

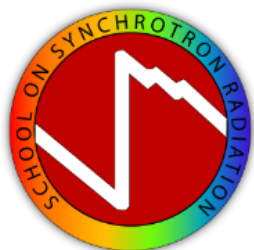


Elettra Sincrotrone Trieste

Introduction to X-ray Imaging

Alessandra Gianoncelli
alessandra.gianoncelli@elettra.eu

Elettra Sincrotrone Trieste, Trieste, Italy



XVIII School on Synchrotron Radiation
"Gilberto Vlaic":
Fundamentals, Methods and Applications
Muggia (Trieste), Italy
21 September – 1 October September 2026



Società
Italiana
Luce di
Sincrotrone





Elettra
Sincrotrone
Trieste



• Outline

- Introduction to X-ray Imaging
- Types of contrast and focusing systems
- X-ray microscopes:
Full-field, STXM, projection
- Standard imaging technique and new advanced ones

- How can we use X-rays to make an image from something we cannot see?

X-ray image contains spatially resolved information about how the sample modifies the X-ray beam:

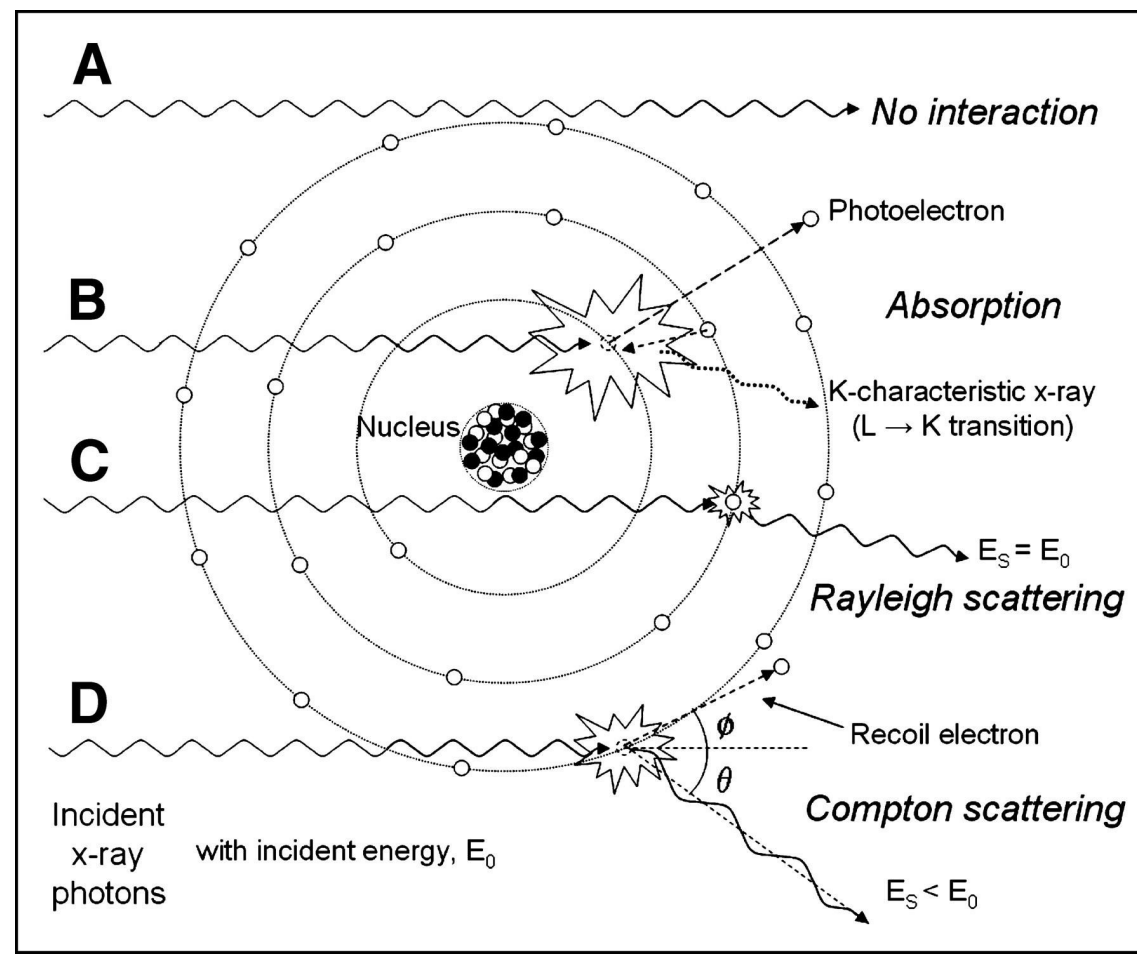
Absorption/attenuation imaging

Phase-contrast imaging

Scattering/diffraction-based imaging

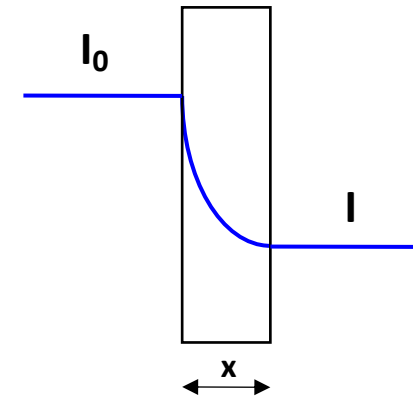
Elemental/chemical imaging

X-ray imaging is not one technique



• Absorption imaging

- Absorption imaging measures the attenuation of the x-ray beam as it travels through the specimen, very much like the x-ray radiographs commonly produced in hospitals.
- This imaging modality is by far the most widespread since it simply entails measuring directly the intensity of the x-rays transmitted through the specimen.
- In an absorption micrograph, the lateral variations of contrast levels are determined by local density and attenuation cross sections of the constituent atoms for a given photon energy.



Beer - Lambert' s law:

$$I = I_0 e^{-\mu x}$$

• Contrast mechanism for X-ray Imaging

- The discovery of x-rays by Röntgen in 1895 led not only to a revolution in medical imaging but also in many other fields of modern science.
- Röntgen could have been only partially aware of the absorption and phase properties of x-rays, especially about the value of the complex refractive index preventing him from focusing his new light 'invention'.
- It was Einstein who first suggested that the refractive index of x-rays, being a bit smaller than unity, should be considered as well



Wilhelm Conrad Röntgen and the first x-ray picture

• X-rays refractive index

$$n = 1 - \frac{n_a r_e \lambda^2}{\pi} (f_1 + i f_2) \equiv 1 - \delta - i\beta \leq 1 \quad \delta = 10^{-6}$$

**“Conventional refractive index”
describing phase change:**

$$\varphi(z) = \frac{2\pi}{\lambda} \delta z$$

**Exploitation of phase contrasts
possible using X-rays ?
Lower radiation damage ?**

**Describing photoelectric
absorption with coefficient:**

$$\mu = \frac{4\pi}{\lambda} \beta$$

**Consequence:
Emission of Auger, photo-electrons
and fluorescence photons, but also
causes radiation damage
(energetic secondary electrons!)**

• Focusing X-rays

For X-rays $n = 1 - \delta + i\beta$

where δ is positive and very small, typically 10^{-6} – 10^{-4} , depending on energy and material.

So the real part is:

$$\text{Re}(n) = 1 - \delta < 1$$

For visible light, by contrast, ordinary materials have approximately:

$$n > 1$$

2. Why does that matter for a lens?

A convex lens is thicker in the middle.

For visible light, because $n > 1$, light travels **more slowly through the glass** than through air.

The thicker central part therefore produces a larger phase delay.

The geometry of the curved surfaces causes the rays to bend **towards the optical axis**, producing focusing.

For X-rays, however:

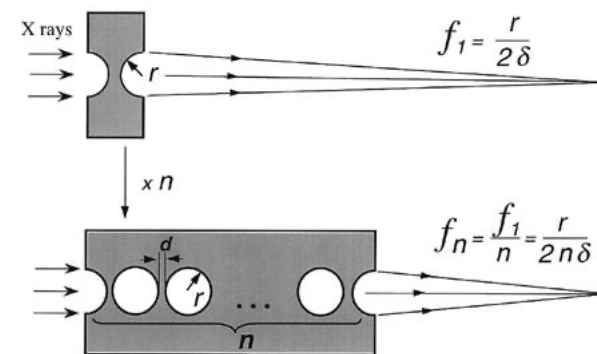
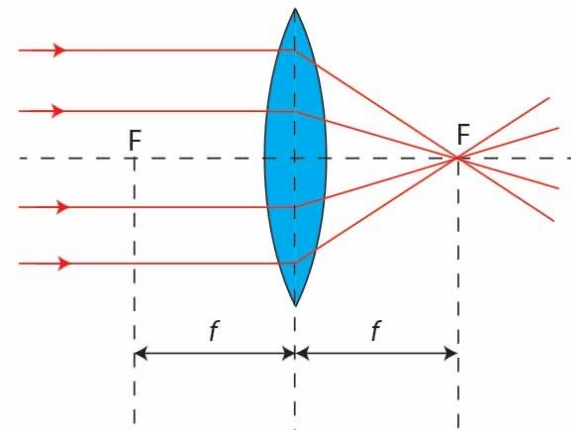
$$n_{\text{X-ray}} < 1$$

The situation is reversed: the phase velocity in the material is slightly **greater** than in vacuum.

Consequently, the refraction is in the opposite direction.

A **convex X-ray lens is therefore divergent rather than convergent**.

To obtain focusing, you need the opposite geometry: a **concave lens**.





• Focusing X-rays

The fact that n is below 1 is not, by itself, the main practical difficulty.

The real problem is that:

$$|n - 1| = \delta \ll 1$$

The difference from unity is **extremely small**.

For example, suppose:

$$\delta = 10^{-6}$$

Then:

$$n = 0.999999$$

The amount by which an X-ray is refracted at an interface is therefore tiny.

For visible light, you might have something like:

$$n_{\text{glass}} \sim 1.5$$

so:

$$n - 1 \sim 0.5$$

For X-rays:

$$n - 1 \sim -10^{-6}$$

That's a difference of roughly **five orders of magnitude**!

For a simple lens, approximately:

$$\frac{1}{f} \approx (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$

Since $n - 1 = -\delta$ is so small, the focal length f becomes very large.

For a single X-ray lens, you can easily end up with a focal length of **many metres**.

That's obviously not very useful if you want to focus an X-ray beam to a micron or nanometre-sized spot.



• Why are X-rays difficult to focus?

$$n = 1 - \delta + i\beta$$

- $n < 1$, so refraction has the opposite sign to visible light
- $\delta \ll 1$, so refraction is extremely weak
- Conventional lenses therefore have very long focal lengths
- Specialized X-ray optics are required:

zone plates, mirrors, compound refractive lenses, multilayer optics

It is not simply “because $n < 1$ ” that X-rays are difficult to focus. It is primarily because n is extremely close to 1. The fact that it is *slightly below* 1 determines the direction of refraction and hence the unusual geometry of refractive X-ray lenses.

The **law of refraction (Snell's law)** written in terms of the refractive indices is:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where:

n_1 = refractive index of medium 1

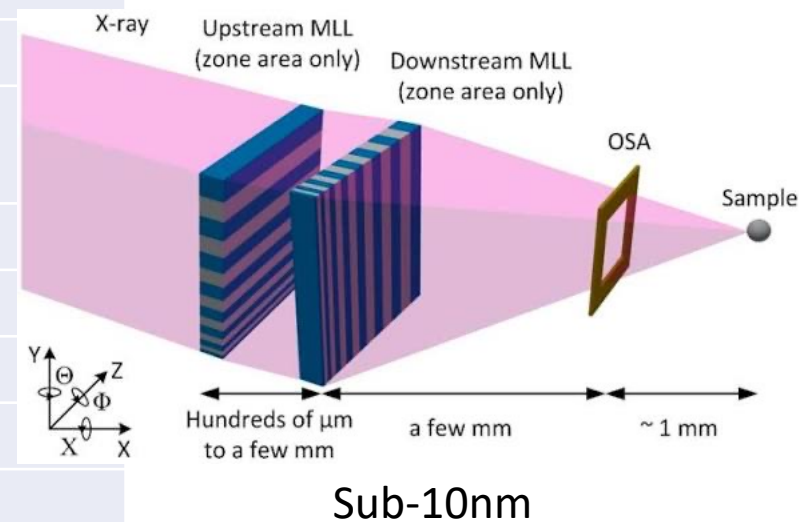
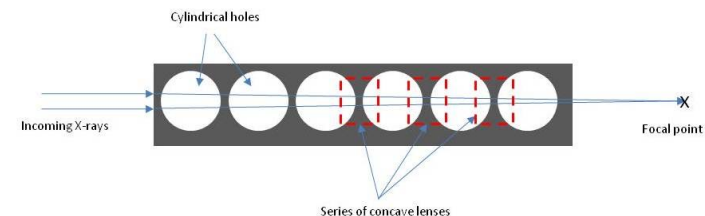
n_2 = refractive index of medium 2

θ_1 = angle of incidence, measured from the **normal**

θ_2 = angle of refraction, measured from the **normal**

• Different type of X-ray focusing optics

Principle	Optics	Typical applications
Refraction	CRL (compound refractive lens)	hard X-ray focusing
	Kinoform lens	hard X-ray focusing
Diffraction	Zone plate	STXM, TXM, nano-XRF
	Phase Fresnel lens	high-efficiency focusing
	MLL (Multilayer Laue Lens)	hard X-ray nanofocusing
Reflection	KB mirrors	synchrotron micro/nanofocusing
	Elliptical mirrors	focusing/imaging
	Toroidal mirrors	beamline focusing
Total reflection	Capillaries	micro-XRF
	Polycapillaries	laboratory XRF
Crystal diffraction	Bent crystals	spectroscopy/XRF
Multilayer diffraction	Multilayer mirrors	focusing/monochromation
Waveguiding	X-ray waveguides	nanofocusing/coherence
Computational	Ptychography	lensless/high-resolution imaging



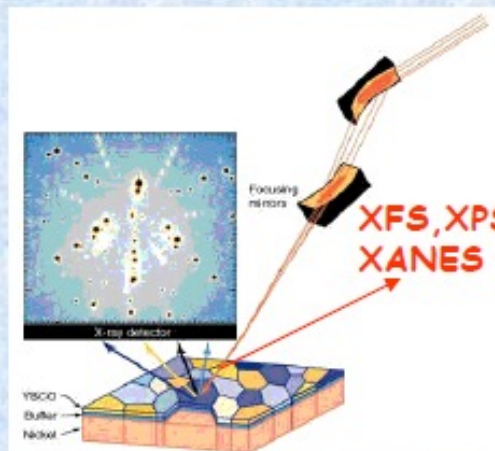
- Different type of X-ray focusing optics



Focusing optics: zone plates, mirrors, capillaries



Zone Plate optics: from ~
200 to ~ 8000 eV
Resolution: 30 nm in
transmission

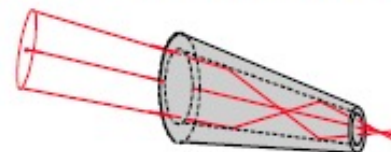


KP-B mirrors each
focusing in one direction:
soft & hard: ~ 1000 nm
Soft & hard x-rays!
chromatic focal point,
easy energy tunability,
comfortable working
distance
Resolution ~ 1000 nm



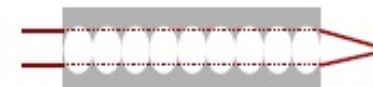
Normal incidence:
spherical mirrors with
multilayer interference coating
(Schwarzschild Objective)
not tunable, $E < 100$ eV
Resolution: best ~ 100 nm

Capillary: multiple
reflection concentrator



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

Refractive lenses



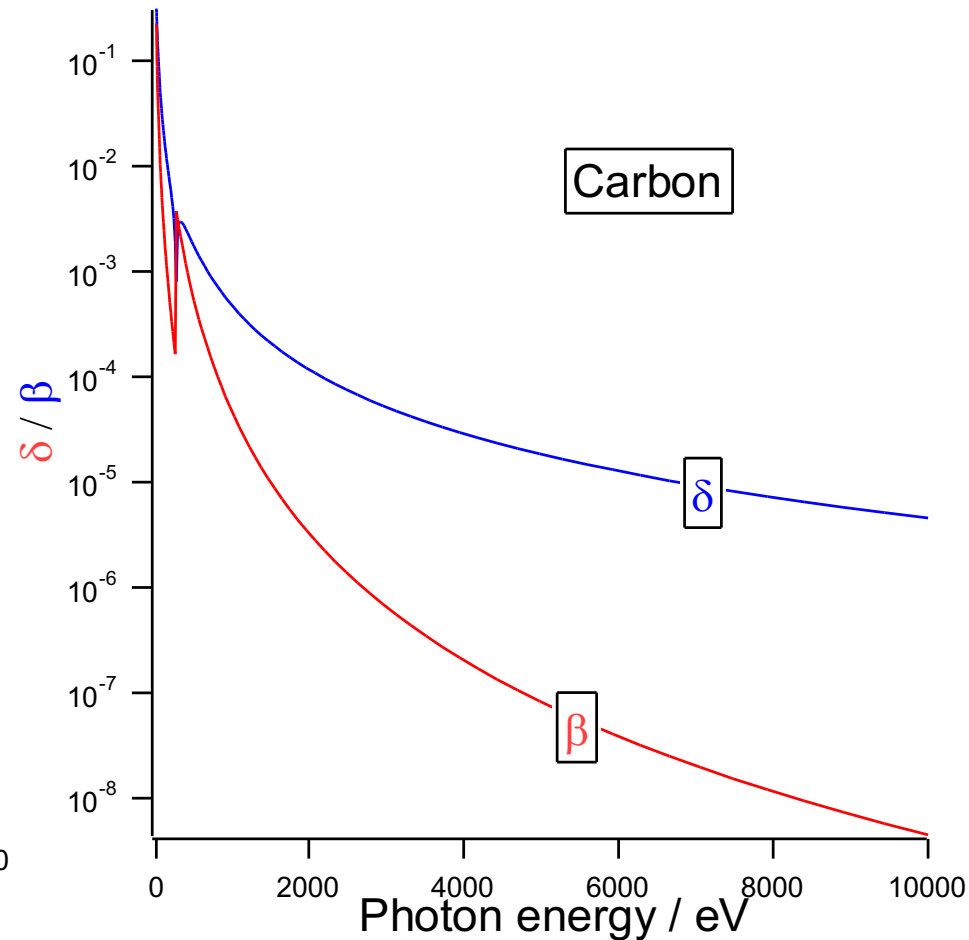
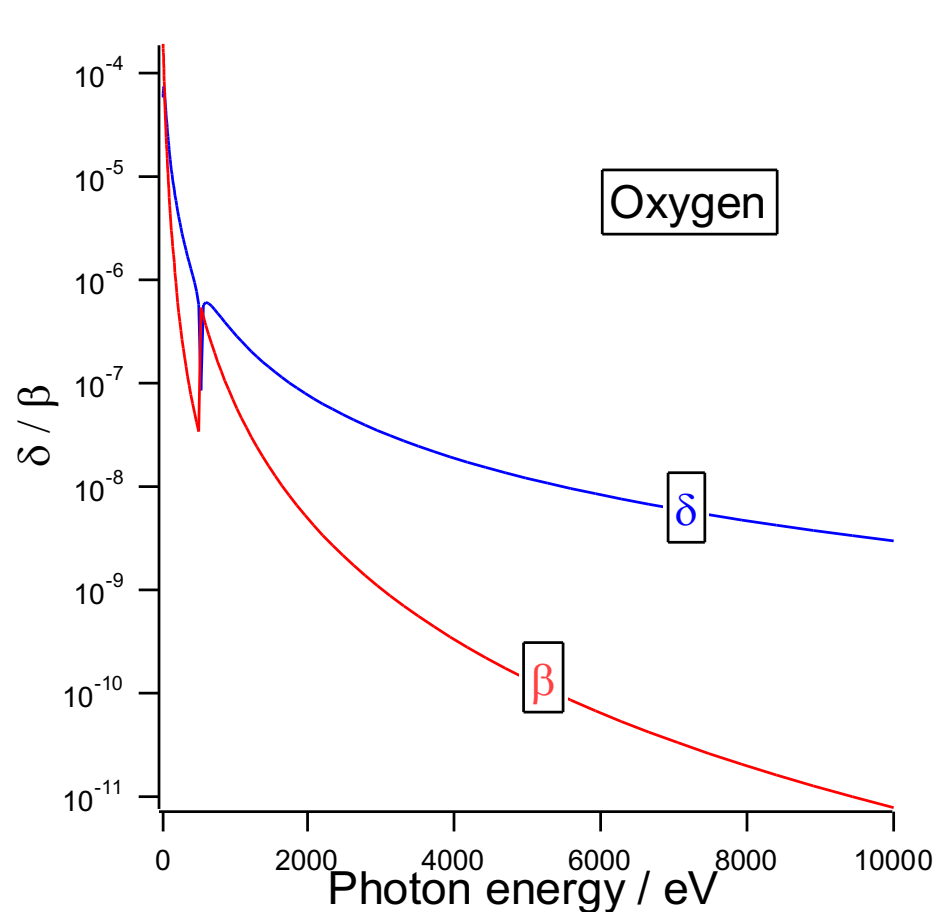
Hard x-rays ~ 4-70 keV
Resolution: > 1000 nm



• Phase contrast imaging

- Absorption can produce little contrast for light (transparent) materials or for materials with similar atomic number (similar attenuation factors).
- Moreover as the energy increases the contrast diminishes (absorption coefficient $\propto 1/E^3$)
- Phase contrast is more sensitive to edges and borders in the sample
- Contrast techniques using the real, phase-shifting part of the complex refractive index are in many cases superior to absorption contrast because:
 - the x-ray dose can be reduced dramatically
 - the throughput is higher (the phase shift dominates the absorption in the x-ray regime)

- Delta versus beta



Delta is orders of magnitude larger !!!

