Phase Contrast Imaging and Micro-Spectroscopy

Diane Eichert

diane.eichert@elettra.trieste.it

X-Ray Microscopy Section
ELETTRA
Basovizza, Trieste, Italy
Outline:

1. Introduction - Generalities
2. Basic interactions
3. X-ray imaging modalities
   - Absorption
   - Fluorescence
   - Phase contrast
4. Microbeam-based techniques
   - SXM
   - STXM
   - XPEM
5. Microtomography
6. Conclusions
Introduction - Generalities

1.7 m

20 cm

Molecule to Atom (Å)

50-100 µm

1.4 µm

2 nm

~1.4 µm

20 cm

Molecule to Atom (Å)
Simultaneous Correlative Micro analysis on the same sample!

- \( \mu \)-X-ray Fluorescence
  - 3D-XRF
  - Resolution around 0.1-1 \( \mu \)m

- \( \mu \)-X-rays Absorption Spectroscopy
  - \( e^- \)

- \( \mu \)-tomography Imaging

- \( \mu \)-Diffraction

- \( \mu \)-FT Infrared

Bending vibrations:
- In-plane rocking
- In-plane scissoring
- Out-of-plane wagging
- Out-of-plane twisting
**Spectral continuity:**

From infrared (~0.1 eV) to hard X-rays (~100 000 eV)

<table>
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<th>Photons energy (eV)</th>
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<td>X-ray Fluorescence</td>
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More ? Confer to the lecture of G. Margaritondo
Microscopy: Imaging, taking a picture

Spectroscopy: spread the light

Photometry: measure how much light

Reveals inhomogeneities and singularities in the sample, coupled with chemical information

Micro-Spectroscopy?
**Imaging, chemical mapping and chemical spectroscopy:**

Illumination (X-ray, IR) and focalisation.

**Microscopy**

**Spectroscopy**

Energies, frequencies X,Y positions.
**Chemical specificity and resolution:**

![Chemical sensitivity and resolution diagram](image)

- NMR
- IR
- RS
- SIMS
- μ-XAS
- μ-XRM
- XPS - AES
- EELS
- SAXS
- SEM TEM
- AFM

Ideal!
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Relevant interactions of X-ray photons with matter:

**X-ray absorption:**

An electron in the given shell (e.g. K) is ejected from the atom by an external primary excitation x-ray photon, creating a vacancy.

**X-ray fluorescence:**

Higher energy core electron fills empty electron level, and ejects an x-ray photon of fixed energy.

**Auger** electron:

The excitation energy from the inner atom is transferred to one of the outer electrons causing it to be ejected from the atom.
**Refractive index and X-ray contrast techniques**

X-ray contrast is generated by *differences* in the complex scattering factor per unit volume

\[ n(\lambda) = 1 - \delta(\lambda) - i\beta(\lambda) = 1 - \frac{n_a r_e \lambda^2}{2\pi} f_1(\lambda) - f_2(\lambda) \]

\[ \beta(\lambda) = \frac{n_a r_e \lambda^2}{2\pi} f_1(\lambda) \]

\[ \delta(\lambda) = \frac{n_a r_e \lambda^2}{2\pi} f_2(\lambda) \]

**Absorption:**
- Bright-field imaging
- Chemical contrast techniques
- Magnetic absorption contrast

**Scattering, refraction:**
- Zernike phase contrast
- Differential phase contrast
- Differential interference contrast
- Dark-field imaging
- Magnetic phase contrast

\( \delta(\lambda) \): Phase sensitive
\( \beta(\lambda) \): Absorption ...
\( n_a \): average atom density
\( r_e \): classical electron radius
\( f_1, f_2 \): atomic form factors
**Definition of contrast:**

**Often applied definition:**

Contrast is defined as the difference in light intensity between the image and the adjacent background relative to the overall background intensity.

\[
C = 100 \cdot \frac{(I_s - I_B)}{I_B}
\]

\(I_s\): Specimen intensity  
\(I_B\): Background intensity

**Definition used for XRM:**

Contrast is defined as the difference in maximum and minimum light intensity normalized to the sum of maximum and minimum light intensity.

\[
C = \frac{(I_{max} - I_{min})}{I_{max} + I_{min}}
\]

\(I_{max}\): Max. image intensity  
\(I_{min}\): Min. image intensity
Relevant interactions of X-ray photons with matter:


Natural amplitude contrast between water and organic matter

Contrast due to dramatic difference in the atomic form factors values of two materials, especially water and organic matter between the C and O K-absorption edges.

