Coherence activities at the ESRF:
Scanning (Transmission) X-ray Microscopy
STXM $\rightarrow$ SXM

A Practical Approach

Jean SUSINI
**Synchrotron based micro-probe techniques**

**X-Ray Fluorescence**
- Composition
- Quantification
- Trace element mapping

**ID13, ID21, ID22**

**ESRF instruments**

**X-ray Diffraction & scattering**
- Long range structure
- Crystal orientation mapping
- Stress/strain/texture mapping

**ID11, ID13, ID22**

**Phase contrast X-ray imaging**
- 2D/3D Morphology
- High resolution
- Density mapping

**ID21, ID22**

**Infrared FTIR-spectroscopy**
- Molecular groups & structure
- High S/N for spectroscopy
- Functional group mapping

**ID21**

**X-ray spectroscopy**
- Short range structure
- Electronic structure
- Oxidation/speciation mapping

**ID21, ID22, ID24**

**Synchrotron based hard X-ray microprobe**

- Spatial resolution: 0.05-1µm
- Spectral resolution: \(10^2 > \Delta E/E > 10^{-4}\)
- Averaged flux: \(10^{10} - 10^{13}\) photons/s/µm²

**ESRF Lecture Series on Coherent X-rays and their Applications, Lecture 6 - Jean Susini**
Synchrotron micro-probes

**Diffractive lenses**
- Resolution determined by probe size and overall stability
- Size of the probe is a convolution of the geometric image of the source and the point spread function of the lens
- Diffraction limited vs aberration limited?
- Coherent illumination required for diffraction-limited resolution but images are not coherent.
- SXMs are coherent (brightness) experiments

**Refractive lenses**

<table>
<thead>
<tr>
<th>Source</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $\beta$, 25x135$\mu$m$^2$ - 17x208$\mu$rad$^2$</td>
<td>50-250m</td>
</tr>
<tr>
<td>Low $\beta$, 25x930$\mu$m$^2$ - 17x29$\mu$rad$^2$</td>
<td>$&lt;50\times50$nm$^2$</td>
</tr>
</tbody>
</table>

**X-ray waveguides**

**X-ray reflectors**

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**Diffraction limited focusing**

Thin lens equation

\[
\frac{1}{f} = \frac{1}{p} + \frac{1}{q}
\]

Numerical aperture

\[NA = n \sin \alpha\]

Geometrical demagnification:

\[s_G = \frac{\Sigma q}{p}\]

Diffraction limited focusing if

\[\Sigma \times \theta = \frac{\lambda}{4\pi}\]

\[s_{DL} = C \frac{\lambda}{NA}\]

where $C=0.61$ for a circular aperture
A trade-off

Central Airy disk

d = \frac{\lambda}{NA} 

for circular lens

Optical aberrations often limit resolution before diffraction limit is reached

- Source size (horiz. vs. vert.)
- Distance source-optics
- Working distance

- Working distance
- Lens aperture
- Beam divergence

Geometrical demagnification

\[ s_G = \Sigma \frac{q}{p} \]

Coherent illumination

\[ s_{DL} = 1.22 \frac{\lambda}{\sin \alpha} \]

Ideal focusing of a point source

- Focusing: equal optical paths source-to-focus
- Ellipse definition: \( p + q = \text{constant} \)
A fundamental limit: “Liouville’s theorem”

1 - The phase-space density of photons cannot be increased.

2 - In fact, because of absorption and finite efficiency of the optical elements, the phase-space density decreases.

3 - Implications for diffraction experiments.

Undulator beam and spatial modes

- The combined RMS widths due to the one-electron pattern and the electron beam are

\[ \Sigma_x = \sqrt{\frac{\sigma_x^2 + \frac{\lambda_b}{4\pi} L}{4\pi}} \]
\[ \Sigma_y = \sqrt{\frac{\sigma_y^2 + \frac{\lambda_b}{4\pi} L}{4\pi}} \]

- Actually unapertured beam

- Similarly we can define the full widths as before \( \Delta_x = \sqrt{2\pi} \Sigma_x \) and \( \Delta_{x'y'} = \sqrt{2\pi} \Sigma' \) etc.