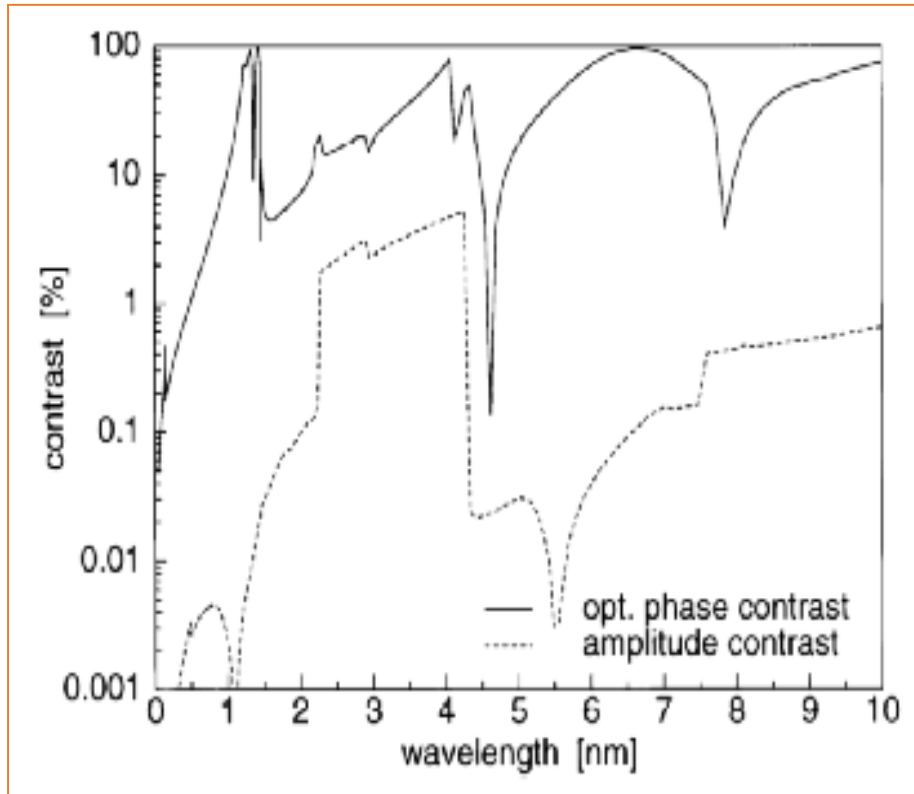
Absorption vs phase contrast techniques

Absorption contrast

Mostly used for chemical studies in combination with XANES and XRF

Phase contrast techniques

- 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 $C_{94}H_{139}N_{24}O_{31}$



X-ray microscopy types

X-ray microscopy:
bridge between visible light microscopy and electron microscopies

Spatial resolution:

visible light microscopy < X-ray microscopy < electron microscopy

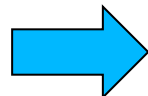
Air

Vacuum
(or air)

Vacuum

X-ray Microscopy vs Electron Microscopy:

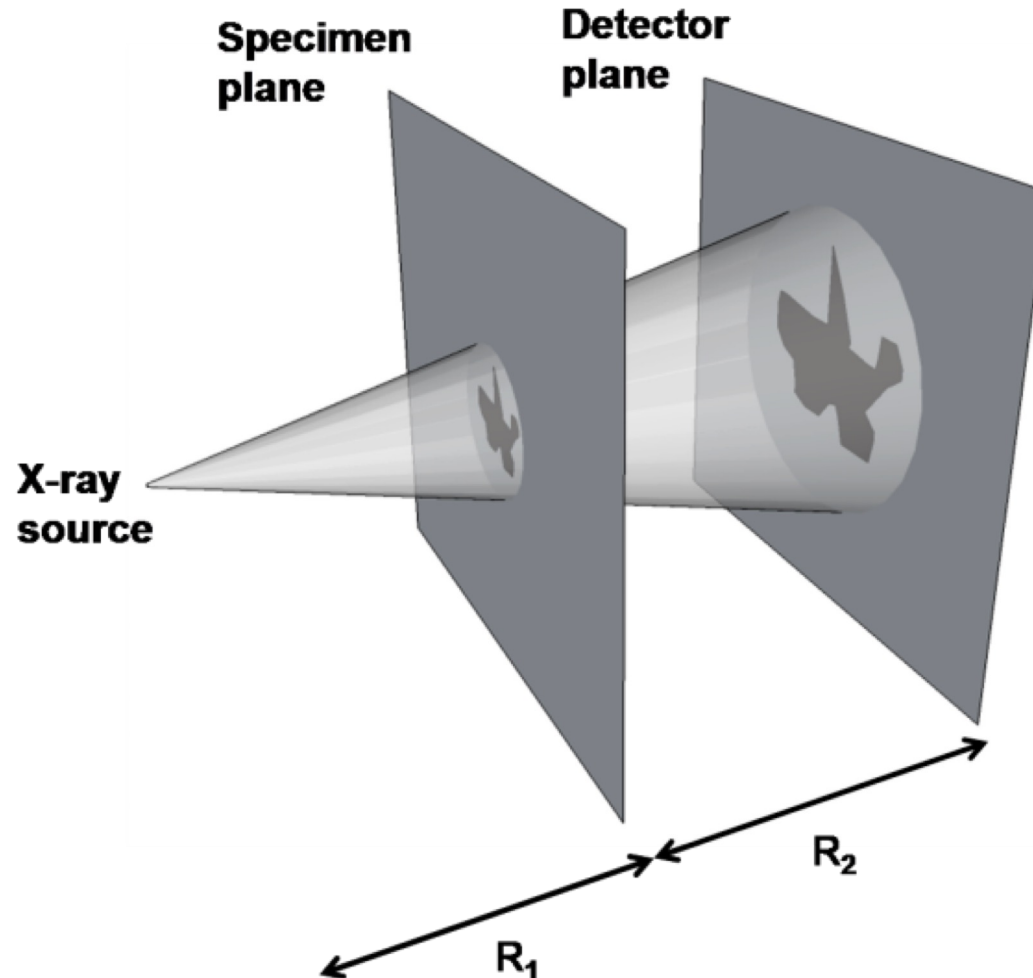
- Easier sample preparation (no metalisation)
- Higher penetration depth of X-rays compared to electrons



thicker samples can be analysed

Projection microscopy

Scheme of a projection microscope with the source to specimen plane distance R_1 and specimen to detector distance R_2

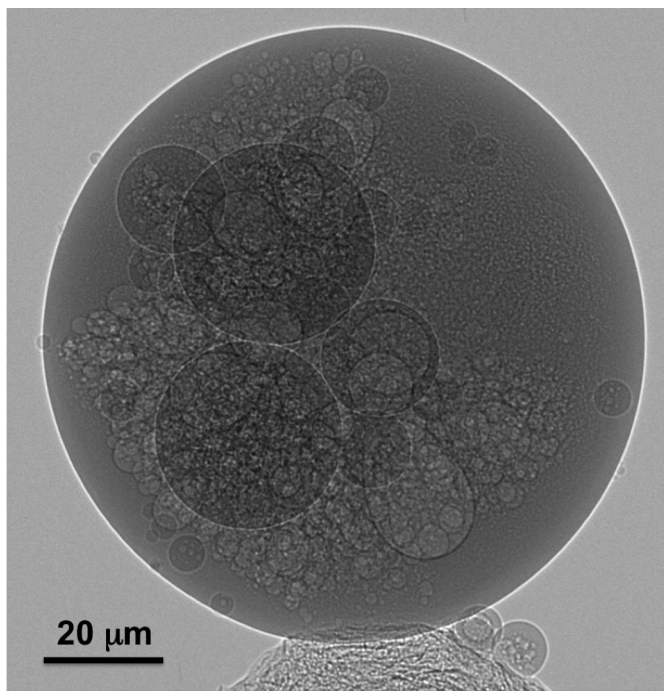


$$M = 1 + R_2/R_1$$

The principle of the projection x-ray technique (see figure 3.1) is to record a magnified shadow image by using a point source. This approach is similar to medical radiography, except that the medical instruments use a much larger x-ray source.

Invented in 1939 by Malsch and Ardenne in Germany.

Projection microscopy

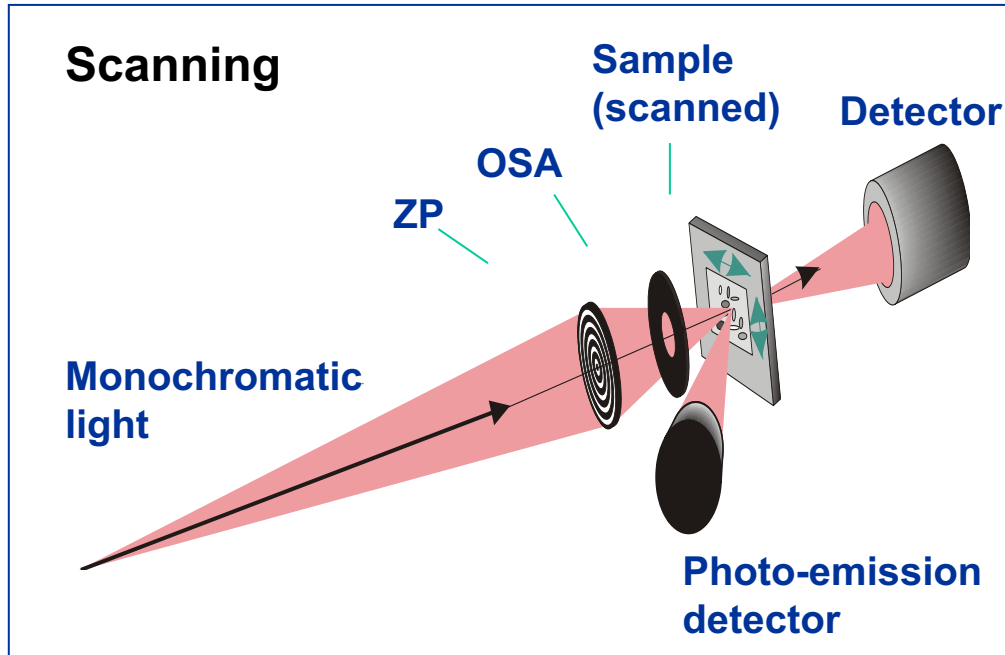


3D phase contrast dataset view, reconstructed cross section of part of a ceramisphere (projection X-ray microscope at the CSIRO, Australia).

The total collection time of the microtomogram was 10 h.
The diameter of the sphere is 110 μm

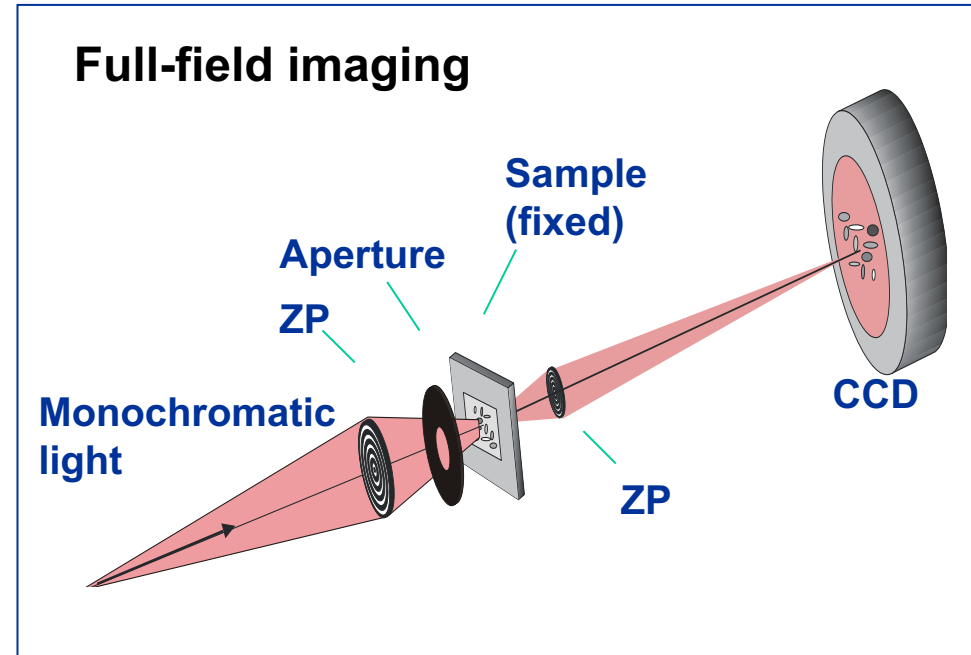
A state-of-the art instrument for projection microscopy, including phase-sensitive imaging and microtomography based on a converted scanning electron microscope, is reported for example by Mayo et al. (Mayo et al 2002; Mayo et al 2003).

Background info: X-ray microscopy types



- + versatile detectors can run simultaneously;
- + easier optics set-up;
- long exposure time;
- complex electronics.

Ideal for spectromicroscopy



- + short exposure time;
- + higher resolution
- static system;
- complex optical alignment.

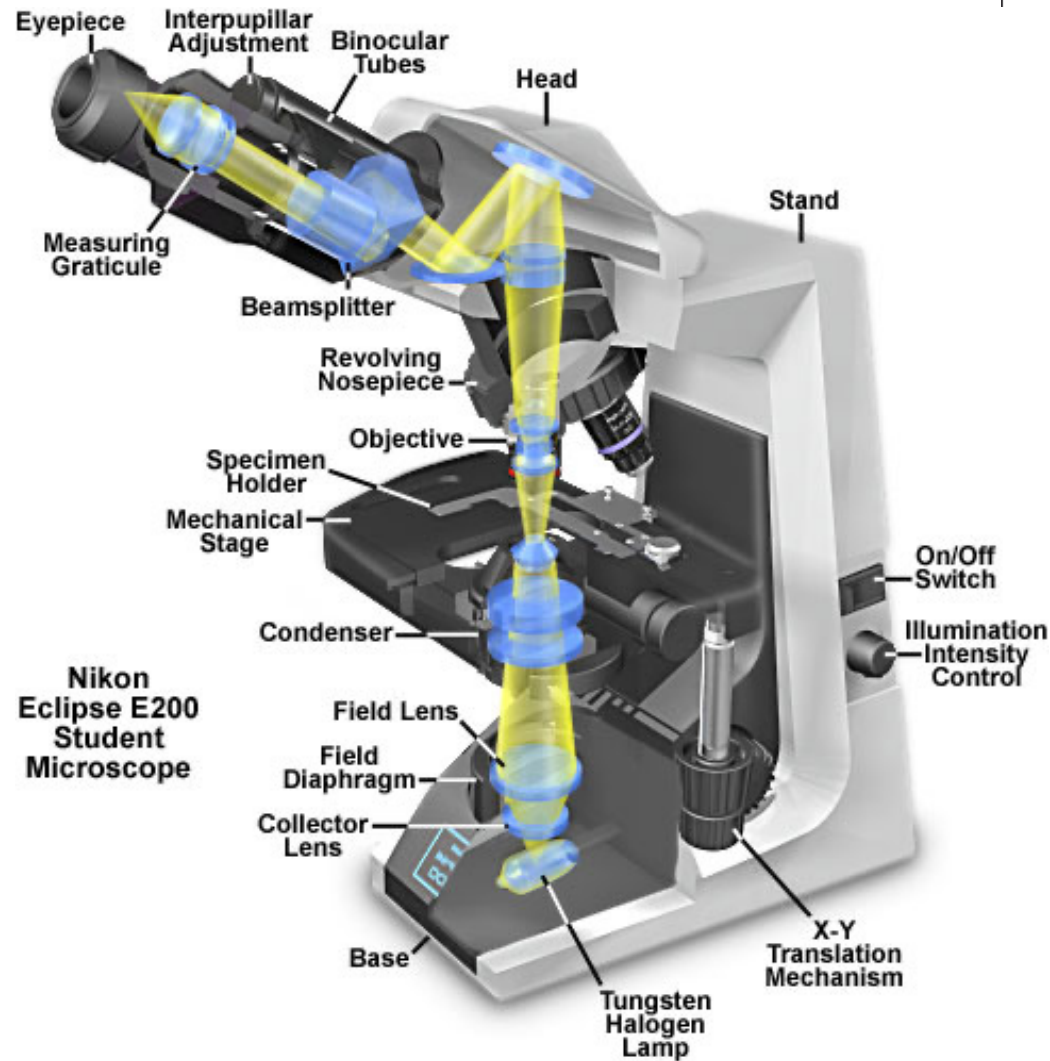
Ideal for dynamic studies and tomography



Elettra
Sincrotrone
Trieste



• Full-field X-ray Microscopy (TXM)



Cutaway diagram of a visible light microscope

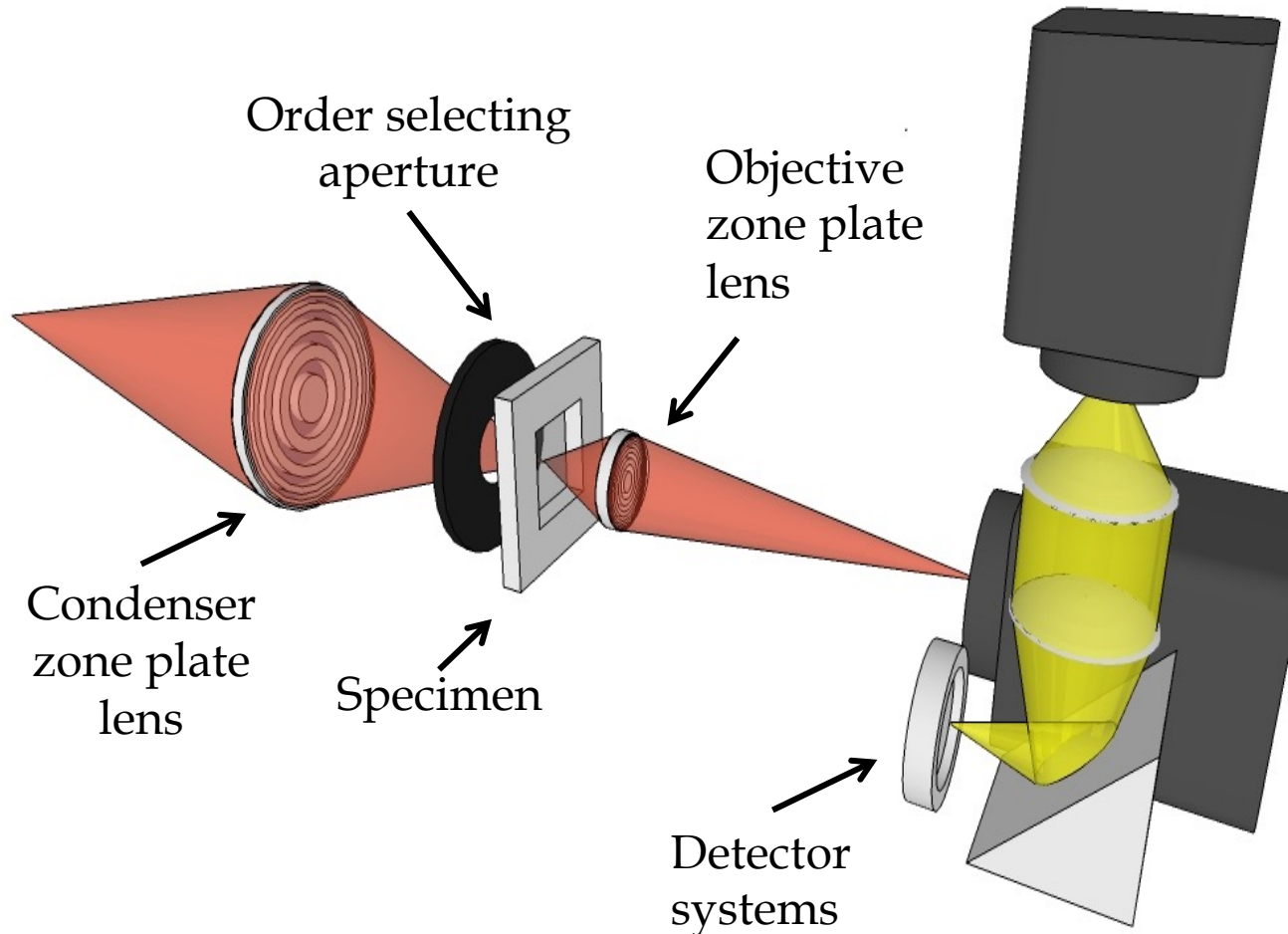
Full-field X-ray imaging or “one shot” X-ray image acquisition can be considered as the optical analogus to a visible light transmission microscope