Note the penetration distance compared to electrons !!!
Chemical sensitivity of X-rays: elemental mapping

Electron binding energies for relevant materials

Photon energy vs. Z Number

K 1s

L 1 2s

L 2 2p\textsubscript{1/2}

L 3 2p\textsubscript{3/2}
2- Basic interactions

Matter

Electron

Photoemission
PEEM
(PES, AES, XANES)

Incident Beam

Absorption

Emission

Absorption Reflectivity...

Transmission

Microscopy Imaging
XAS

Scattered X-rays, Diffracted X-rays

Elastic scattering
Diffraction imaging

Radiation effect

Change in energy

Inelastic scattering

Sample Environment:
- Temperature
- Pressure
- Fields (E, H)
All chemical specific spectroscopies are based on absorption of the photons by the matter and following excitation and de-excitation processes.

- XAS
- FS
- XPS
- IR
X-ray absorption spectroscopy: tunable x-ray source requested

X-rays are absorbed when their energy matches the binding energy of an atom’s electron. At higher energies the absorption efficiency decreases but important secondary processes occur, related to ejection of photoelectrons. Absorption edges are elemental fingerprints!

X-ray absorption spectra are generally produced in the range 200 - 35 000 eV
**X-ray Absorption Spectroscopies:**

Reflect the modulation of $\mu(E)$ by multiple scattering with surrounding atoms.

*More? Cf lectures from P. Fornasini*
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Absorption mode: radiography

X-rays penetration depth advantage:
- samples can become partly transparent

Few scattering effect and few refraction effect:
- x-ray don’t change direction traversing the sample

Set up very easy:
- absorption mode contrast

\[
\text{Beer - Lambert’s law:} \\
I = I_0 \exp \left( -\mu x \right) \\
\mu: \text{absorption coefficient}
\]
Electron binding energies, in eV

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<th>L2 2p1/2</th>
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</table>


http://xdb.lbl.gov/xdb.pdf
Bacteria and clay dispersion:

Destruction of associations of clay particles by soil microbes

X-ray images acquired with the full-field imaging microscope, @ 520 eV

Imaging in the natural hydrated state of the sample:
→ no alteration of the environment of the sample

J. Thieme et al., IRP, Uni Goettingen / G. Machulla, Uni Halle, D
**Brightfield imaging at “higher” photon energies:**

Characterization of morphology and defects in modern semiconductors with a full-field imaging microscope (@ 1.8 keV, XM1/ALS)

**Sample preparation:**
Back side thinning of Si wafer

![Graph showing the penetration depth of different materials](image)

Schneider G., BESSY, Germany
Energy K-edge subtraction imaging technique:
Iodine absorption coefficient:

**Edge energies (keV):**
K: 33.169
L_I: 5.1880
L_{II}: 4.8521
L_{III}: 4.5571
M_I: 1.0721
M_{II}: 9.3050
M_{III}: 8.7460
M_{IV}: 6.3130
M_{V}: 6.1940
**K-edge subtraction:**

Step 1: Contrast agent injection: iodine, gadolinium...
Step 2: Acquisition of two images: Above (A) and Below (B) the K-edge
Step 3: Image processing: “contrast agent” and tissue images
Number of detected photons per pixel $N$ in the image with energy $E$ is related to the number of incident photons $N_0$ by:

$$N = N_0 \exp \left( -\sum_j \left( \frac{\mu}{\rho} \right)_j c_j x_j \right)$$

$j$ denotes different materials (e.g. contrast agent, soft tissue...) which are characterized by their energy dependent mass absorption coefficients ($\mu/\rho$) and their mass density $c_j x_j$.

**Two measurements:**

- Above (A) and Below (B) the K-edge

\[
N_A = N_{A0} \exp \left( -\sum_j \left( \frac{\mu}{\rho} \right)_{j,A} c_j x_j \right)
\]
\[
N_B = N_{B0} \exp \left( -\sum_j \left( \frac{\mu}{\rho} \right)_{j,B} c_j x_j \right)
\]

We can retrieve the mass densities of the iodine and the tissue and then retrieve their respective images!
**K-edge imaging:**
Improving the visualisation of coronary problems...

