \( m_{\text{spin}} \)

REFERENCES

XMCD imaging of a skyrmion

the illumination geometry, \textit{in plane} component of M

\textbf{(d) Chemical image of a magnetic nanostructure}

\textbf{(e) Magnetic image of a skyrmion}

Tomographic imaging in magnetic wires

Observation of Bloch-point domain walls in cylindrical magnetic wires

Examples of XMCD-PEEM applications

IMAGING OF MAGNETIC DOMAINS & DOMAIN WALLS

Co nanodots on Si-Ge

patterned structures

domain wall motion induced by spin currents


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

Limited probing depth of XMCD: MnAs/GaAs

Experiment: Straight walls; Head to head domains

Simulation: Cross sectional cut: diamond state

Samples fabrication issues

- **In situ prepared**
  - grow your own samples! (e-beam evaporation/lengthy)
  - Surface science approach

- **Ex-situ prepared**
  - complex multilayers (MBE facility)
  - Advanced lithography
  - Issue: contaminations due to exposure to atmosphere / capping layers needed
  - Contacting nanostructures
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

\[
I(\vartheta, \theta, T) = a + b(3 \cos^2 \vartheta - 1) \langle Q_{zz} \rangle \\
+ c(3 \cos^2 \theta - 1) \langle M^2 \rangle_T + d \sum_{i,j} \langle \hat{s}_i \cdot \hat{s}_j \rangle_T
\]

1\textsuperscript{st} term: quadrupole moment, i.e. electronic charge (not magnetic!)
2\textsuperscript{nd} term determines XMLD effect; \(\vartheta\) is the angle between \(E\) and magnetic axis \(A\); XMLD max for \(E \parallel A\);
Applications of XMCD and XMLD

Direct observation of the alignment of ferromagnetic spins by antiferromagnetic spins


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

LaFeO₃ layer
XMLD Fe L₃

Co layer
XMCD Co L₃/L₂

Normalized Intensity (a.u.)

Photon Energy (eV)
Adding the time domain to PEEM

TR-PEEM methods
Time-resolved PEEM: the stroboscopic approach

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

Time resolved XMCD-PEEM: applications

- **Switching processes** (magnetisation reversal) in magnetic elements (in spin valves, tunnel junction)
  - Nucleation, DW propagation or both
  - Effect of surface topography, morphology crystalline structure etc.
  - Domain dynamics in Landau flux closure structures.
- response of vortices, domains, domain walls in Landau closure domains in the **precessional regime**
- **Stroboscopic technique:**
  - only reversible processes can be studied by pump – probe experiments
  - Measurements are quantitative
Magnetic excitations in LFC structures

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. Buehler1

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 \( \alpha \).

Torque \( \vec{T} = -\gamma_0 \vec{M} \times \dot{\vec{H}}_{\text{eff}} \)
Summary

• 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.

• XPEEM or energy-filtered PEEM adds true chemical sensitivity to PEEM. Modern instruments allow to combine chemical imaging with electronic structure imaging 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).
Reviews on x-ray spectromicroscopy and XPEEM