BUT

Refractive index n is very close to unity and smaller than unity!!!

$$n = 1 - \delta(\lambda) - i\beta(\lambda) < 1$$

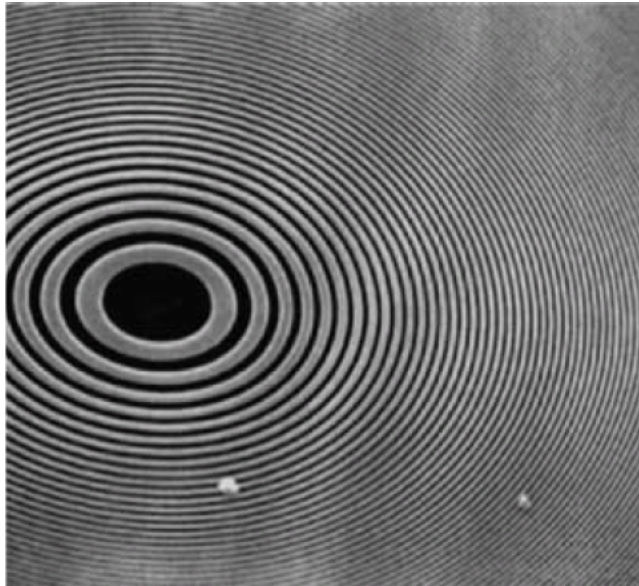
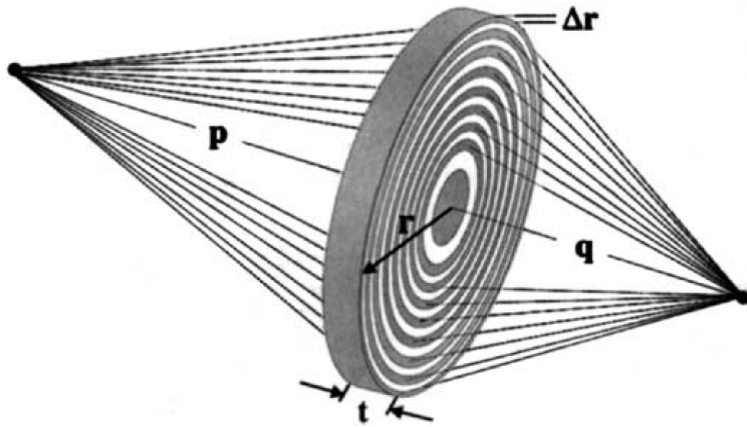
• Full field Imaging mode



- Similar to conventional visible light microscope
- Analysis of morphology in transmission
- Fast imaging, dynamics, microtomography

- **Zone plate Diffractive Optics**

Zone plate (ZP) is a circular diffraction grating with radially increasing line density



$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad \text{if } n > 100; \quad f = \frac{2r\Delta r}{\lambda}$$

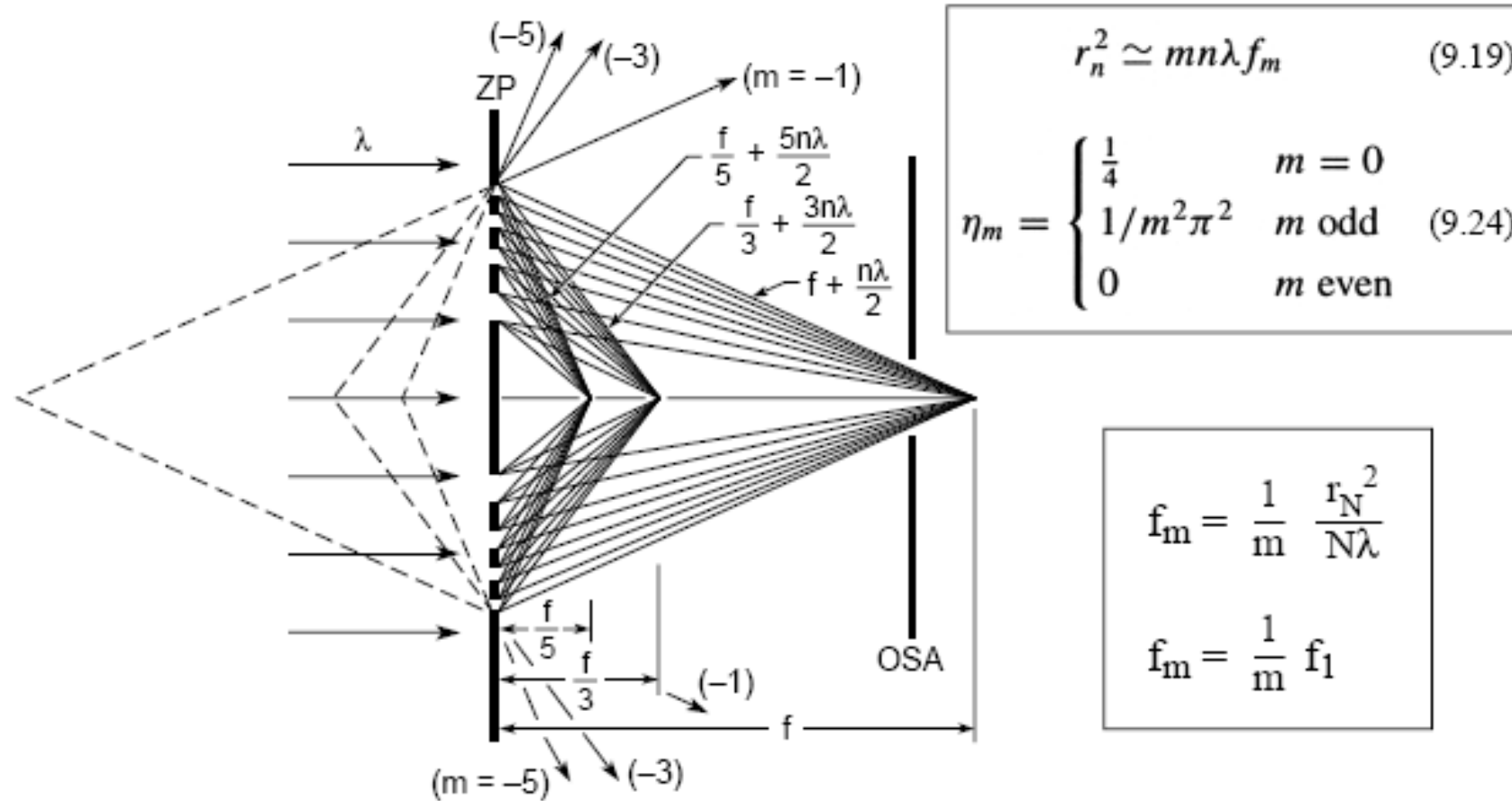
Lateral resolution of a ZP (Rayleigh):

$$NA \equiv \frac{r}{f} = \frac{\lambda}{2\Delta r}$$

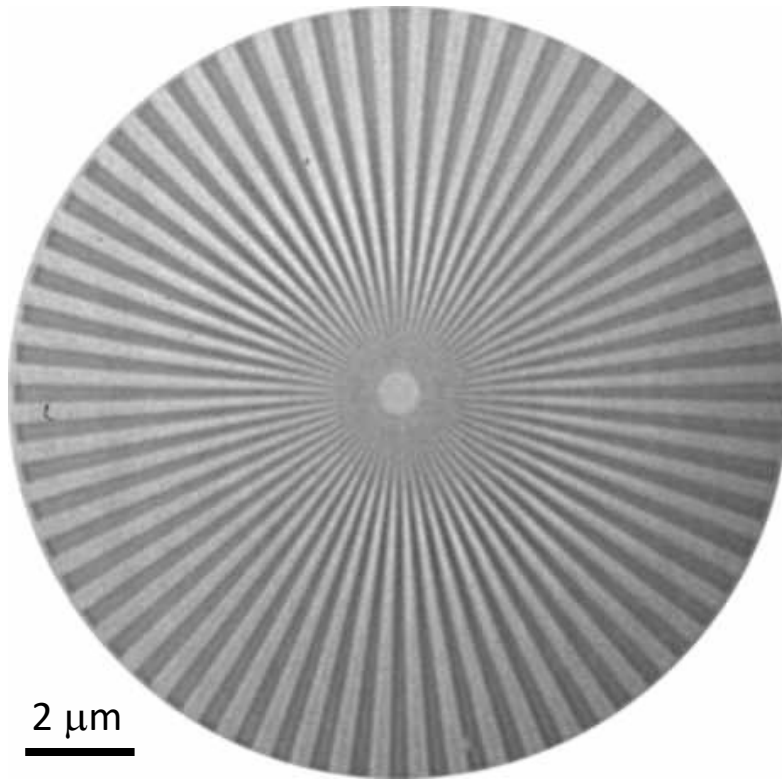
$$\partial_{\text{Rayleigh}} = \frac{0.61\lambda}{NA} = 1.22\Delta r$$

(not smaller than the diffraction limit of the wavelength)

• Background info: Diffraction by a grating



• Resolution tests in full-field imaging



*Experiment performed by
M. Prasciolu and D. Cojoc, TASC/ INFM)*

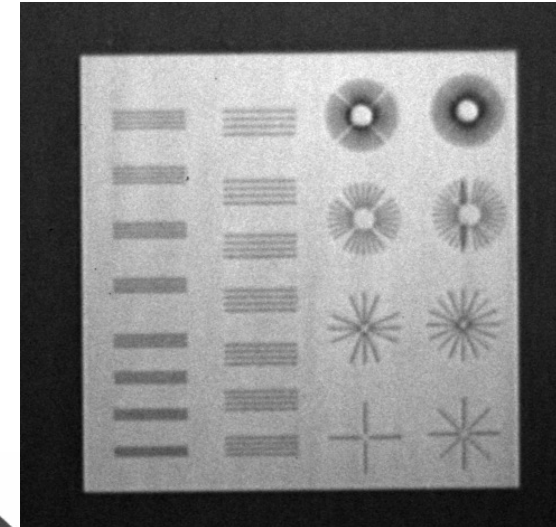
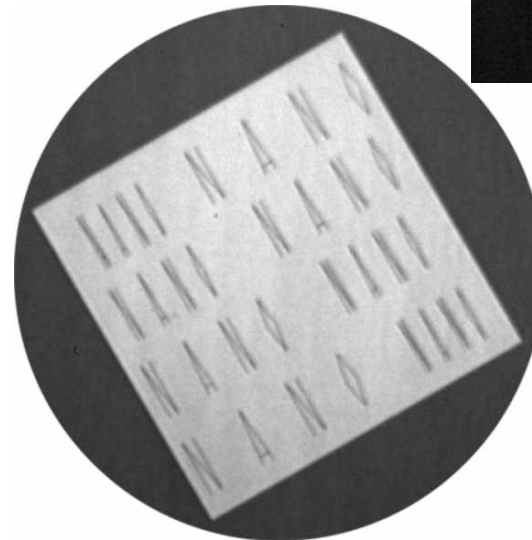
ZP parameters:

110 μm diameter

50 nm outer zones

f=3.2 mm @ 720 eV

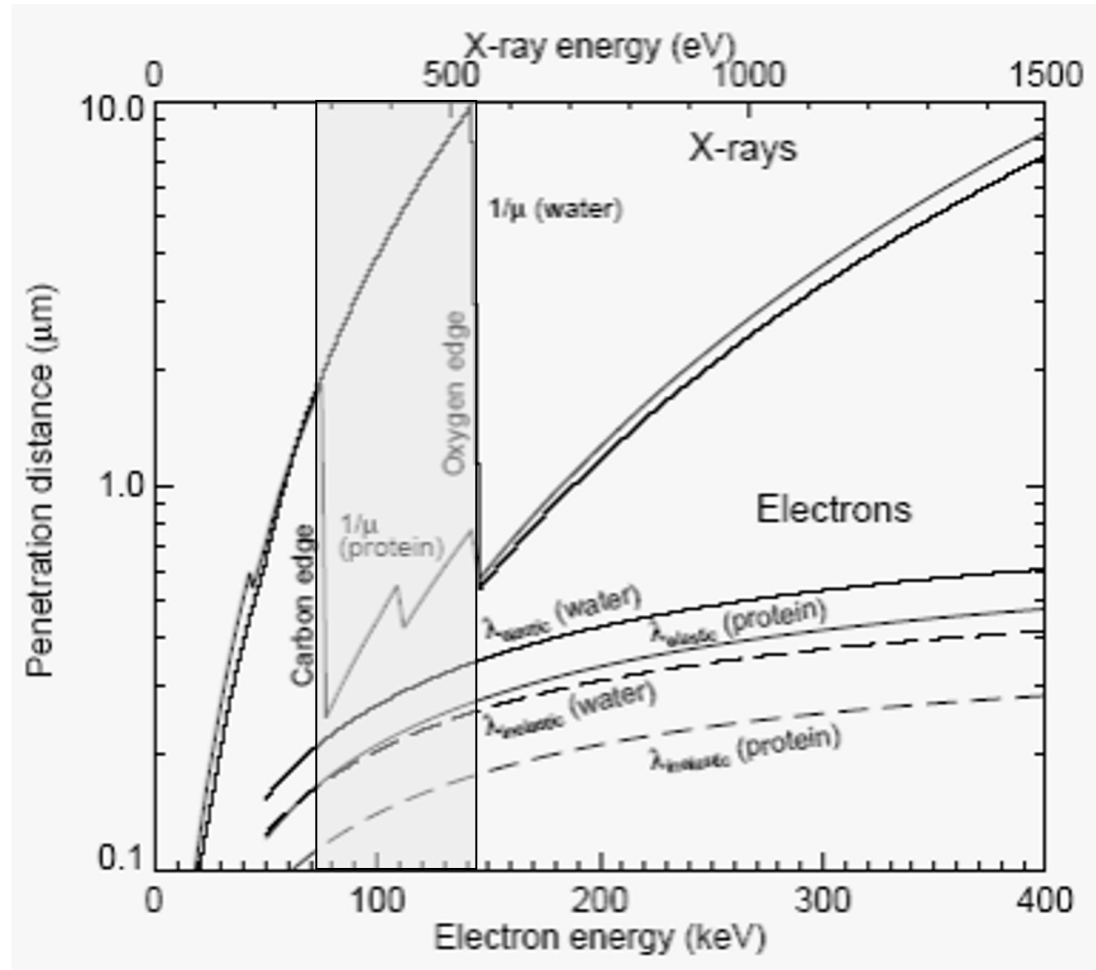
fabricated by TASC/
INFM



2 μm

Test pattern with
30 nm features
(fabricated by
TASC/ INFM)

- **Natural amplitude contrast between water and organic matter**



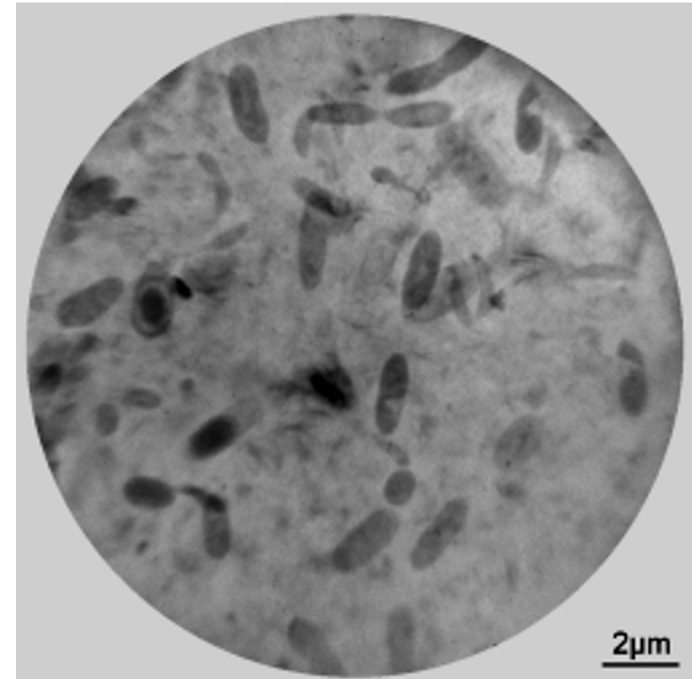
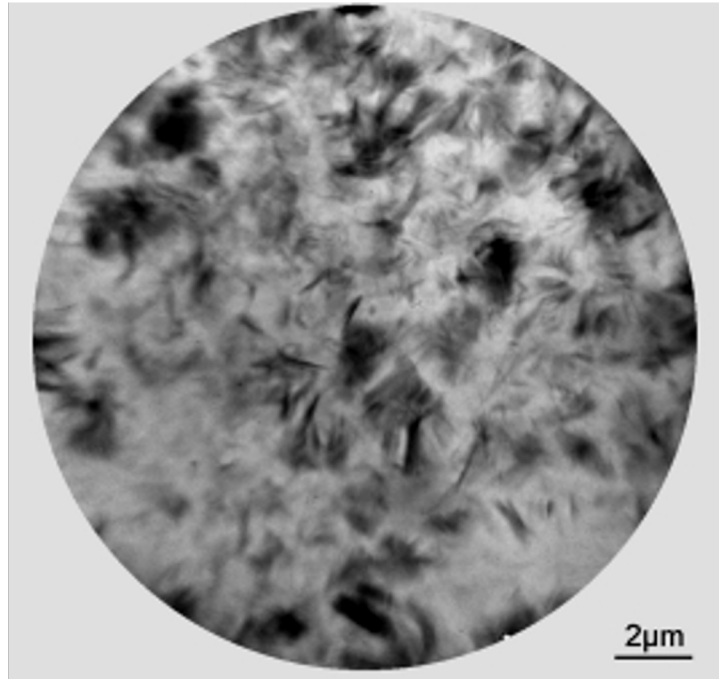
The "Water Window":

Due to dramatic difference in the f_2 values of two materials, especially water and organic matter between the C and O K-absorption edges.

Note the penetration distance compared to electrons !!!