**Magnetic absorption contrast:**

The X-ray absorption coefficient depends strongly on the relative orientation between the helicity of the photons and the projection of the local magnetization onto the photon propagation direction.

**X-ray Fluorescence:**

Energy continuum

- Photo-electron

Energy dispersive detector

**Attributes (with SR):**

- Element Specific
- Co-localization
- Quantification
- High sensitivity
- Chemical information (XAS)
X-ray lines and transitions:

Characteristic $K$, $L$, and $M$ x-ray line energies for elements with $3 < Z < 95$.
Only the strongest lines are included: $K\alpha_1$, $K\alpha_2$, $K\beta_1$, $L\alpha_1$, $L\alpha_2$, $L\beta_1$, $L\beta_2$, $L\gamma_1$, and $M\alpha_1$.

http://xdb.lbl.gov/xdb.pdf

**Photons energies, in eV, of principal K and L emission lines**

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<th>Kα₂</th>
<th>Kβ₁</th>
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http://xdb.lbl.gov/xdb.pdf

Fluorescence yield $\omega$

* $\omega$ is the probability that an x-ray photon will be emitted as a result of ionization of a specific shell. For a given series of X-ray lines (e.g., K-series) $\omega$ is numerically equal to the ratio of original K-shell ionizations.

* The fluorescence yield for K lines increases monotonically as a function of the atomic number, and algebraic models accurately predict the empirical data.

* This factor means that the sensitivity of the x-ray method decreases for the lighter elements. The decrease, however, is partly compensated by the higher photo-absorption cross sections in light elements.

Example: $Zn$ (Z=30) $\omega_k=0.45$  
$Na$ (Z=11) $\omega_k=0.02$

**XRF mapping:**
trichomes of *Arabidopsis Thaliana*

E = 5.8 keV, probe size: 0.3x0.2µm², dwell time: 800 ms/pixel.

**Phytoextraction in accumulator plants:**

*Cs* accumulation in Arabidopsis Thaliana

20 mM K, 0 mM Cs

20 µm

20 mM K, 1 mM Cs

15 µm

0 mM K, 1 mM Cs

22 µm

20 µm

$E = 5.8$ keV, probe size: 0.7x0.4 µm², dwell time: 500 ms/pixel.

**Phase contrast vs absorption:**

for a simple transmission

**Absorption**

**Phase**

Absorption techniques can yield little contrast for light materials and materials with similar atomic number (similar attenuation factors). This gets worse as higher energies since the absorption coefficient is $1/E$ dependent...

$$\mu \sim Z^4 E^{-3}$$

**Purposes of phase contrast:**

* improving the sensitivity !
* diminishing the dose

$$\mu \sim Z^4 E^{-1}$$
Phase contrast vs absorption:

**Absorption contrast**

\[ \mu \sim Z^4 E^{-3} \]

Mostly used for chemical studies in combination with XANES and XRF

**Phase contrast techniques**

- \( \mu \sim Z^4 E^{-1} \)
- Use of phase shifting, real part of the refractive index
- Orders of magnitude higher contrast (gain 100 to 1000)
- Tremendous reduction of dose applied to object (dose \( \sim t^{-4} \) with spat. resolution \( t \))
- Additional transmission information on low side of absorption edges (XANES, XRF !)

Amplitude and phase contrast for a model protein \( C_{94}H_{139}N_{24}O_{31} \)
**Polymer sphere with two layers:**

In absorption:
Due to the material, very low absorption and thus contrast
Due to the similarities in composition between the different layers, no contrast...

Thanks to phase contrast:

![Diagram of the polymer sphere with two layers and propagation details](image)

\[ D = 83 \text{ cm}, \lambda = 0.7 \text{ Å} \]
Phase sensitive techniques:

Phase retardation:
\[ \Delta \varphi = -(2\pi/\lambda) \delta. \Delta s \]

Deflection
Phase gradients
\[ \Delta \alpha = - (\lambda/2\pi) (\partial \varphi/\partial x) \]

At zero distance:
Intensity
\[ I_0 = |\mu_0| = I \cdot \exp (- \int \mu dz) \]

→ all phase information is lost
Phase contrast imaging methods:

Crystal interferometers imaging
Bonse (1965) *Appl. Phys. Lett.* 6
Momose (1995) *NIMA* 352

Analyzer based imaging
(Diffraction Enhanced Imaging)

Grating interferometer imaging
David (2002)