- The phase space areas in \( x \) and \( y \) are now \( A_x A_{y'} \) and \( A_{x'y} A_{y'x} \)

- Of course we could define the beam width and angle by slits - then we could write the phase space areas in \( x \) and \( y \) as \( \Delta_{x'} A_{y'} \) and \( \Delta_{y'} A_{x'} \)

- If the phase space area in \( x \) is \( m \) times bigger than the coherent phase space area then we say that the beam has \( m \) modes in \( x \) and similarly for \( y \) - therefore for the unapertured beam we would have

\[ m_x = \frac{\Delta_{x'} A_{y'}}{\lambda/2} \]
\[ m_y = \frac{\Delta_{y'} A_{x'}}{\lambda/2} \]

From lecture 4, M. Howells
Some source parameters

Electron beam parameters (RMS)

**High beta section** (even IDs)
- Size H: 415.0µm
- Div. V: 2.9µrad
- Size V: 8.6µm
- Div. H: 10.3µrad

**Low beta section** (odd IDs)
- Size H: 51.0µm
- Div. V: 2.9µrad
- Size V: 8.6µm
- Div. H: 108.0µrad

Photon source parameters (RMS)

**High beta section**
- Size H: 415.0µm
- Div. V: 13.5µrad (5-40keV)
- Size V: 8.6µm
- Div. H: 16-11µrad (5-40keV)

**Low beta section**
- Size H: 51.0µm
- Div. V: 13.5µrad (5-40keV)
- Size V: 8.6µm
- Div. H: 108.0µrad

Some beam parameters

A coherent experiment uses only one mode!!

What about the wasted modes?

High beta sources provide a slightly more "coherent" beam
ESRF Lecture Series on Coherent X-rays and their Applications,
Lecture 6 - Jean Susini

Source demagnification: Scheme 1

A "short" beamline with a secondary source

- Requires a small pinhole (difficult to produce for hard X-ray?, heat load?, ….)
- Compromises the energy tunability ?
- Compact and stable instrument
- Overfilling of the slits makes the beamline less sensitive to drifts and vibrations
- Optical optimization is possible
- The secondary slit can be used to clean-up the beam (speckles from upstream components)
- Trade-off flux vs. resolution is tunable

See also lecture 3 (A. Snigirev)

Source demagnification: Scheme 2

Long beamline with a direct source demagnification

- Exploits the source size (low $\beta$ or apertured high $\beta$ )
- Allows long working distance
- Preserves the coherence
- Preserves the energy tunability (spectroscopy)
- Preserves the vertical divergence tunability (diffraction)
- Overall stability
- Flux losses or large aperture optics
- Cost

See also lecture 3 (A. Snigirev)
High energy = very grazing incidence

- Small $\theta \rightarrow$ Long mirror (> 1m) or small NA
- Off-axis geometry
- Aberrations (spherical aberration, astigmatism, figure errors)

Radii of curvature

\[
R_m = \frac{2}{\sin \theta} \left( \frac{pq}{p+q} \right), \quad R_s \approx R_m \theta_c^2, \quad \theta < \theta_c \sim 10 \text{mrad}
\]

\[
R_s = \text{mm}, \quad P_m = \text{km}
\]

\[
\theta_{\text{[ideal]}}, E_\text{L[keV]} = 19.83 \frac{\sqrt{\rho [\text{g/cm}^3]}}{E_{\text{L[keV]}}}
\]

Mirror shapes: $z = \alpha y^2(1+\beta y+\gamma y^2), \quad R_c \sim 1/2\alpha$

- Ellipsoidal: point-to-point focusing

\[
\alpha_e = \frac{\sin \theta}{4p} \left(1 + \frac{p}{q}\right)
\]

\[
\beta_e = \frac{\cos \theta}{2p} \left(\frac{p}{q} - 1\right)
\]

\[
\gamma_e = \frac{1}{4pq} + \frac{5 \cos^2 \theta}{16p^2} \left(1 - \frac{p}{q}\right)
\]


"ideal" ellipse are extremely difficult to manufactured
Kirkpatrick-Baez geometry