- **Environmental science: Imaging in liquids**

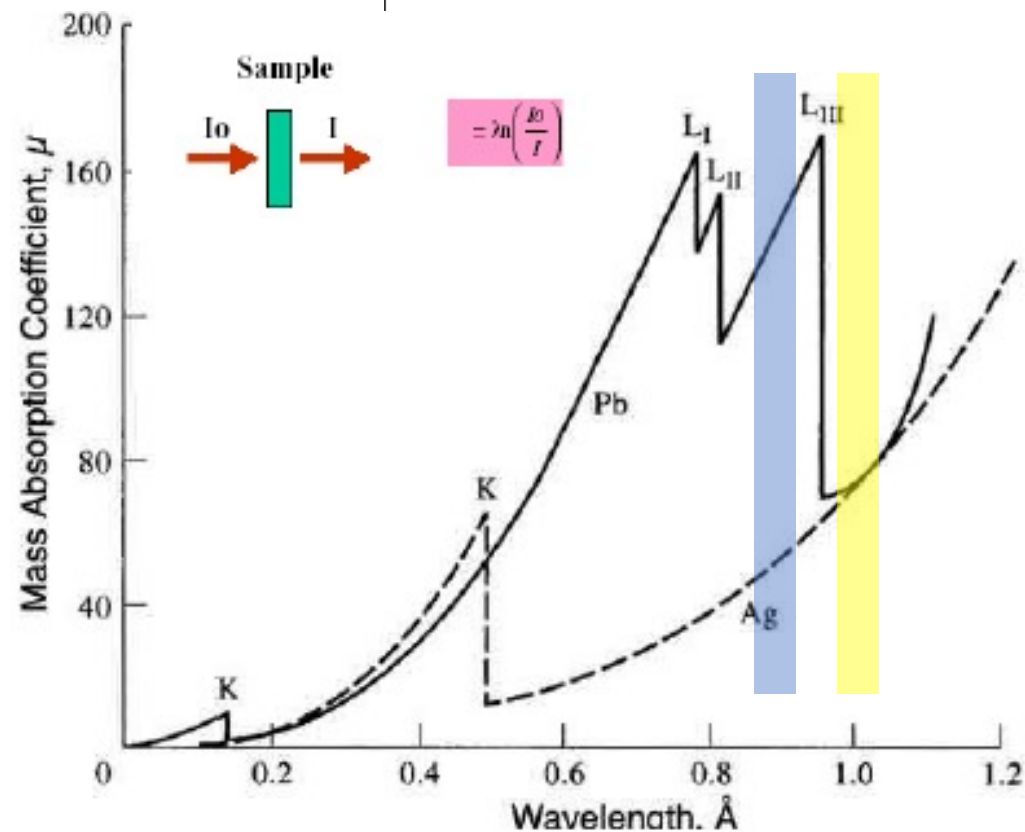
Bacteria and clay dispersion: Destruction of associations of clay particles by soil microbes



X-ray images acquired with the full-field imaging microscope at BESSY I @ 520 eV

Samples analysed in the natural hydrated state:
→ **no alteration of the environment of the sample**

• Across edge imaging



Discontinuities due to absorption

The absorption occurs when the incoming X-rays are matching the electron binding energies

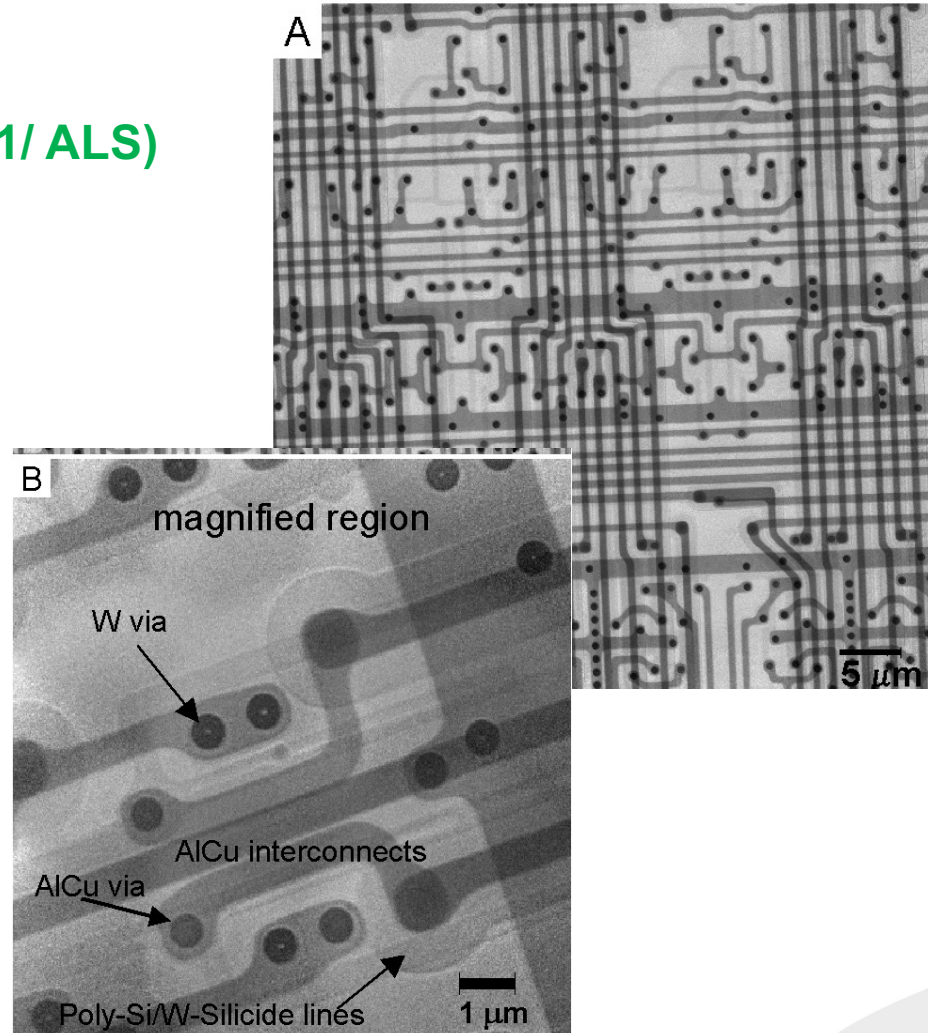
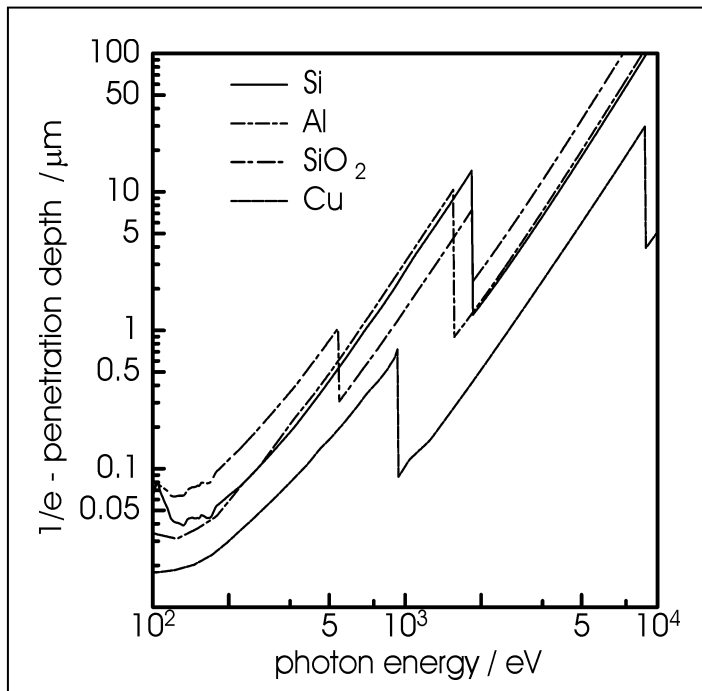
Absorption edges are fingerprints $\Rightarrow$ they can be used to identify the chemical elements

By taking two images, one above and one below a specific absorption edge, the correspondent chemical element will give a high contrast difference in the two images

- **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

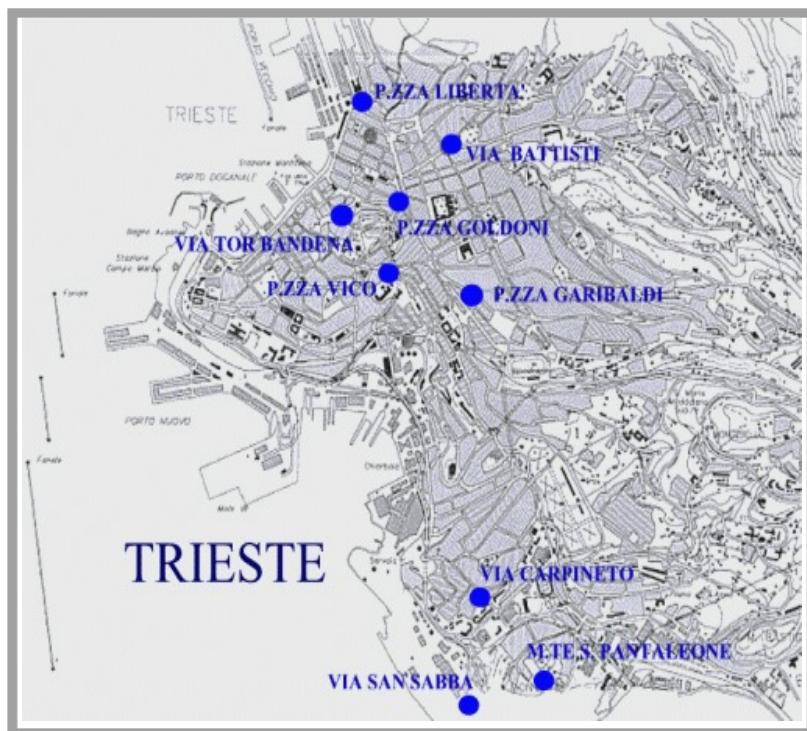




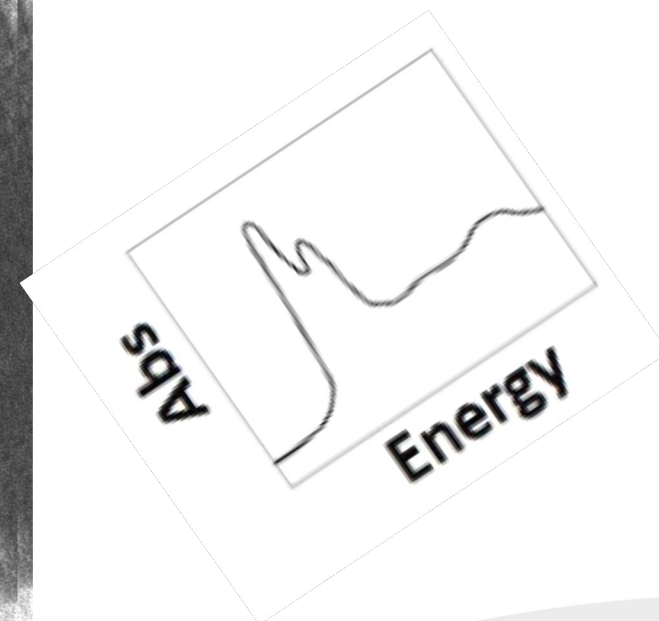
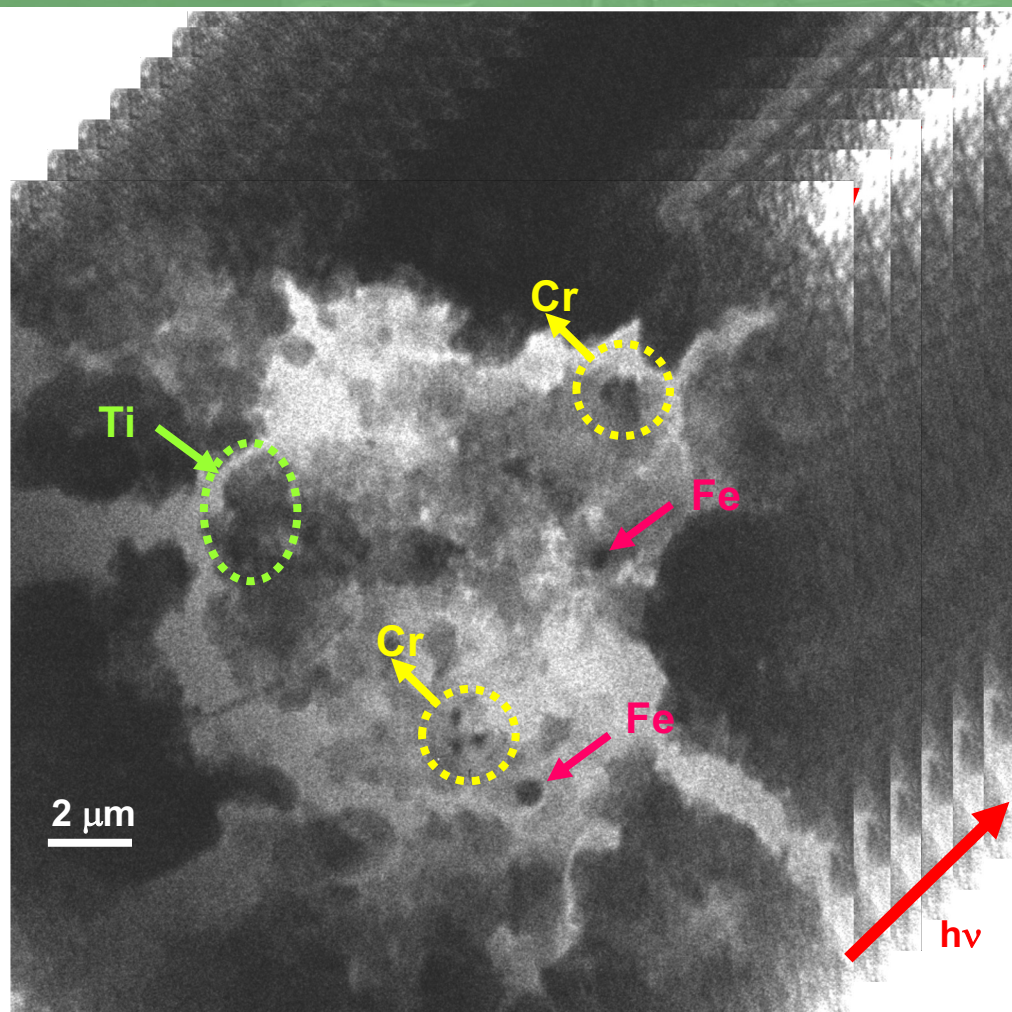
Elettra
Sincrotrone
Trieste



- Environmental science: Analysis of air particulate matter



*P. Barbieri et al.,
Dept. of Chem., Univ. Trieste, I*



• Basics of Zernike phase contrast

A detector measures intensity:

$$I = |E|^2$$

and therefore **does not directly measure the phase**.

For a weakly absorbing sample, you can have a large phase shift but very little absorption contrast. So a conventional absorption image may look almost invisible.

The basic idea of Zernike phase contrast

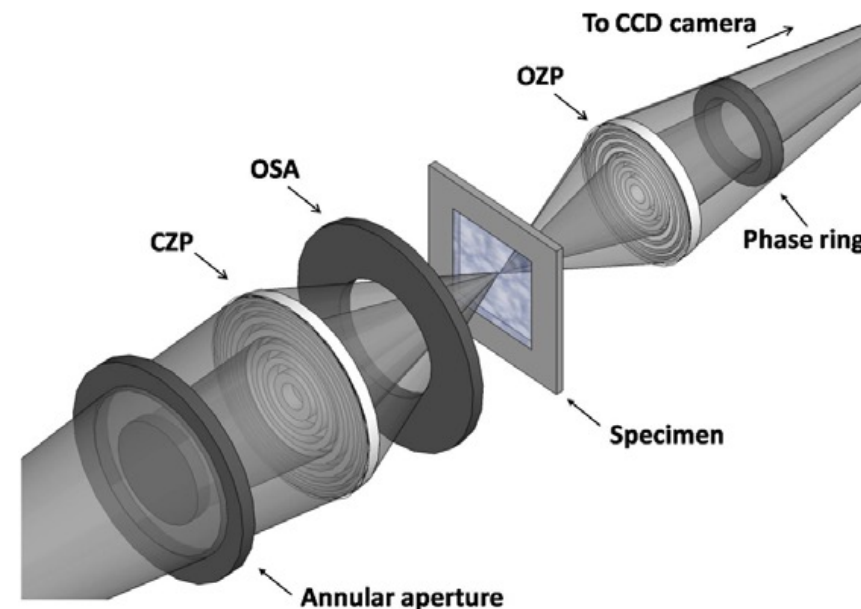
The clever idea is:

Convert differences in phase into differences in intensity.

This is done using a **phase ring** placed in the back focal plane of the objective.

The geometry is essentially:

X-ray source → sample → objective → phase plate → detector



• Basics of Zernike phase contrast

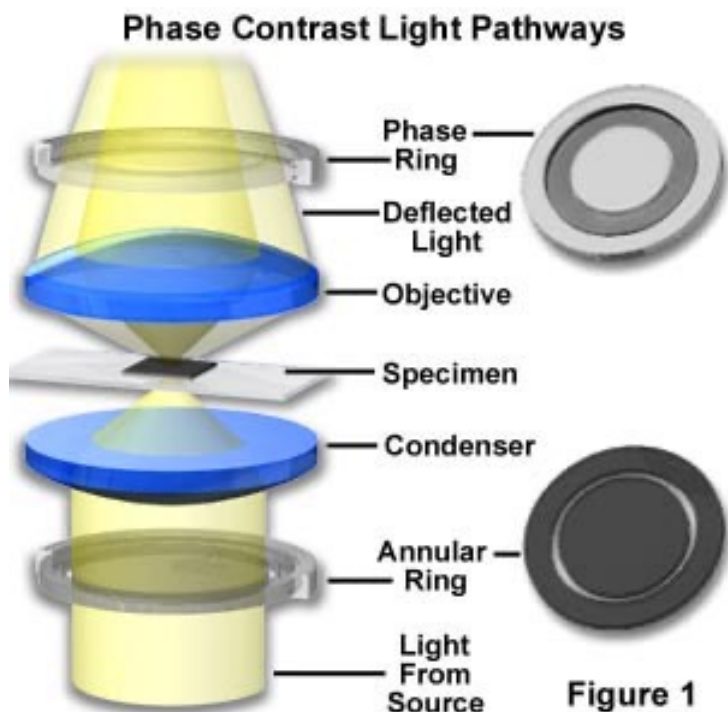
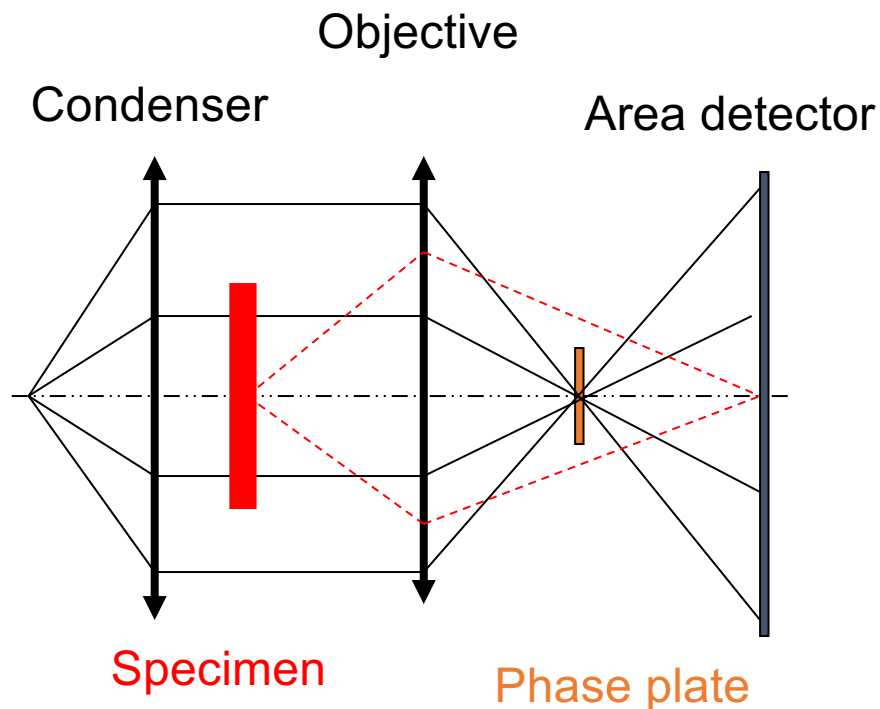


Figure 1



A small ring is positioned exactly where the **direct beam** falls.

The phase ring does two things:
attenuates the direct beam
shifts its phase by approximately $\pi/2$

The scattered/diffracted radiation largely passes around the ring and is therefore not given the same phase shift.

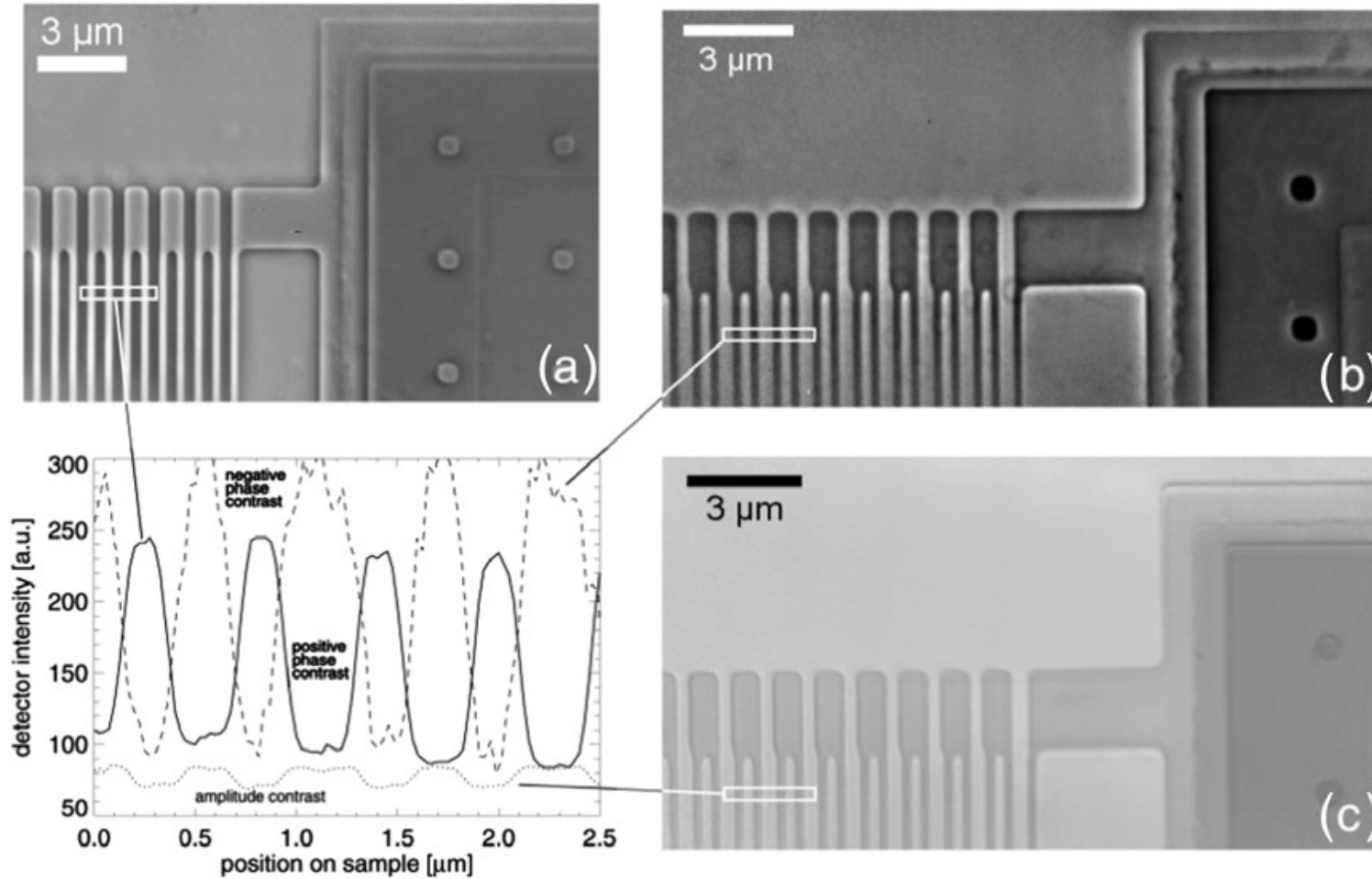
Separate the unscattered and scattered waves and deliberately change the phase of one relative to the other so that their interference produces intensity contrast.

$$A_{specimen} = A_{surr} e^{i\Phi} = A_{surr} e^{i \frac{2\pi}{\lambda} \Delta t} \approx A_{surr} (1 + i\Phi) \quad \Phi \ll 1$$

Phase plate in “back-focal” plane: Phase of A_{surr} can be shifted by $\pm \pi/2$!!!