Free-space propagation imaging
Crystal interferometer imaging:

- I crystal -> splits the monochromatic beam into two beams with the same phase
- II crystal -> acts as a mirror
- III crystal -> recombines the two beams
- A phase shift on the probe beam is produced by the presence of the sample
- The beams re-combined at the analyzer position generate an interference pattern registered by the detector
- Brag reflection are used as beam splitter
- Access to $\Phi(x,y)$ directly
- Extremely sensitive to subtle phase variations
- Limited field of view
Crystal interferometer imaging:

Phase contrast imaging of a polystyrene / PMMA plastic composite

Analyser based imaging (diffraction enhanced imaging)

- A perfect crystal (Brag crystal) is used as an angular filter to select angular emission of X-rays. The filtering function is the rocking curve (FWHM: 1-20 µrad)
- Analyzer and monochromator aligned -> X-ray scattered by more than some tens µrad are rejected
- Small misalignments -> investigation of phase shift effects (refraction angle is roughly proportional to the gradient of δ)
- With bigger misalignments the primary beam is almost totally rejected and pure refraction images are obtained by measurement of local beam deflection \( \nabla \Phi(x,y) \)
- Large field of view
Analyser based imaging (diffraction enhanced imaging)

Cylindrical plastic fiber:

Minus 0.5: Absorption and refraction contrast

Top: absorption + scattering rejection contrast

Plus 0.5

Plus 0.1 Refraction contrast

After Lewis, SPIE 2002
**ABI: image manipulation**

\[ I_L = I_R \left( R(\Theta_L) + \frac{\partial R}{\partial \Theta} (\Theta_L) \Delta \Theta \right) \]

\[ I_H = I_R \left( R(\Theta_H) + \frac{\partial R}{\partial \Theta} (\Theta_H) \Delta \Theta \right) \]

\[ \Theta_Z = \text{refraction Image} \]

\[ I_R = \text{apparent absorption image} \]

(absorption+extinction)

\[ \Theta_Z = I_H \cdot R(\Theta_L) - I_L \cdot R(\Theta_H) \]

\[ I_L \cdot \frac{dR}{d\Theta}_{\Theta_H} - I_H \cdot \frac{dR}{d\Theta}_{\Theta_L} \]

\[ R(\Theta_L) \cdot \frac{dR}{d\Theta}_{\Theta_H} - R(\Theta_H) \cdot \frac{dR}{d\Theta}_{\Theta_L} \]

Analyser based imaging (diffraction enhanced imaging)

Apparent absorption

Refraction image

**Free-space propagation imaging:** incline phase contrast

The technique exploits the high spatial coherence of the X-ray source and need high resolution detector.
- $z = 0 \rightarrow$ absorption image
- For $z > 0 \rightarrow$ interference between diffracted and un-diffracted wave produces edge and contrast enhancement; it makes use of Fresnel diffraction.

A variation of $D$ is detected
- Measure of $\nabla^2 \Phi(x,y)$
- Real space information
- Edge enhancement
Free-space propagation imaging:
from near field to far field

Contact: Only absorption is visible

Near field:
- Edges enhanced more and more with D
- Phase object visible
- Resolution degrades with higher D

Towards far field:
Images lose resemblance with real-space object
Free-space propagation imaging:

Polystyrene foam: non-absorbing foam
$E=18 \text{ keV}$

Phase retrieval with images at different distances

Tomography:
Repeated for ~ 1000 angular positions

3D distribution of phase
Improved resolution

Grating interferometry imaging:

- Beam splitter causes intensity fringes
- The sample distorts these modulations and the analyzer turns these fringe displacements into intensity values on the detector
- Measurement of $\nabla \Phi(x,y)$, phase shift effects
- Large field of view
- Moderate spatial resolution
Grating interferometry imaging:

X-ray tube (40 keV)!
Talbot-Lau interferometer

Absorption image  Differential phase contrast images

Outline:

1- Introduction - Generalities
2- Basic interactions
3- X-ray imaging modalities
   Absorption
   Fluorescence
   Phase contrast
4- Microbeam-based techniques
   SXM
   STXM
   XPEM
5- Microtomography
6- Conclusions
**Different types of X-ray microscopes:**

- **Scanning Transmission X-ray Microscopy (STXM):**
  - X-rays from a zone plate focusing lens
  - Scanning sample stage
  - Detector

- **Transmission X-ray Microscopy (TXM):**
  - X-rays from a condenser zone plate
  - Aperture
  - Sample
  - CCD camera

- **X-Ray Photoemission Electron Microscopy (XPEEM):**
  - X-rays from a phosphor screen
  - Magnified image
  - Photoelectrons
  - Lenses
  - Sample
Chemical imaging and micro-spectroscopy

2D maps of energy window:
the contrast reflects element concentration (XPS & XFS), different chemical states (XPS & XANES), BB shifts (XPS) etc.