**Principle:** perpendicular meridian planes

*P. Kirkpatrick and A.V. Baez,*
“Formation of optical images with X-rays”
*J. Opt. Soc. Amer.,* **38**, (1948)

Kirkpatrick-Baez mirror pair

Spherical aberrations $\sim \frac{1}{L^2}$

Multilayer coating:
Bragg angle $\Rightarrow$ shorter mirror or larger aperture

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**Kirkpatrick-Baez system at the ESRF**

**microfocus on ID19 (20.5 keV)**

<table>
<thead>
<tr>
<th>Aperture (V\times H) ((\mu m))</th>
<th>Focus Size FWHM ((\mu m))</th>
<th>Flux (Ph/s@90mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 (\times) 50</td>
<td>92 (\times) 87</td>
<td>5 (\times) 10^{-7}</td>
</tr>
<tr>
<td>400 (\times) 100</td>
<td>70 (\times) 74</td>
<td>2 (\times) 10^{-7}</td>
</tr>
<tr>
<td>600 (\times) 160</td>
<td>90 (\times) 70</td>
<td>4.5 (\times) 10^{-7}</td>
</tr>
</tbody>
</table>

ESRF: **40nm**

Spring8: **25nm**
Fresnel Lenses – Zone Plates

Diffractive X-ray Lenses
Circular transmissive diffraction gratings with radially decreasing line width giving focusing effect

Alternate ‘zones’ modify phase/amplitude of incident wavefront:
for material of thickness, $t$, wavelength, $\lambda$, refractive index $1-i\beta$,
phase shift, $\Delta \phi$, is:

$$\Delta \phi = \frac{2\pi \delta t}{\lambda}$$

For X-rays:

Fresnel zone plates: a Gabor hologram of a point object

Planar wavefront
Hologram (Fresnel Zones)

Reconstruction by coherent illumination

Diffraction limit ($\delta=1.22\Delta r$)

- requires coherent illumination
- $\lambda/\Delta \lambda > N$

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Lecture 6 - Jean Susini
**Fresnel Zone Plates**

- **Resolution:** \( \delta_m = 1.22 \frac{\Delta r_N}{m} \)

- **Focal length:** \( f_m = \frac{D \Delta r_N}{m \lambda} \)

- **Depth of focus:** \( \text{DOF} = \pm \frac{4 \Delta r_N^2}{m \lambda} \)

- **Dimensions:**
  - \( m=1 \)
  - \( \Delta r_N=50\text{ nm} \)
  - \( D=100\mu m \)

- **Results:**
  - 8\mu m @500eV
  - 160\mu m @10keV
  - 2mm @500eV
  - 40mm @10keV

**Soft X-ray zone-plates**

- **Dimensions:**
  - \( \Delta r_N = 25\text{ nm} \)
  - \( D = 63\mu m \)
  - \( N = 618 \text{ zones} \)
  - \( f = 650\mu m \)
  - \( NA = 0.05 \)
  - @ \( \lambda = 2.4\text{ nm} \)

- **Results:**
  - \( \Delta r_N = 15\text{ nm} \)

Zone plate aspect ratio
structure height, $t$, critical for efficiency, $\Delta r_N$ for resolution

Aspect ratio for $\Delta r_N = 50\text{nm}$
Practical limit for small $\Delta r_N$ is $\sim 10\text{-}15\text{:1}$

<table>
<thead>
<tr>
<th>Material</th>
<th>$t$ (µm)</th>
<th>$\varepsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E=0.5keV</td>
<td>Ge 0.28</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Ni 0.25</td>
<td>24</td>
</tr>
<tr>
<td>E=2.0keV</td>
<td>Ni 0.60</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Au 0.45</td>
<td>24</td>
</tr>
<tr>
<td>E=8.0keV</td>
<td>Ta 1.70</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>W 1.50</td>
<td>33</td>
</tr>
</tbody>
</table>

**Fresnel zone-plates: several strategies**

* Grating with equal lines and spaces

$$
\varepsilon_m = \frac{1}{m^2\pi^2} \left( 1 + e^{-2K\Phi} - 2e^{-K\Phi} \cos\Phi \right)
$$