Phase differences are converted in amplitude differences !!!

• Comparison



X-ray micrographs of a microelectronic test structure with the buried copper interconnect lines imaged in (a) positive phase contrast, (b) negative phase contrast and (c) absorption contrast mode. (d) The line scans across the serpentine structures demonstrate that Zernike phase contrast strongly enhances the image contrast and the visualization of weakly absorbing object details

• Darkfield or darkground imaging

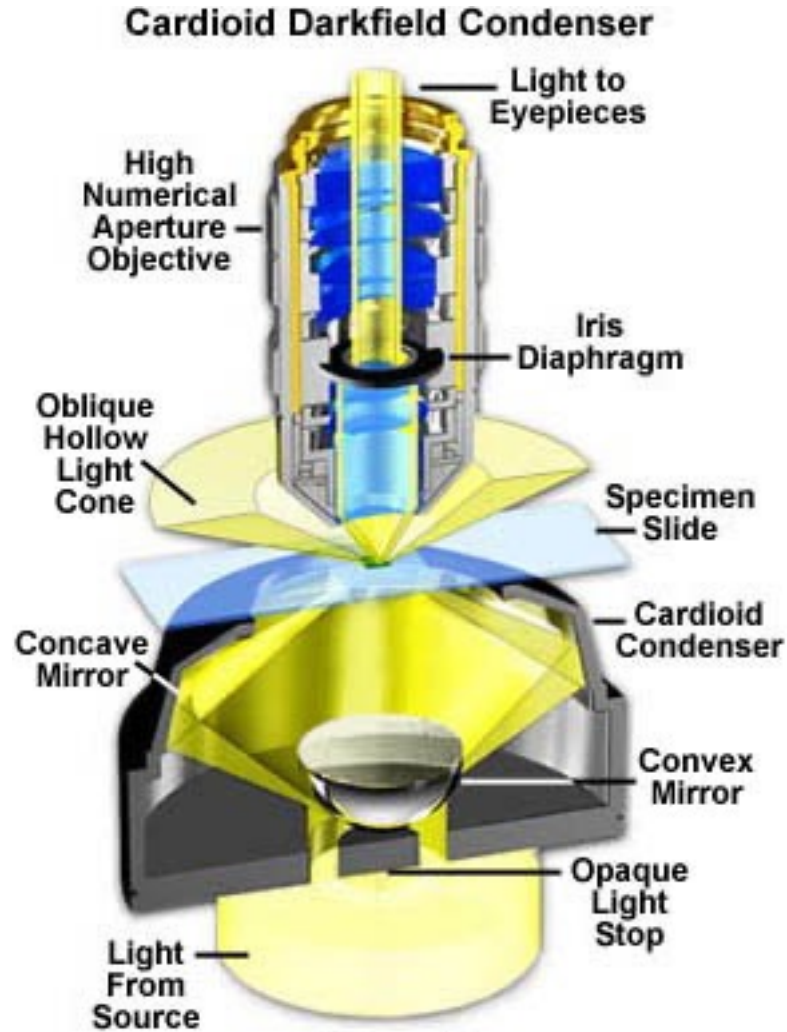
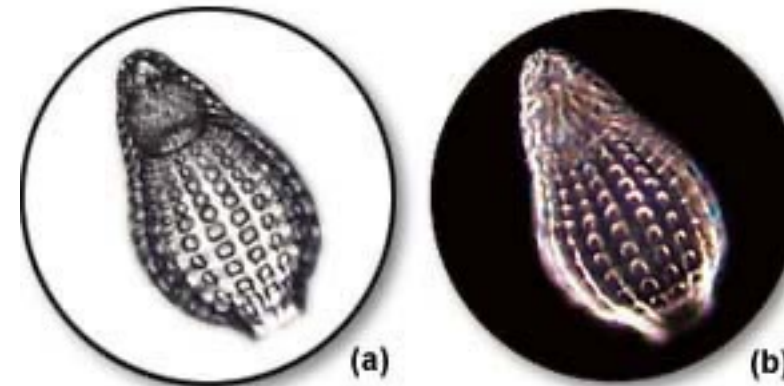


Figure 1

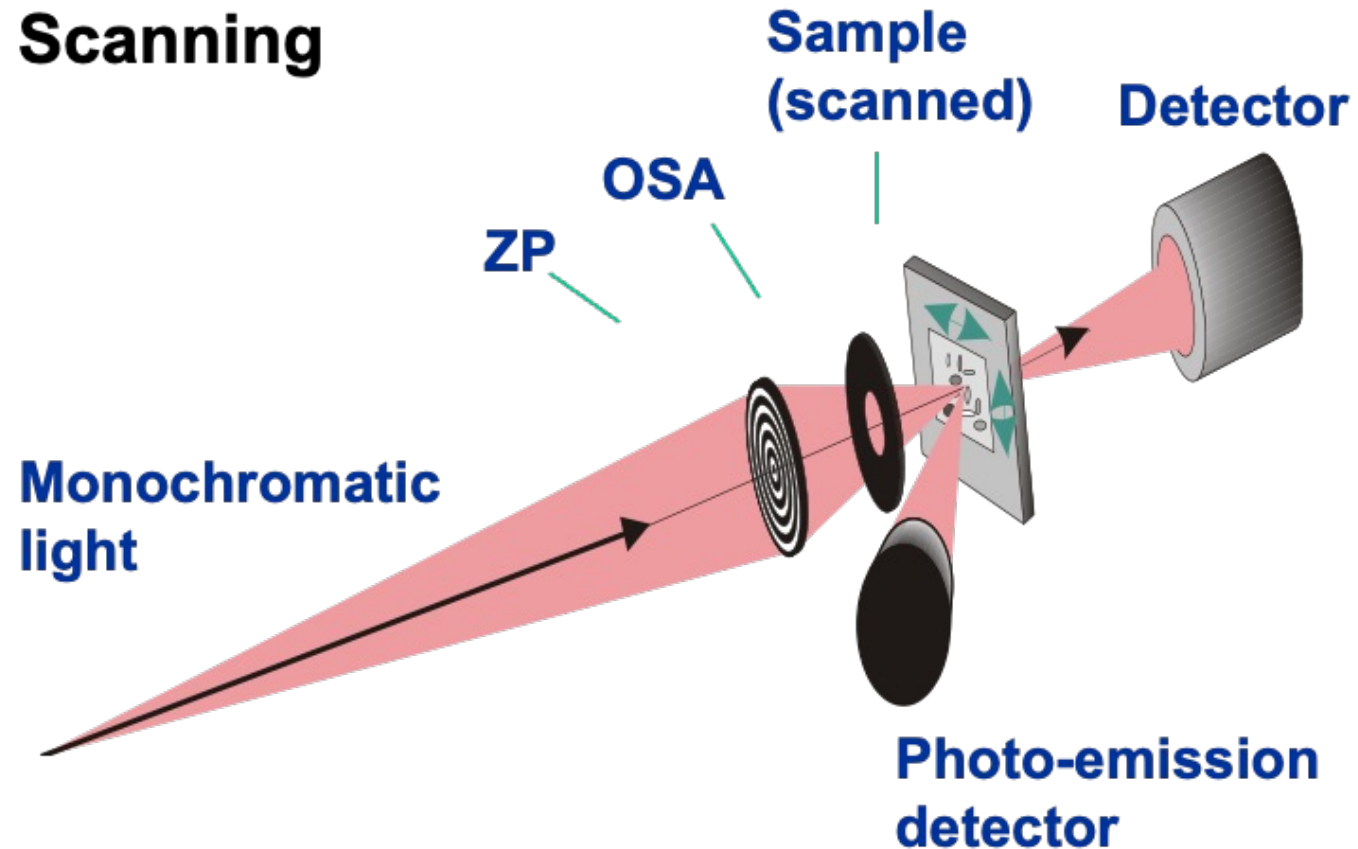
Darkfield illumination requires blocking out of the central light which ordinarily passes through and around (surrounding) the specimen, allowing only oblique rays from every azimuth to "strike" the specimen.



Visible light micrographs of silica skeletons from a small marine protozoan (radiolarian)

• Scanning X-ray microscope (STXM)

Scanning



- + versatile detectors can run simultaneously;
- + easier optics set-up;
- long exposure time;
- complex electronics.

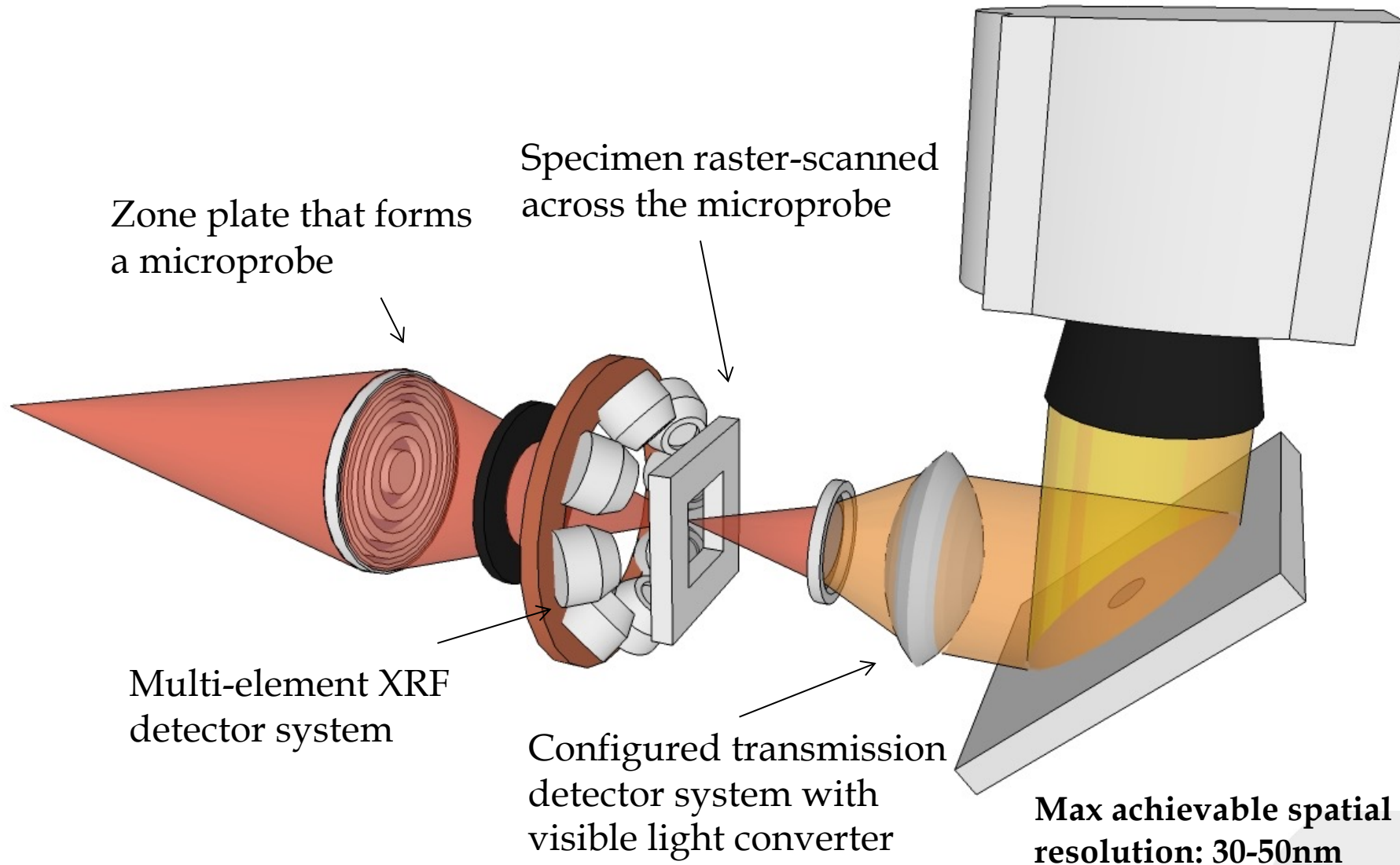
Ideal for
spectromicroscopy



Elettra
Sincrotrone
Trieste

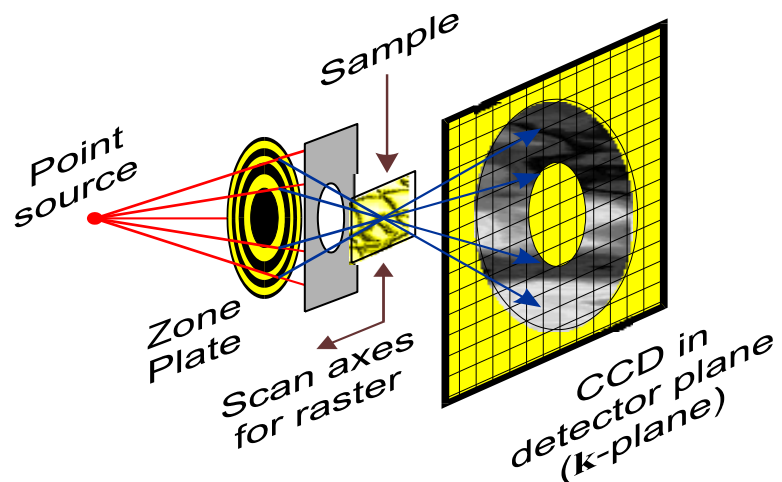
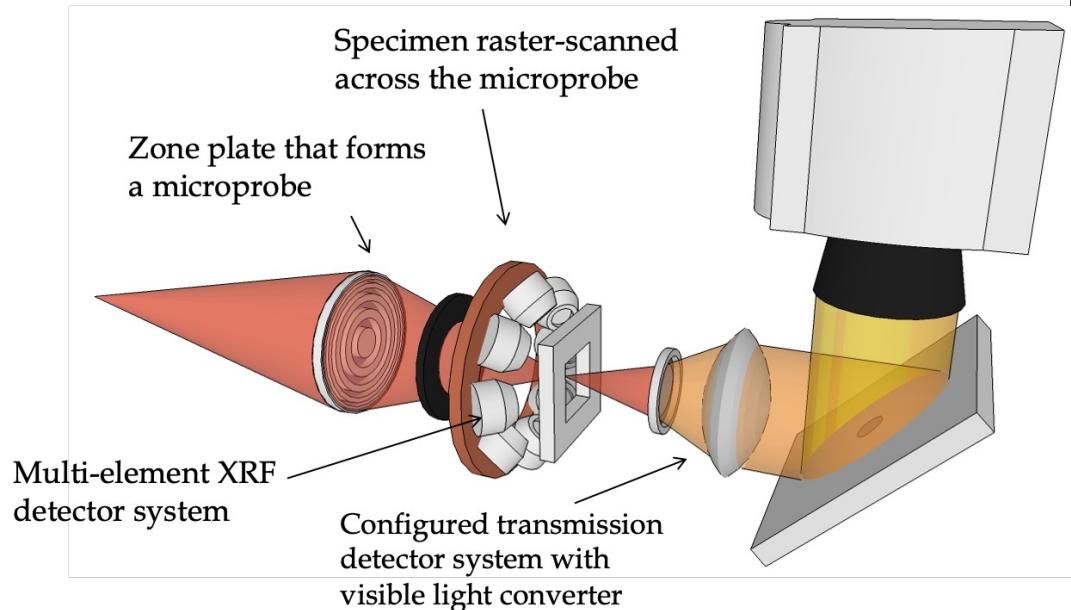


• Scanning X-ray microscope (STXM) at Elettra (TwinMic beamline)





Elettra
Sincrotrone
Trieste



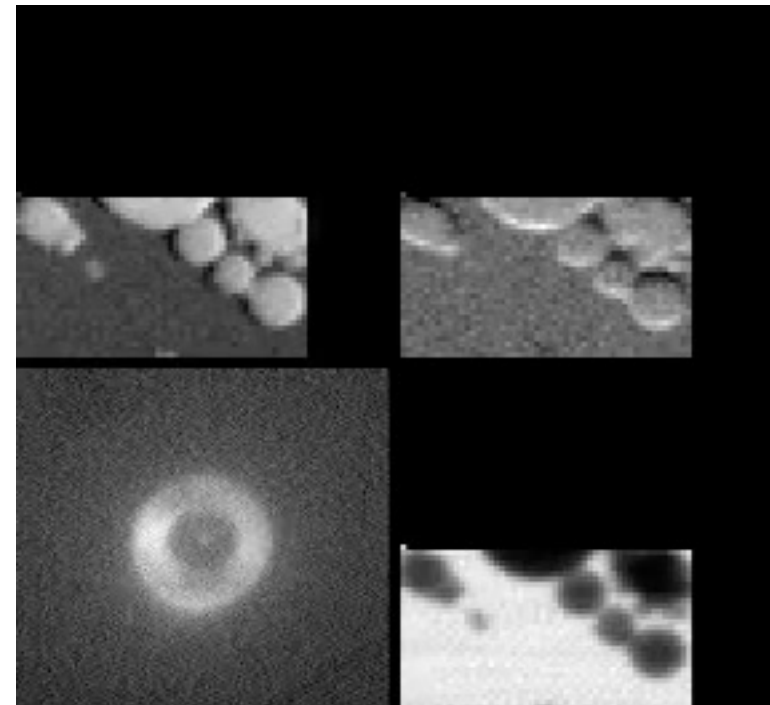
Morrison, G. et al., IPAP Conf. Series 7, 377-379 (2006)
Gianoncelli A. et al., Appl Phys Lett 89, 251117 (2006)

• TwinMic beamline - STXM mode

400-2200 eV

In the future 250-4200 eV

High vacuum: 10^{-6} mbar

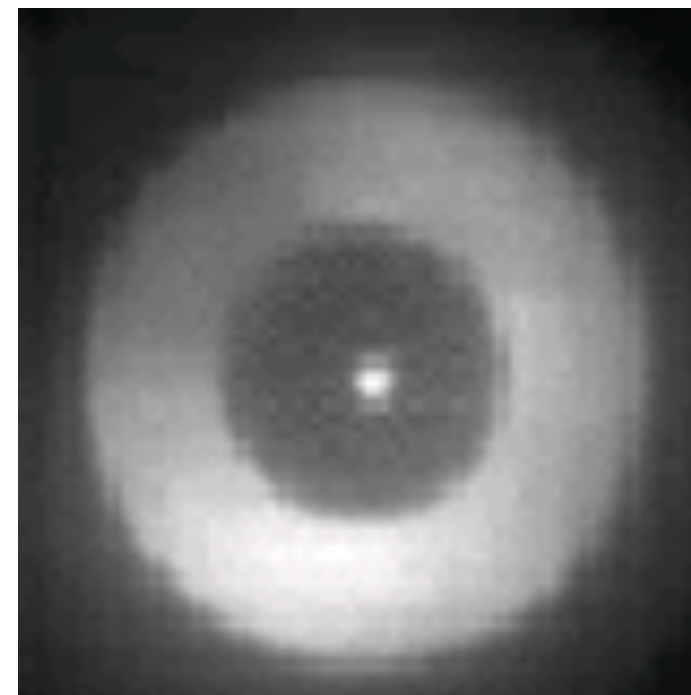
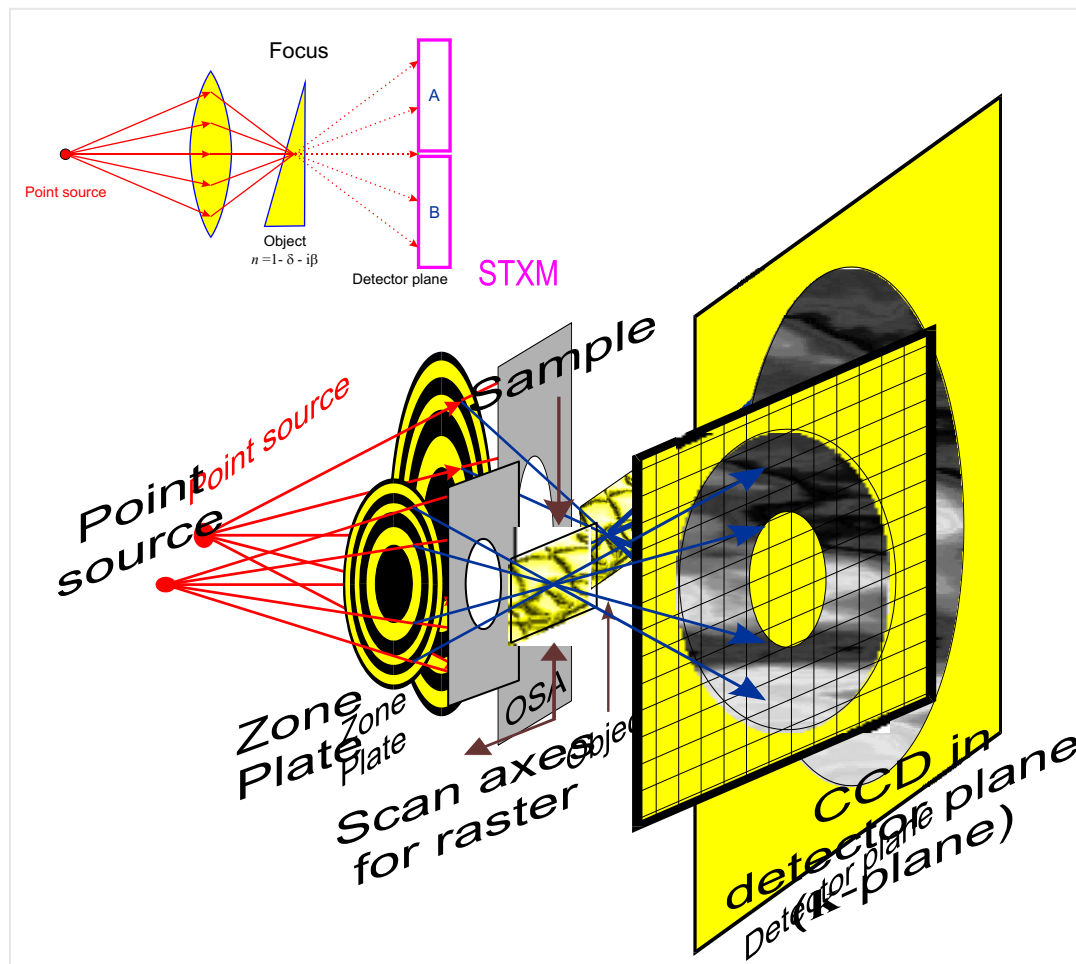