Detailed characterization of coexisting micro-phases via microspectroscopy
XPS, XFS or XANES from selected spots: fingerprints of local composition, chemical state, electronic properties, BB, charging state, magnetic spin, MOs etc...
Focusing optics:

**Diffractive lenses**

**Zone Plate optics:**
from ~ 200 to ~ 10000 eV
Resolution: 25 nm in transmission

**Refraction lenses**

Hard x-rays
~ 4-70 keV
Resolution: > 1000 nm

**Normal incidence:**
spherical mirrors with multilayer interference coating
(Schwarzchild Objective)
not tunable, E < 100 eV
Resolution: best ~ 100 nm

**source**
25x200μm²

**focus**
< 50x50nm²

**Capillary:** multiple reflection concentrator

Hard x-rays ~ 8-18 keV
Resolution: > 3000 nm

**KP-B mirrors each focused in one direction:**
soft & hard: ~ 1000 nm
Soft & hard x-rays!
chromatic focal point,
easy energy tunability,
comfortable working distance
Resolution ~ 1000 nm

**X-ray waveguides**

**X-ray reflectors**
Photoemission electron microscope:

- Qualitative and quantitative elemental information: CL
- Chemical composition and chemical bonding: Core Level & Valence Band
- Electronic and magnetic structure (VB, ARUPS, PED, XMCD-XMLD with secondary electrons).
- Information depth < 10 nm (surface sensitive)

Information depth = dsinθ
\[ d = \text{Escape depth} \sim 3\lambda \]
\[ \theta = \text{Emission angle relative to surface} \]
\[ \lambda = \text{Inelastic Mean Free Path} \]

More? Cf lectures G. Paolucci, A. Locatelli and G. Stefani
**Mapping core level electron emission (CLEE):**

'concentration' inhomogeneity of solid materials

---

**Ti6Al7Nb (wt%):**

biocompatible alloy used for implantation in bone surgery:
surface composition affect the local reactivity and in turn the degree of acceptance by the human body:

**SEM has inferior chemical sensitivity**
Mapping core level electron emission (CLEE):
Characterization of nanomaterials MoS$_2$-nanotubes

Twisted chiral bundles of Mo-S individual cylinders: Mo 3d maps

Due to the low dimensionality and/or presence of I the S 2p, Mo 3d and VB spectra, reflecting the electronic properties, differ significantly from those of the MoS$_2$ crystal. SPEM revealed I (used as a carrier) in interstitial positions between the tubes bonded to outer S atoms.

J. Kovac, A. Zalar, M. Remaskar et al, Josef Stefan Inst., Luibljana,& ESCAMicroscopy
**Full-field microscope**

Advantages:
- fast, suitable for tomography
- high spatial resolution
- one spectrum per image pixel
  
  Spectromicroscopy with “energy stacks”
- morphological and chemical information

Disadvantages:
- transmission detection only
- dose inefficient
Analysis of air particulate matter

Environmental purposes: understanding the dispersion of the pollution

Spatially resolved X-ray spectromicroscopy:
Chemistry and in-situ cartographies of heavy metals

TwinMic, ELETTRA

P. Barbieri et al., Dept. of Chem., Univ. Trieste, I
Brightfield imaging in the “water window”

Location of Splicing Factors in whole, hydrated human mammary epithelial cells (ALS, TXM XM1)

Control nucleus, no primary antibody

Single nucleus labeled using antibodies specific for splicing factors

Same nucleus, splicing factors colored blue

Larabell, Live Science Division, LBL, USA
Zernike Phase Contrast with TXM:
Probing the status of microprocessors...