$K = \frac{\beta}{\delta}$ and $\Phi = \frac{2\pi\delta}{\lambda}$

- **Amplitude**: Opaque zones ($K \to \infty$)
  - $\varepsilon_1 \sim 10\%$ and $\varepsilon_3 \sim 1\%$

- **Phase**: weak absorbing and phase reversal zone ($K \to 0$ and $\Phi = \pi$)
  - $\varepsilon_1 \sim 40\%$

$$
\varepsilon_m(p) \approx \frac{1}{m^2} \left( \frac{\sin \left( \frac{\pi}{p} \right)}{\frac{\pi}{p}} \right)^2
$$

- $\varepsilon_1(2) = 40.5\%$
- $\varepsilon_1(3) = 68.5\%$
- $\varepsilon_1(4) = 81.2\%$

- **Amplitude**
  - X-ray opaque material
  - X-ray phase shifting material

- **Phase**
  - Ideal
  - 3-level approximation

* Blazed

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray opaque material</td>
<td></td>
<td>X-ray phase shifting material</td>
</tr>
</tbody>
</table>
Blazed zone plate: 3 level lens

- Material: Nickel
- Diameter: 150 µm
- \( \Delta R_N : 150 \text{nm} \)

\[7 \text{ keV} : \varepsilon \approx 57\%\]

Rejection of the unwanted diffraction orders

Zone-plate based SXM = Central stop + ZP + OSA
Multilayer Laue Lenses

- Deposit varied line-spacing grating on flat substrate (thinnest structures first)
- Section to 5-20 µm thickness (high aspect ratio structure)
- Assemble two into a single device (MLL)

Tentative of comparison

- Resolution: ++ ++++++++ ++++++++ ++++++++ ++++++ +++
- Achromaticity: -(-) +++(+) --(-)
- Efficiency: + +++(+) ++
- Imaging (MTF): ++++ ++ +++

Zones plates
Mirrors
Refractive lenses

Energy

X-ray Fluorescence: a brief reminder

- Element specific
- Co-localization
- Quantification

Energy dispersive detector
XRF on synchrotron beamline = low detection limit

- Low background
- Tunable energy (XANES)

Only a few degrees collection angle!

Detector developments
Dwell time < 100ms

μ-XRF in Trichomes of Arabidopsis Thaliana

E_{ex}: 5.8 keV, probe size: 0.3x0.2μm², dwell time: 800 ms/pixel.

M.P. Isaure et al., Biochimie, 88, 2006
Fluorescence tomography (3D-µXRF)

- Pixel-by-pixel acquisition
- Sinogram(s)
- 2D-Slice or 3D-Volume

The reconstruction problem is far more difficult compared to transmission tomography:
- self absorption corrections
- $\mu(E_{\text{a}}, \chi)$ is a priori unknown
- weak fluorescence signal for light elements
Fluorescence tomography (3D-µXRF)

Pixel-by-pixel acquisition

Algorithmic solution:
Optimal estimation of attenuation maps by combination of transmission, fluorescence and Compton tomographies


Geometrical solution:
Collimation of the detection angle to define a voxel: confocal geometry


Combining several signals

Compton tomography ($\sigma_{\text{Compton}} \sim Z$)
- Electronic density maps

Absorption tomography ($\sigma_{\text{photo}} \sim Z^4$)
- Absorption coefficient maps

Integration of the information
Absorption + Compton + Fluorescence

QUANTIFICATION

B. Golosio et al., APL 84 (2004)
**Single Fly Ash Particle**

Transmission Tomography

Combined Tomographies

![Image of a fly ash particle with color-coded distributions of Rubidium, Iron, and Manganese](image)

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**XRF Tomography – “confocal geometry”**

- **Si(Li) detector**
- **Optical microscope**
- **Focusing lens**
- **Sample**
- **CCD Alignment & imaging**

![Diagram of XRF Tomography setup](image)