Simultaneous acquisition of:

- Absorption or transmission
- Differential phase contrast
- Darkfield images

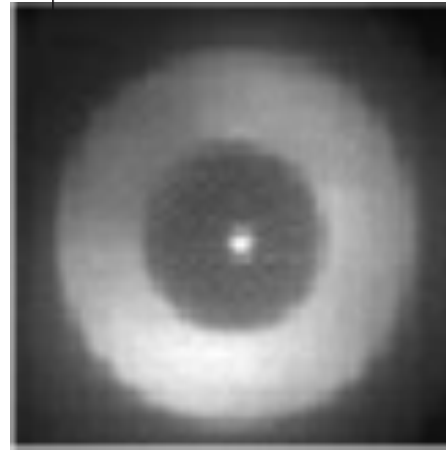
Spatial resolution 50nm-2 μ m

- *Detector based contrast technologies in scanning X-ray microscopy:*



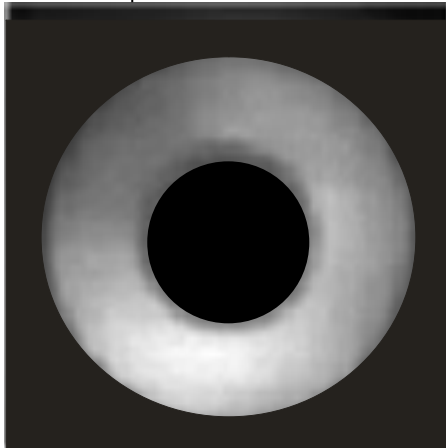
Acquired with Andor Ixon DV860A
Frame transfer back-illuminated
Electron Multiplying CCD with shutter
and light converting system
(128x128px, 5 Mhz, 110f/s)

*Computational
extraction of
contrasts
by masking:*

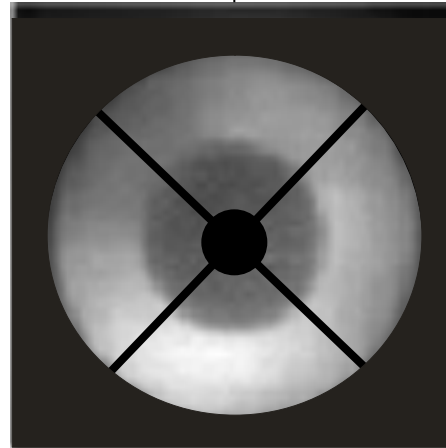


Raw data acquisition of
first diffraction order image
for each pixel of the raster
scan

Applying different masks



Bright field

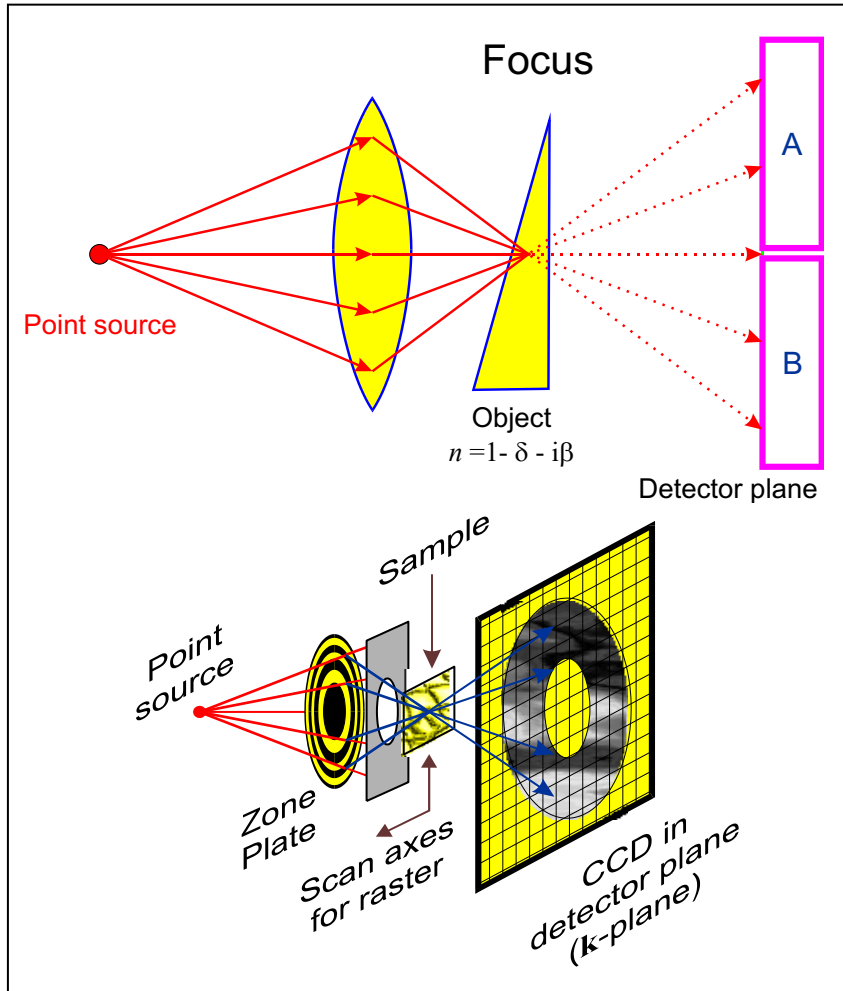


**Differential phase
and absorption**

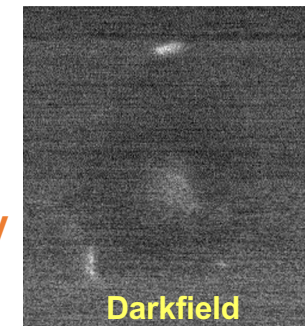
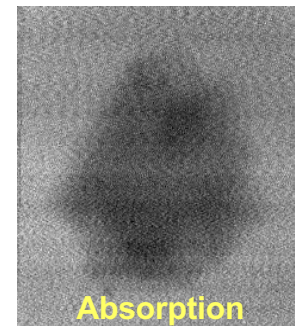
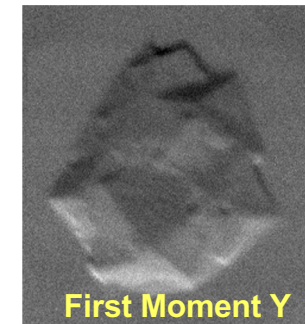
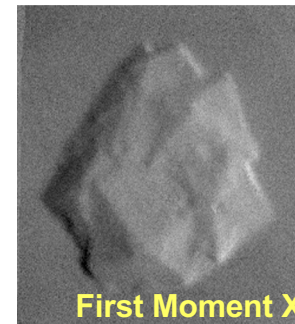


Darkfield

• Principle: Differential phase contrast



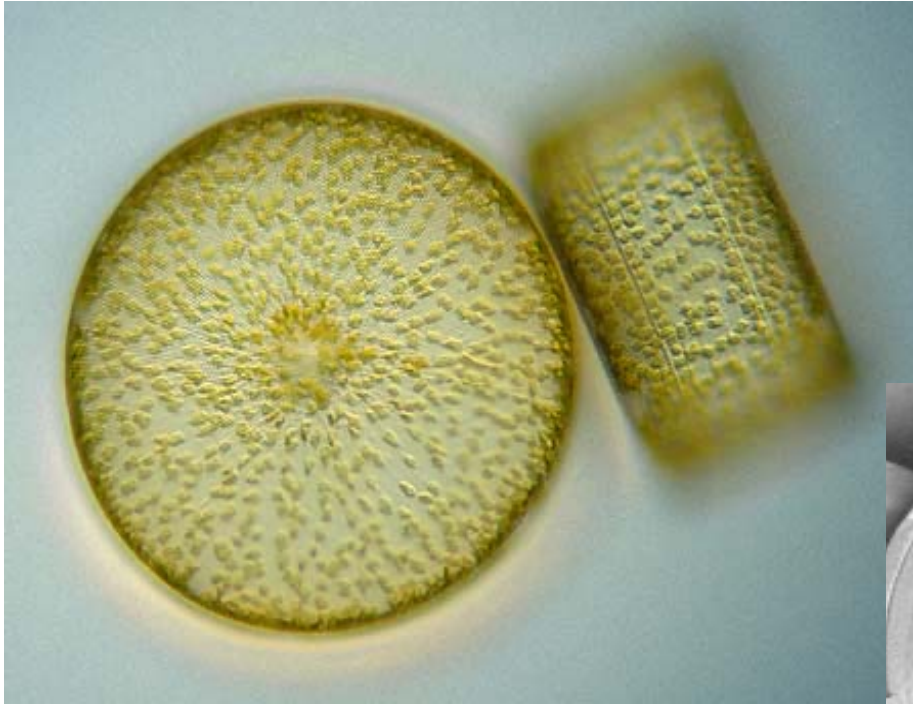
- The detector can be split into several elements
- The sum signal gives the incoherent bright-field signal
- Anti-symmetric signal combinations relate to the *phase gradient* of the object transmittance.



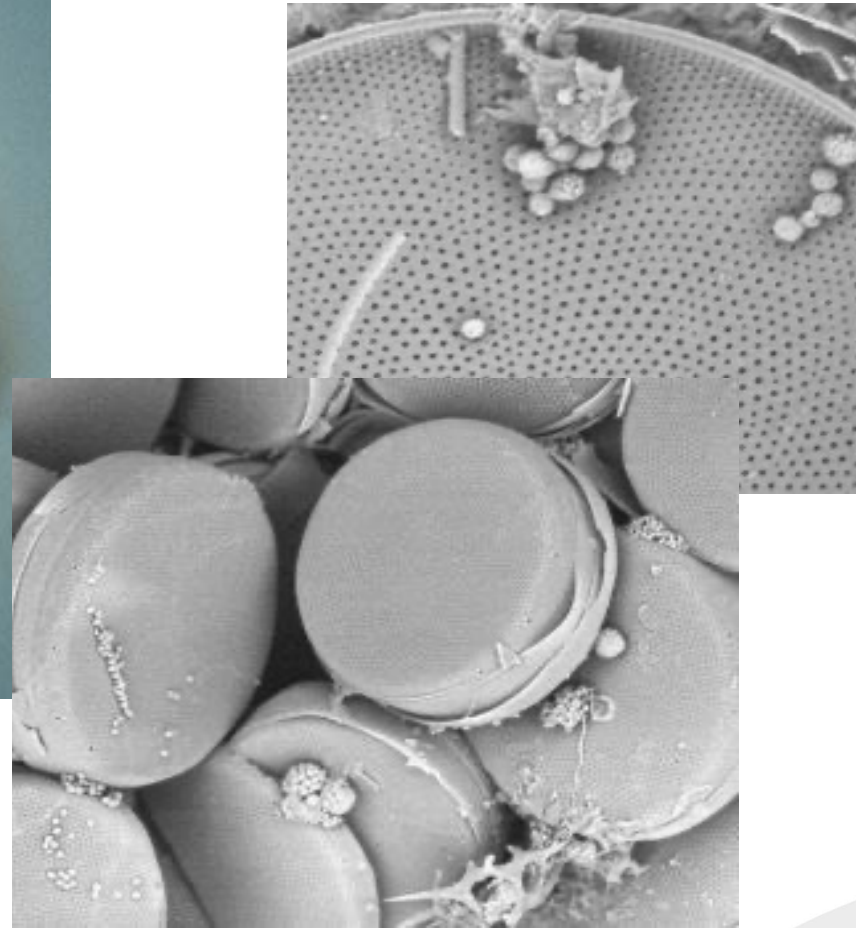
10 μm

3.3 keV

Marine biology: Imaging of giant diatoms

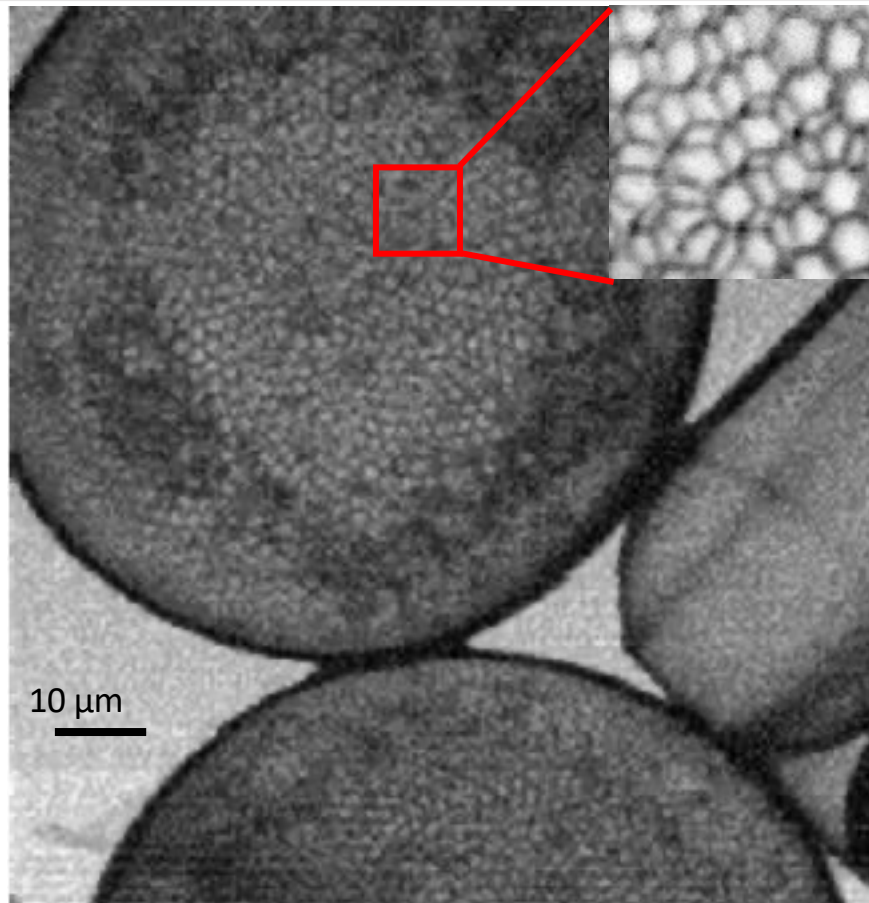


Planktonic diatom *Coscinodiscus* sp.
(A. Beran, Laboratory for Marine Biology, Trieste, I)

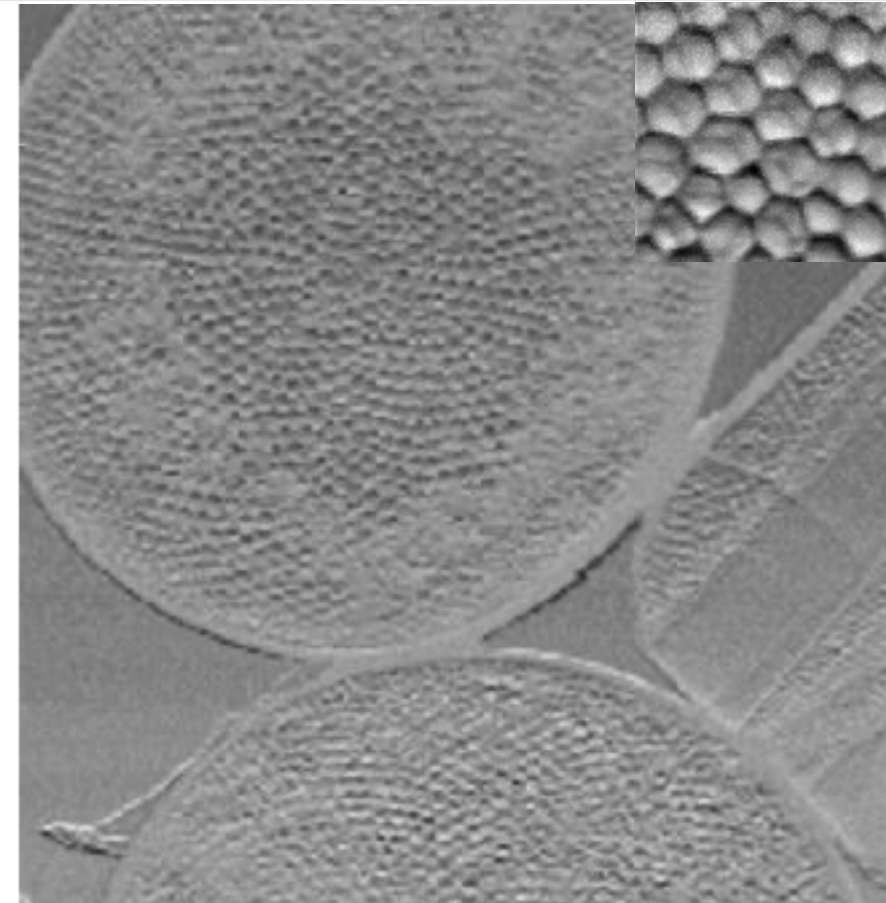


- Simultaneous absorption and phase contrast imaging

Planktonic diatom “Casciodiscus sp.” (provided by LBM, Trieste, I)



Biology, Trieste, I)
Bright field image

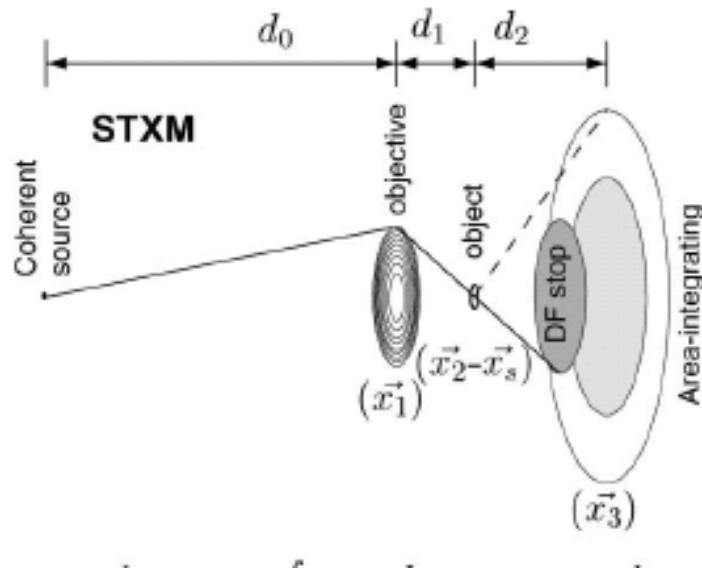


DPC mode – X-moment

Images acquired in STXM mode with FRCCD camera; E=1320 eV, 200x190 px, 50ms dwell/px