Studies on defects in a microprocessor chip
Possibility of probing bulk material (20 µm thick)

Cu interconnect structures imaged at 4 keV photon energy

Neuhaeusler (2003) SRN
Zernike phase contrast in X-ray microscopy

Amplitude and Zernike phase contrast images of an alga *Euglena gracilis*

$E = 500$ eV, accumulated dose is $3 \times 10^6$ Gray

Amplitude: 3 s
Phase contrast: 15 s

**Drawbacks of Zernike phase contrast:**

- Halos around structures
- Quantitative analysis difficult
- Limitation in spatial resolution
- Not all spatial frequencies are treated equally

Scanning transmission X-ray Microscope:

Versatile detector geometries
Simultaneous acquisition with different detectors
Optics as well as detector based imaging contrasts possible

Advantages:
- Dose efficient
- Multiple detection in parallel
- Applicable to bulk materials
- Variable image field size
- Spectromicroscopy “point by point”
- Morphological and chemical information

Disadvantages:
- Slow
- Sophisticated instrument
**XRF mapping:**
trichomes of *Arabidopsis Thaliana*

Spatially resolved chemical information: Fluorescence spectra
**Chromium compounds problems:**

**Harmful:**
-6 e-
Cr (VI) hexavalent

**Safe:**
-3 e-
Cr(III) trivalent

24 electrons
Different oxidation states!
Different reactivities...
With XAS, we probe the oxidation state
Chemical sensitivity
Chemical state of chromium in cells:

Micrograph

Potassium

Cr total

Cr (VI)

Cr(VI) enters the cell!

Causes of degeneration and atrophy of neurons:

* oxidative stress
* excitotoxicity
* protein aggregation
* mitochondrial dysfunction

changes in main bio-organic components such as nucleic acids, lipids, proteins...

Fe can be involved in all these processes

As metals in tissue are bounded into metallo organic complexes, access to their localization and concentration is important

Substantia nigra of brain
4- Micro-beam based techniques

XANES at the iron edge:
Probing iron oxidation state in melanized neuron

Pre-peak and white line are shifted towards higher energy

Control group  Parkinson’s disease

$\text{Fe}^{2+}$  $\text{Fe}^{3+}$

2s/pt, $\Delta E=0.3$eV

Chwiej J. et al. (2005) Analytical Chem. 77, 2895
Szczerbowska-Baruchowska et al. (2005) X-Ray Spectrometry 34, 514
Identification of organic compounds
On different areas that were probed with the x-ray beam

Huge differences in the nucleic acids normally present in high proportions inside the neurons

By coupling the x-rays and IR techniques, access to the localization of the element and the organic compounds inside the cell

New insights in the comprehension of neurodegenerative process
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Microtomography:

Precious for investigation of internal features without sample sectioning:

→ in many cases the sectioning procedure modifies the sample structure
→ the sample can be after studied by other experimental techniques,
→ or submitted to several treatments (mechanical, thermal, etc...)
Microtomography:

Uses the SAME processes and imaging modalities:
  absorption
  fluorescence
  phase contrast
The images are taken for different angles of the sample, realigned,
deconvoluted and the 3D volume is reconstructed

E=26 keV
Absorption tomograph
of trabecular bone

Samples by: D.Dreossi, F.Vittur, F.Cosmi
University of Trieste
Microtomography:
Reconstructed volume from a sample of pig trabecular bone

Access to bone morphology, bone density

More on microtomography? Cf. Giuliana Tromba courses!
Fluorescence micro-tomography

Rubidium (yellow)
Manganese (brown)
Iron (blue)
Iron detached particles

The external layer of the particle has different elemental composition than its inner part. These observations provide unique information about the possible fly-ash formation mechanisms (e.g. volatilization, condensation, diffusion, solid solution formation) during combustion.

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Advantages of Synchrotrons for X-ray Imaging, Structure and Speciation

- Source is bright: intense, well-collimated, with a small source
  - Can focus to a small spot

- X-ray spectrum is continuous, can select optimum energy for a specific element, or use continuum for efficient excitation of a large number of elements
  - Energy resolution (spectroscopies)

- Source is partially coherent
  - Required for forming smallest probes and some contrast mechanisms

- X-rays are linearly polarized, minimizing scattered background radiation, improving sensitivity

- High-energy x-rays which can be used to study thick samples or high Z samples
* Synchrotron based microscopy techniques have became an important analytical tool in synchrotron facilities

* Samples in their NATURAL state or little modified

* Good S/N and higher spatial resolution

* Large range of applications

* Association with conventional techniques is desirable

* Complementarities with other synchrotron based techniques are highly potential especially if combined studies are performed on the same sample.
Thank you!