> Spatial resolution: 5-10µm

---


L. Vincze et al., Anal.Chem. 76(22) (2004)
From 3D-confocal XRF to quantification

Quantitative micro X-ray fluorescence analysis

<table>
<thead>
<tr>
<th>Element</th>
<th>Larime (5-CaSiO₃) (ppm)</th>
<th>CaSiO₃-walstromite (ppm)</th>
<th>Th-rich phase (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>29.6 ± 5.9%</td>
<td>18.6 ± 5.4%</td>
<td>1.2 ± 0.4%</td>
</tr>
<tr>
<td>Mn</td>
<td>391 ± 25</td>
<td>386 ± 26</td>
<td>47 ± 10</td>
</tr>
<tr>
<td>Fe</td>
<td>254 ± 13</td>
<td>220 ± 16</td>
<td>114 ± 11</td>
</tr>
<tr>
<td>Sr</td>
<td>431 ± 3</td>
<td>48 ± 1</td>
<td>92 ± 3</td>
</tr>
<tr>
<td>Y</td>
<td>9 ± 1</td>
<td>61 ± 2</td>
<td>22 ± 3</td>
</tr>
<tr>
<td>Zr</td>
<td>35 ± 1</td>
<td>233 ± 2</td>
<td>29 ± 2</td>
</tr>
<tr>
<td>Hf</td>
<td>&lt; DL</td>
<td>3 ± 1</td>
<td>1 ± 1</td>
</tr>
<tr>
<td>Pb</td>
<td>7 ± 2</td>
<td>2 ± 1</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>Th</td>
<td>&lt; DL</td>
<td>1 ± 1</td>
<td>5 ± 2</td>
</tr>
<tr>
<td>U</td>
<td>&lt; DL</td>
<td>4 ± 1</td>
<td>6 ± 2</td>
</tr>
</tbody>
</table>

unusual high Ca concentration

“Ca-rich lithology in the Earth’s deep (> 300 km) convecting mantle”

B. Vekemans et al., JAAS. 19(10) (2004)
F.E. Brenker et al., EPSL 236 (2005)

X-ray Absorption Near Edge Spectroscopy (XANES)

Electronic transitions to bound states, nearly bond states or continuum

Continuum states

Rydbert states

σ^*

π

σ

X-ray

Energy

Norm. fluo yield or -log I/I₀

Cr(III)

Energy (eV)

Cr(VI)
Chromium chemical mapping in cells

Micrograph

Potassium

Cr (total)

1(a.u.)

0

Cr(VI)


Absorption and Phase contrasts

Refractive index \( n \) for X-ray wavelengths: \( n \approx 0.999999 \)

\[
 n = 1 - \delta + i \beta
\]

Phase contrast

\( \sim 1 / E \)

Absorption contrast

\( \sim 1 / E^3 \)

See lecture 5 - P. Cloetens
### X-ray microscopy techniques using phase shifting

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>SXM</th>
<th>TXM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonse / Hart</td>
<td>X-ray interferometer based on double crystal in Laue geometry</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>keV photons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schmahl et al</td>
<td>Zernike phase contrast with phase shifting annular plate in back-Fourier plane of imaging objective</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>(1993)</td>
<td>(soft X-rays &amp; keV photons)</td>
<td></td>
<td></td>
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<tr>
<td>Morrison et al</td>
<td>Differential phase contrast using a quadrant detector similar to SEM</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>(1996)</td>
<td>soft X-rays &amp; keV photons</td>
<td></td>
<td></td>
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<tr>
<td>Polack / Joyeux</td>
<td>Differential phase contrast using Young type slits or a Fresnel bi-mirror</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(1995)</td>
<td>Using 2 zone-plates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaulich / Wilhein</td>
<td>Differential phase contrast using 2 zone-plates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2002)</td>
<td>soft X-rays (keV photons)</td>
<td></td>
<td></td>
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</tbody>
</table>

### Phase contrast in SXM?

- **Intensity variation?**
  - **Phase gradients**: due to material inhomogeneities or thickness variations

**2 options**

- **Differential Phase Contrast (DPC)**
  - Beam deflection
  - + Configured detector
  - = intensity variation

- **Differential Interference Contrast (DIC)**
  - Phase effects
  - + interference fringes
  - = intensity variation
**DPC: SXM and configured detectors**

Phase gradients due to material inhomogeneities or thickness variations cause a deflection of the microprobe beam.