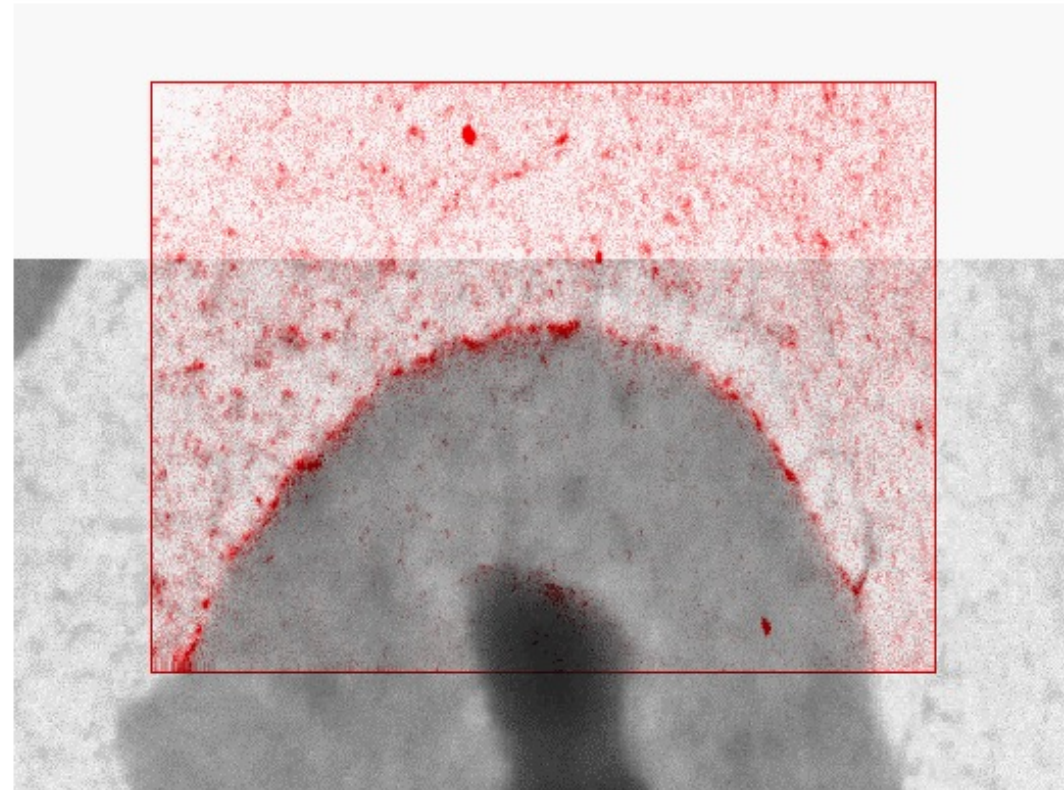
- **Darkfield imaging in scanning X-ray microscopy**

Technique is especially suited for small, strongly scattering particles as for example a few 10nm diameter labelling spheres



Brightfield image of a cell with Au labelling spheres overlaid with a darkfield image

Images acquired with STXM at the NSLS

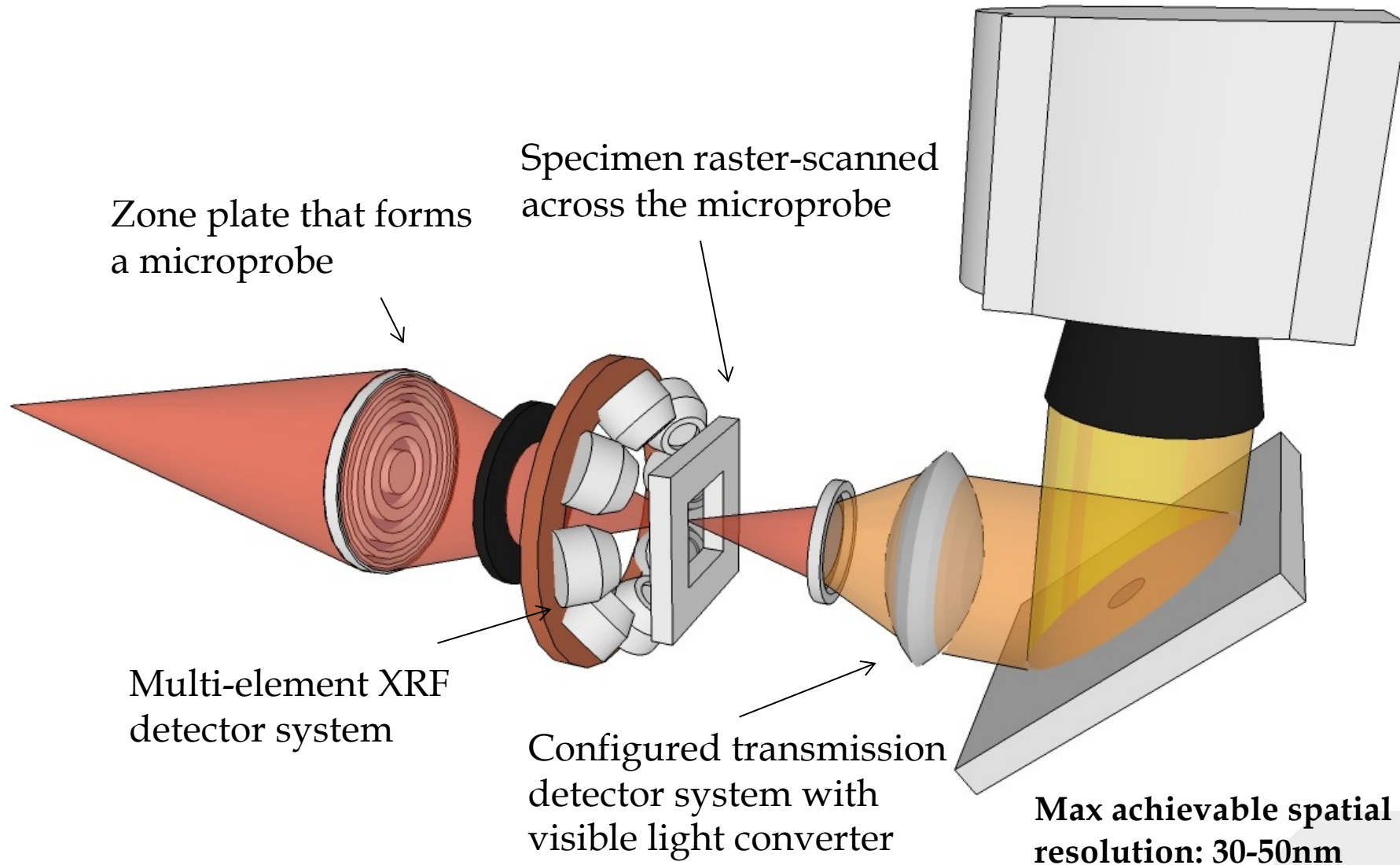




Elettra
Sincrotrone
Trieste



• Scanning X-ray microscope (STXM) at Elettra (TwinMic beamline)

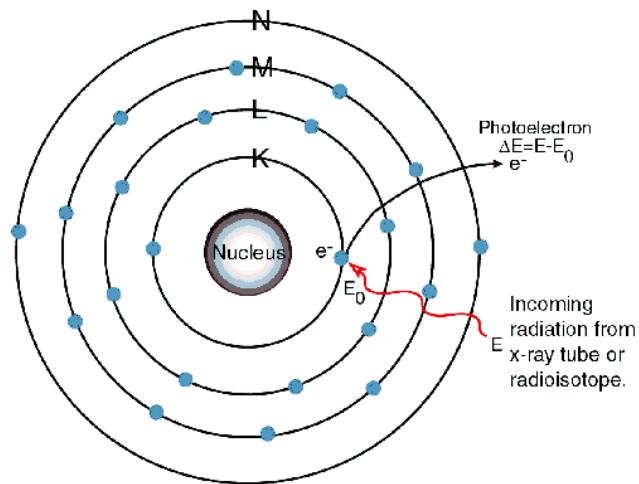




• X-ray Fluorescence contrast

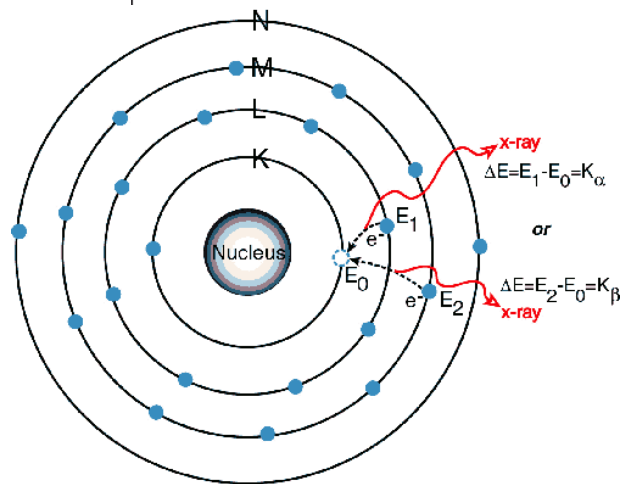
- X-ray fluorescence (XRF) is the characteristic x-ray emission resulting from the de-excitation process after x-ray absorption and electron ejection, which is unique for each element.
- This makes XRF spectroscopy an excellent tool for elemental and chemical analysis.
- The main advantage of combining XRF mapping with STXM microscopy is the possibility to collect simultaneously absorption and phase contrast images and the corresponding elemental distribution maps. Thus the specimen morphology can be directly correlated with the elemental distribution.
- The possibility to combine the XRF setup with high brilliance micro- or nanobeam sources has also opened new opportunities in the field of XRF microtomography, where several transmission and XRF image projections are collected by rotating and translating the specimen under the x-ray probe. This requires a high-precision goniometer and translation stages for the specimen and an appropriate algorithm to reconstruct the 3D information.

• Photoionization



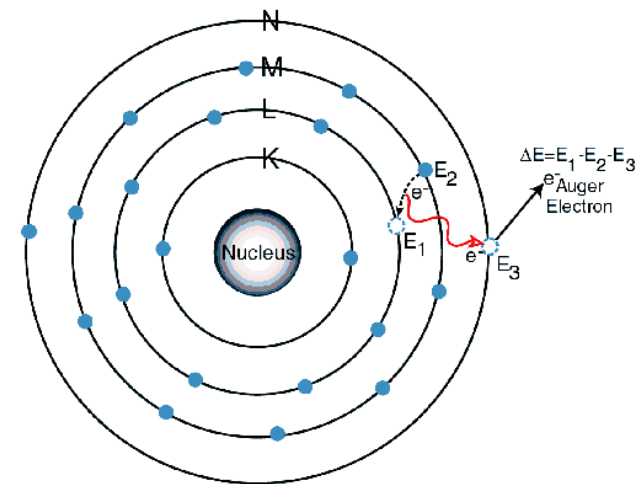
**X-ray absorption
(through photoelectric
effect)**

The primary X-ray photon causes the ejection of electrons from the inner shells, creating vacancies



X-ray Fluorescence

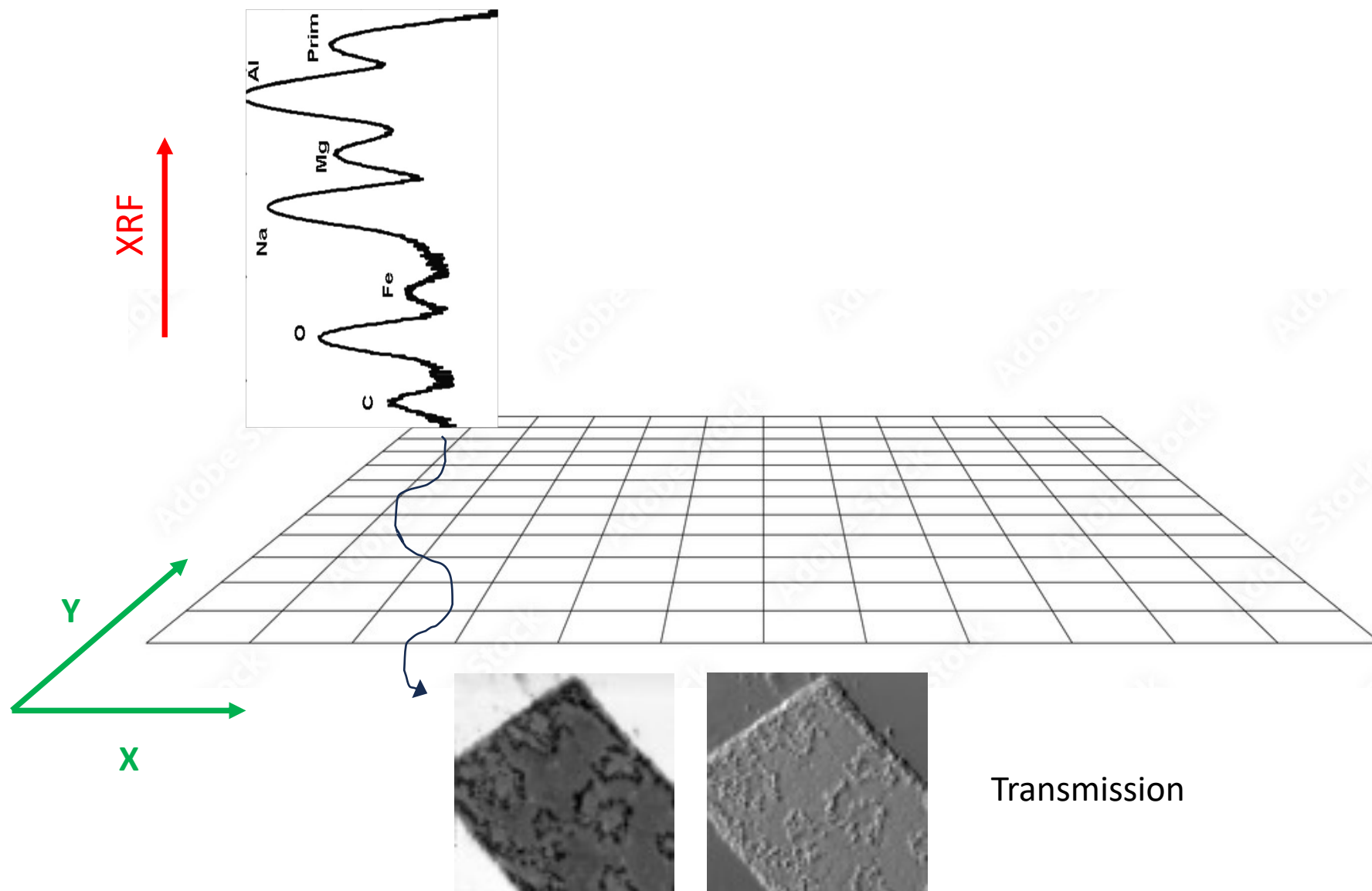
The vacancy created by the primary X-ray photon is filled by an electron coming from an outer shell causing the emission of a characteristic X-ray photon whose energy is the difference between the two binding energies of the corresponding shells



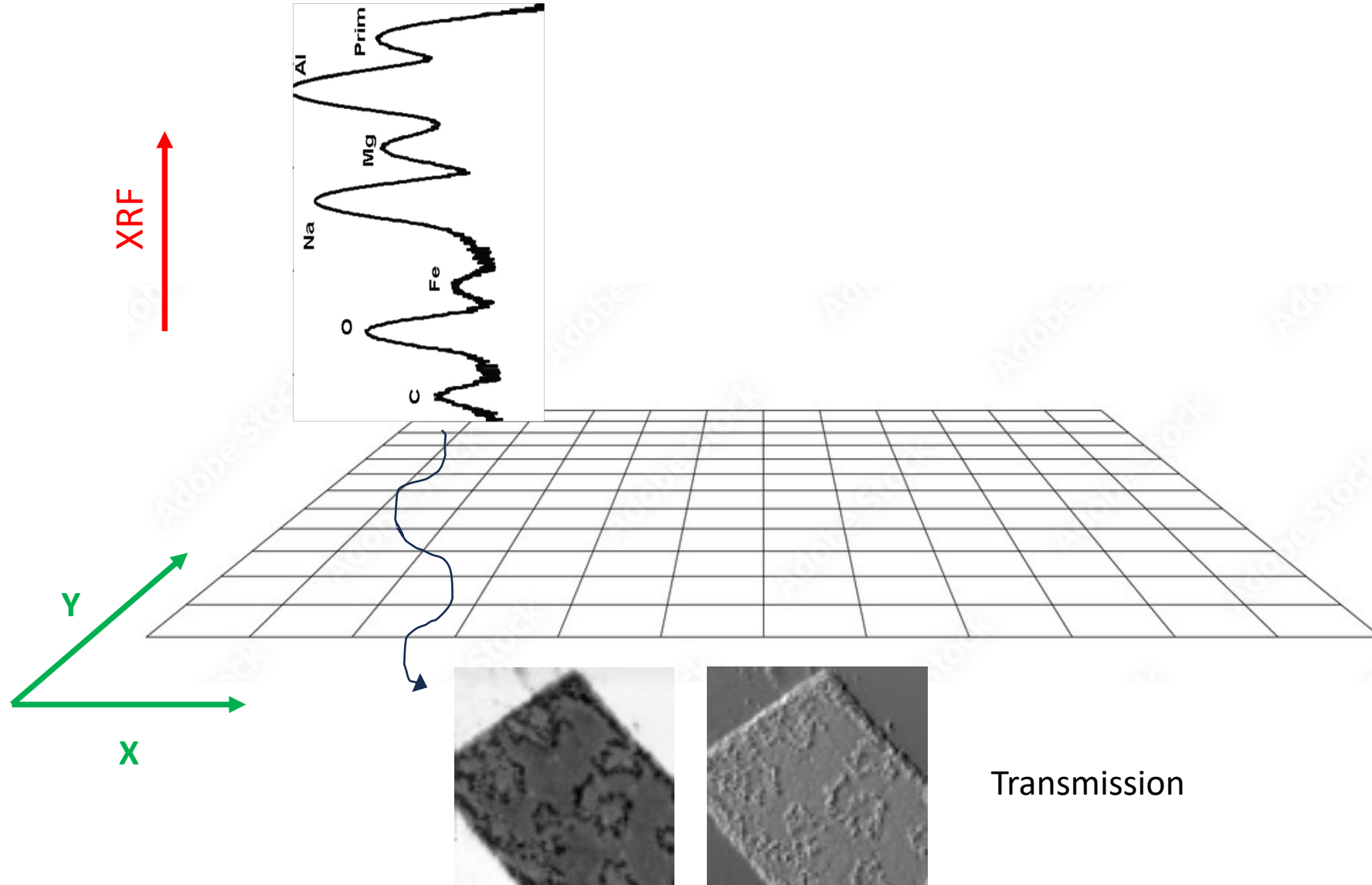
Auger effect

The vacancy created by the primary X-ray photon is filled by an electron coming from an outer shell and the energy is transferred directly to one of the outer electrons, causing it to be ejected from the atom.