- A single element detector would record the intensity but no information on the degree of deflection → Absorption only
- If the detector is split into several pixels, the beam deflection leads to intensity variation can be detected → Phase information can be extracted.

Reciprocity Principle

- STXM and TXM imaging modes can produce equivalent image contrast
- The roles of source and detector can be interchanged
- STXM mode allows some imaging conditions to be realized more easily than in TXM mode,
  - … and vice versa!

See also Lecture 4 (M. Howells)

**DPC and fast-readout CCD array detector**

- 80x80 pixels
- Spreads signal across many detector elements
- Extends the dynamic range for which photon counting is possible.
- Allows flexible choice of imaging modes (with simultaneous absorption, phase and dark field contrast)


CVD Diamond
ID21
3.3keV
100nm pixel size

G.R. Morrison et al., *Journal de Physique IV* 104 (2002)
Configured segmented detector


Diatom
10keV
Beamline 2-ID-E
APS

Differential Interference Contrast (DIC)

Visible light microscopy

The image of DIC microscopes is formed from the interference of two mutually coherent waves with lateral displacements (shear) of the order of the minimum size of the imaged structure and are phase-shifted relative to each other.

The intensity distribution in measured DIC images is given by a non-linear function of the spatial gradient of a specimen's optical path length distribution along the direction of shear.

- Two plane polarizers are involved, one before the condenser and one after the objective.
- Birefringent prisms act on the plane polarized light first to split the beam in two, and later to recombine the two beams.
Visible light microscopy

X-ray microscopy

G. Nomarski, 1960

- T. Wilhein et al., Optics Communication 193, (2001)
- B. Kaulich et al., Optics Express, 10(20) (2002)

**Differential Interference Contrast (DIC)**

ZP1 - ZP2

Shear of wave front division or distance of Airy disks in focal plane is smaller than optical resolution ("differential")

\[
\Delta s < \delta
\]

\[
\Delta f < D.O.F
\]

- Distance \(\Delta f\) of both ZPs smaller than depth of field
- Displacement \(\Delta s\) smaller than resolution \(\delta\)

\(\lambda = 0.3\,\text{nm}\)

\(f_{ZP1} \neq f_{ZP2}\)

ESRF Lecture Series on Coherent X-rays and their Applications,
Lecture 6 - Jean Susini
X-ray Differential Interference Contrast (DIC)

Development of multi-spot zone plates by reconstruction of the hologram of a plane wave and several spherical waves (TASC-INFM, Trieste, Italy)

E. di Fabrizio et al., Optics Express, 11(19) (2003)
**X-ray Differential Interference Contrast (X-DIC)**

- **E = 5.8keV (λ=2.1 Å)**
- **Dwell time: 50 ms/px**
- **Probe size: 0.6x0.7 µm²**

*Cell membranes of maize plant cells*

- Absorption
- X-DIC (phase)

**X-DIC+XRF microscopies = Quantification?**

*Arabidopsis thaliana*

- μ-XRF
- X-DIC

Intensity maps → Density+thickness map → quantification
Multi-keV X-ray microscopy

- **Geometry**
  - Spatial res.: 1000nm → 30nm
  - Field of view: variable
  - Depth of field > 10µm
  - Working distance > 20mm

- **Contrast mechanisms**
  - Phase contrast
  - X-ray fluorescence
  - Micro-spectroscopy (XANES)

- **Sample**
  - Hydrated-frozen
  - Thick
  - Minimum preparation

Lower exposure dose
- Trace element detection
- Quantitative XRF analysis
- Chemical state specificity

Cryo is mandatory
- No labeling
- No sectioning

Needs for a multi-modal approach

- **Source and optics**
- **Scale**
  - mm
  - µm
  - nm
- **In-situ**
- **Quantification**
  - 3D
- **Abundance**
  - %
  - ppm
  - ppb
- **Quality**
  - Structural
  - Chemical
  - Elemental
- **Detectors**
- **Multi-modal analysis**
- **Multi-variate data processing**