• XRF acquisition

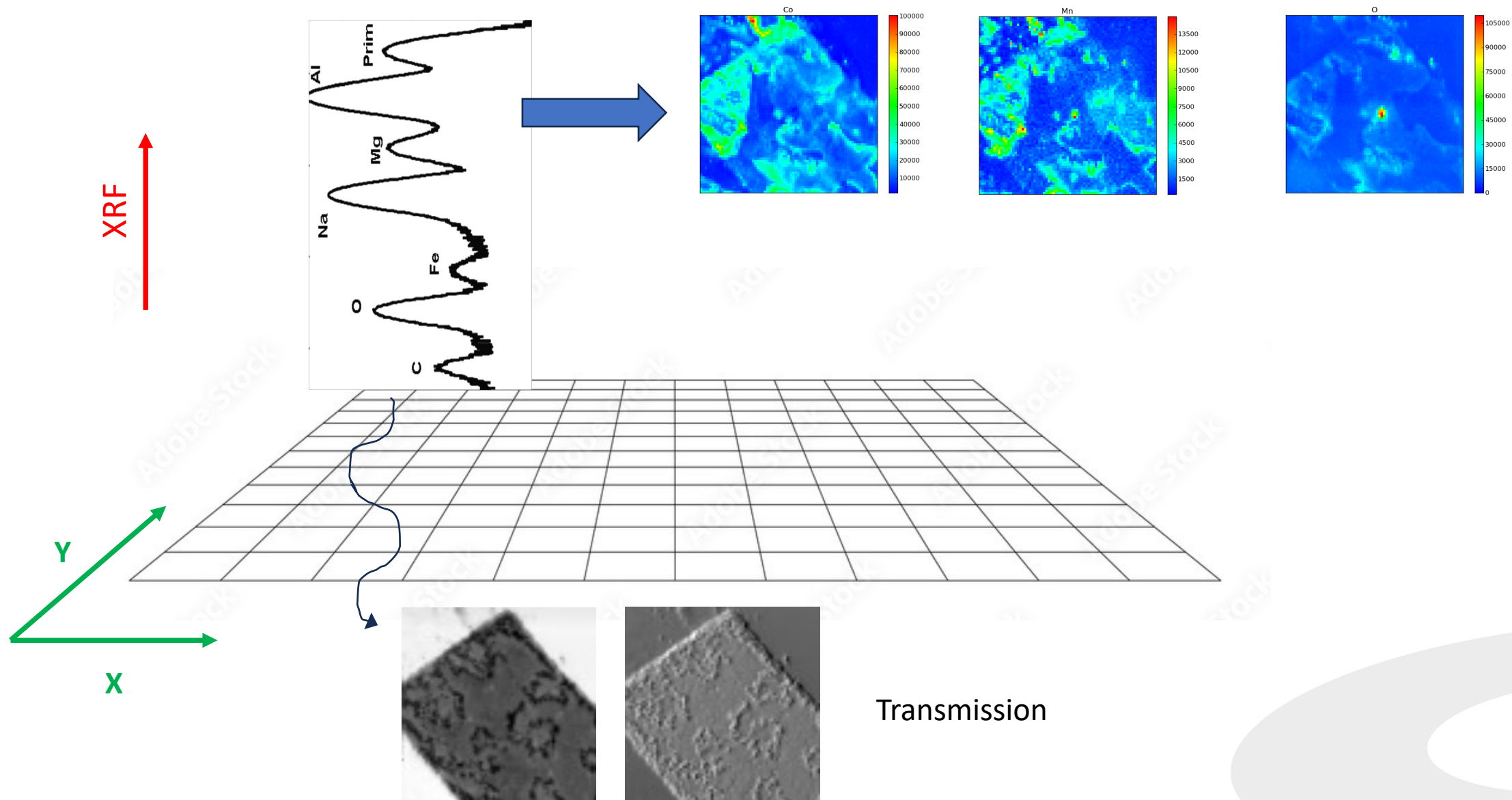


• XRF acquisition

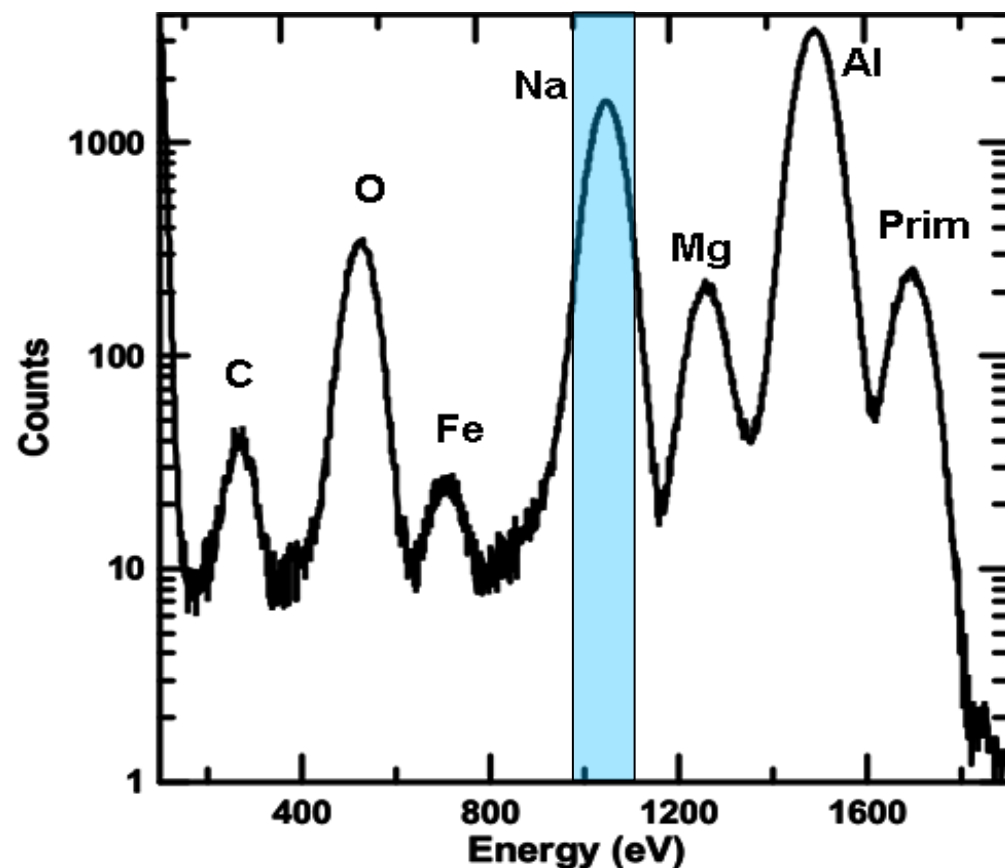




• XRF acquisition



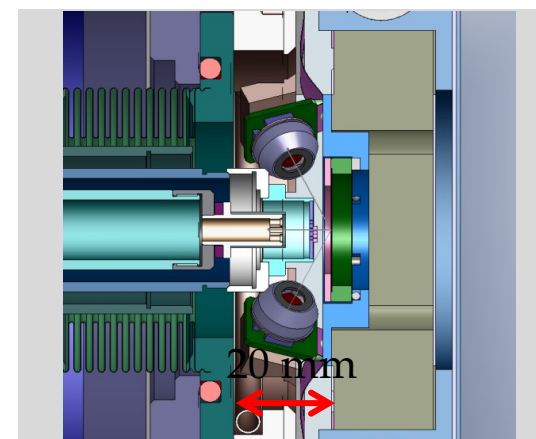
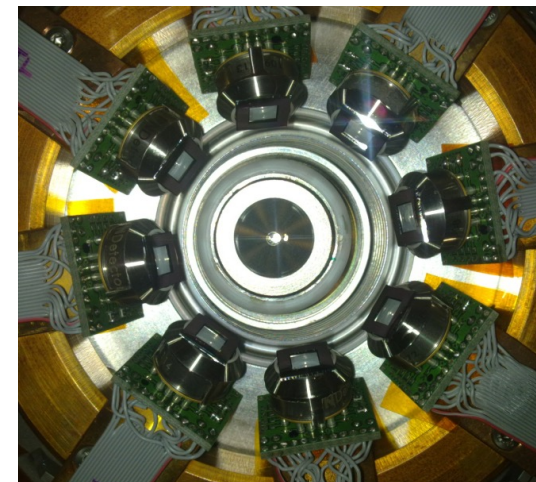
Low-energy X-ray fluorescence:



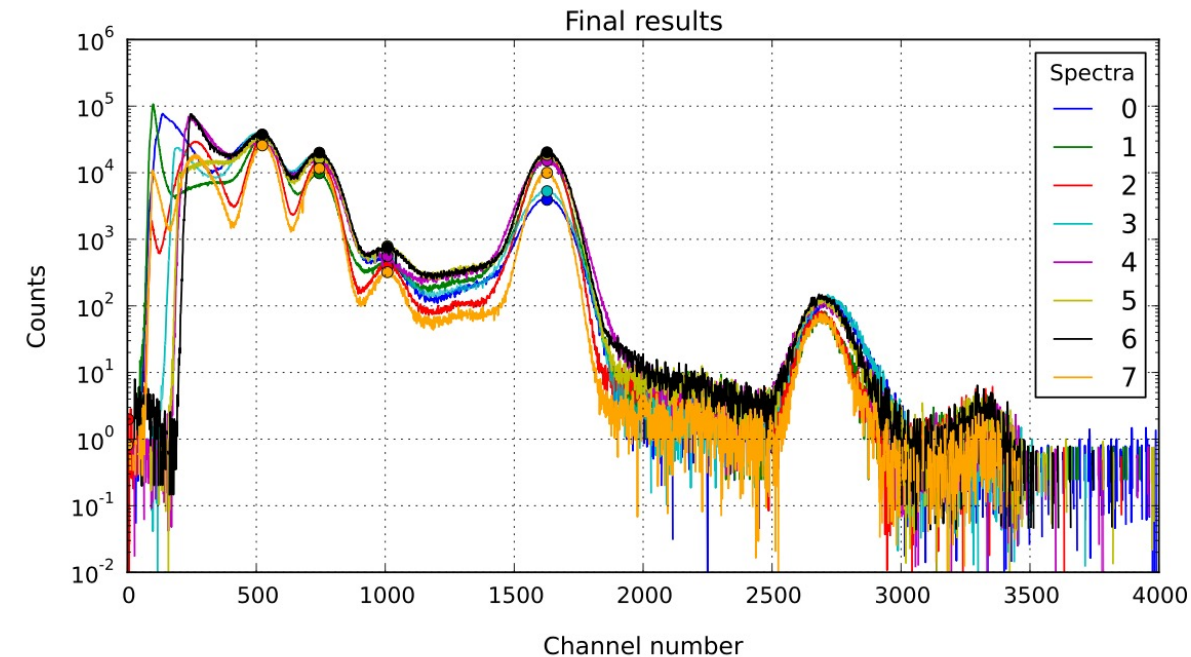
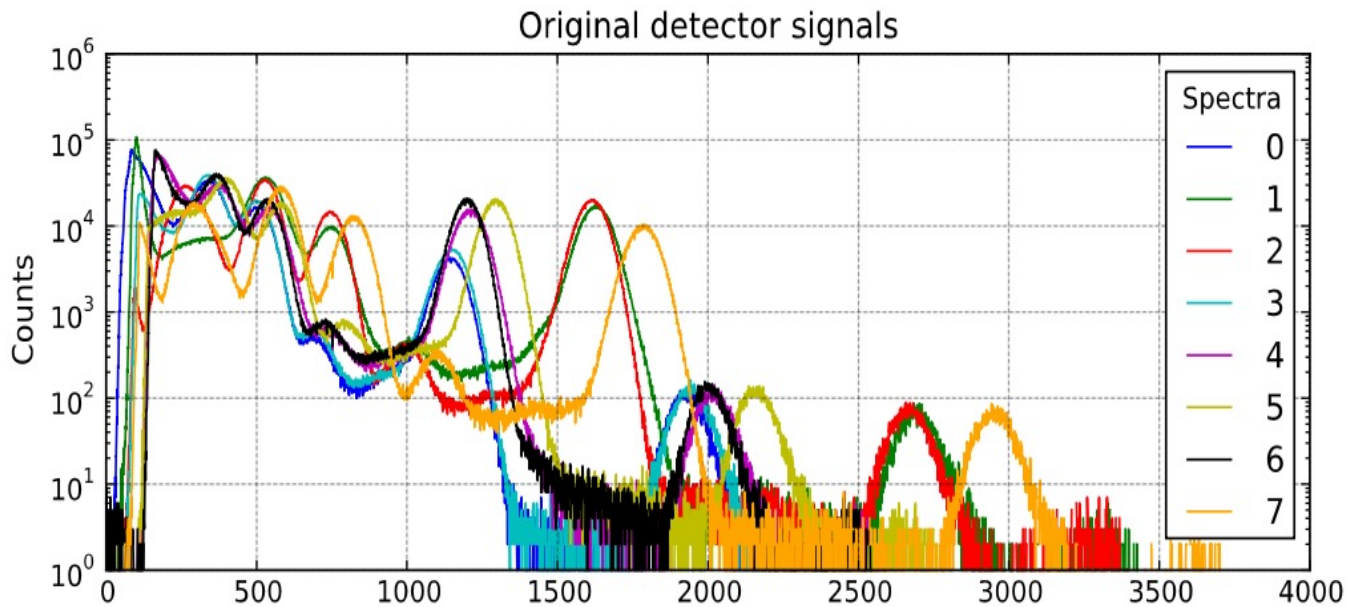
TwinMic LEXRF spectrum with unfocused beam of a test organic matrix on a metal shim

Dynamic range: up to 30 kcounts/s

Average FWHM energy resolution @ C- K edge: 69 eV



- Spectra alignment



- Spectra alignment is necessary when system with multiple XRF detector are used
- Manual alignment can be performed in the case of a few detectors
- For multiple detector automated way are the way to go (*Kourousias et al, X-Ray Spectrom. 2017, 46, 44–48*)

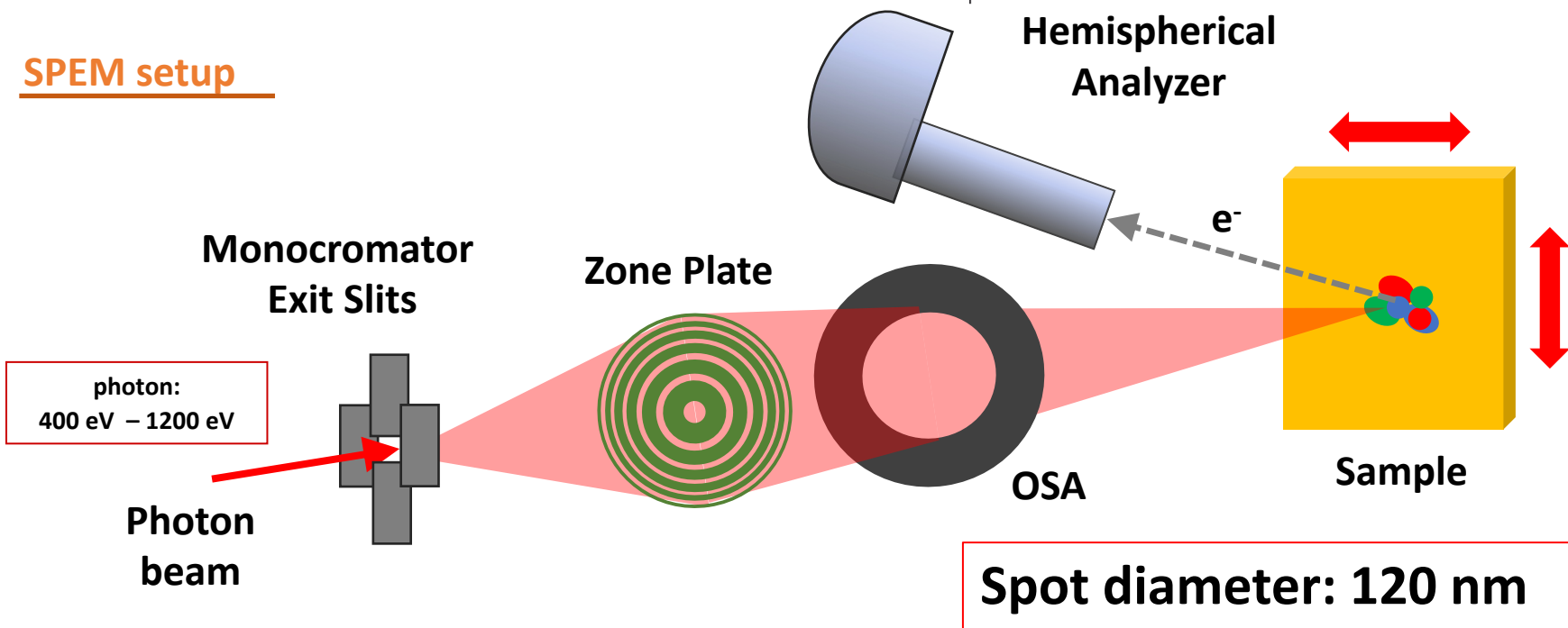


Elettra
Sincrotrone
Trieste



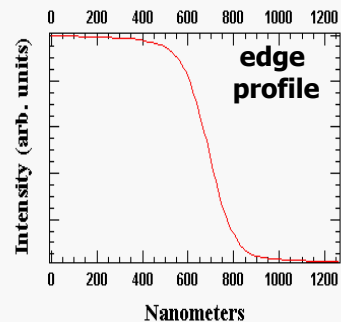
• Scanning PhotoEmission Microscopy (SPEM)

SPEM setup



SPEM actual performances

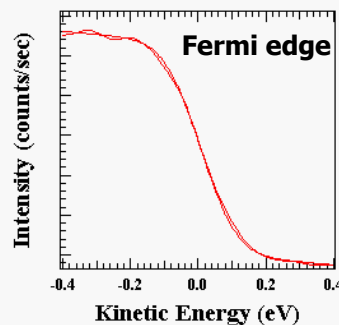
Spatial resolution



- Focal distance: 5 – 15 mm
- Spot diameter: 120 nm

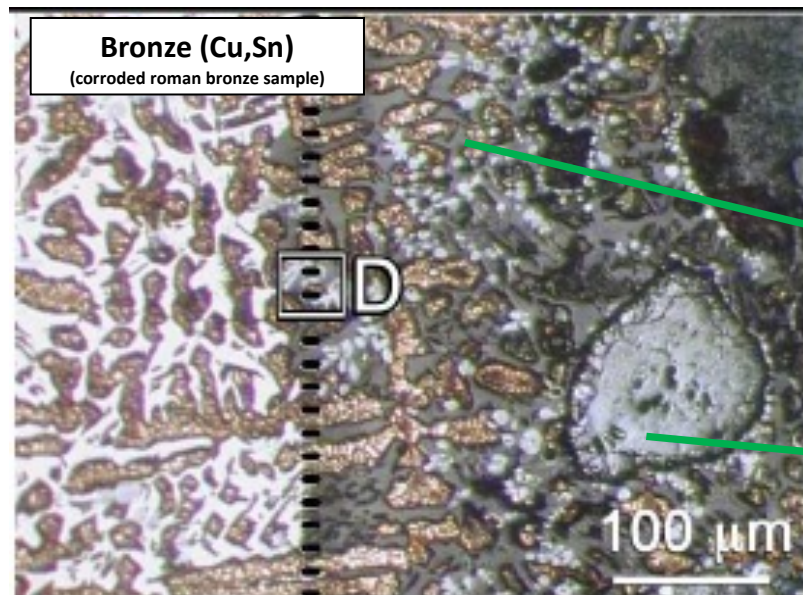
- Imaging: < 50 nm
- Microspectroscopy: 120 nm

Overall energy resolution

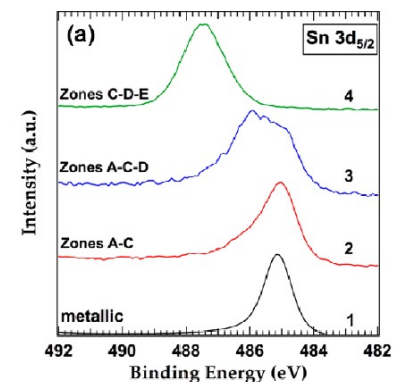
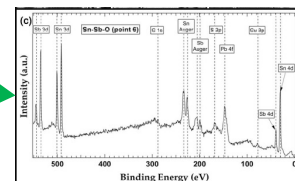
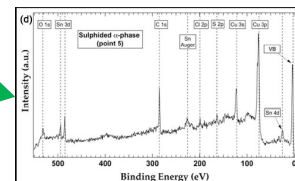


- Energy resolution: ~180 meV
- Standard conditions
- Room Temperature
- Photon Energy: 500 eV

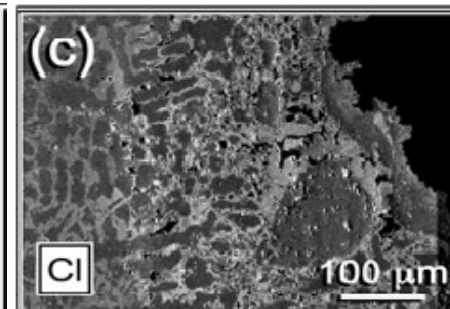
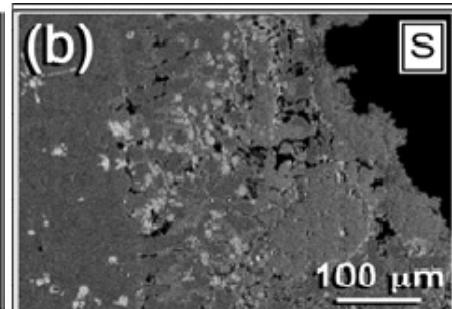
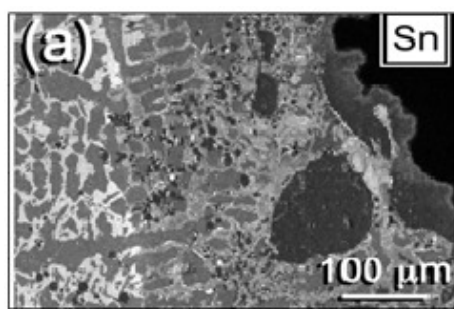
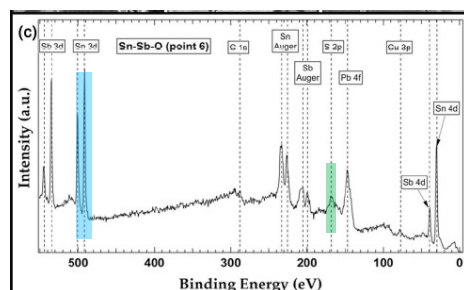
- ESCAmicroscopy – Scanning PhotoElectron Microscopy (SPEM)



XPS from a sub-micron spot
(spectra mode)



Photoelectron maps
(image mode)





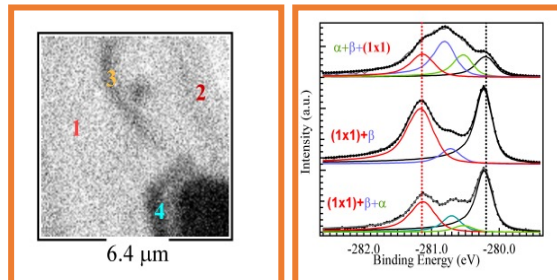
Elettra
Sincrotrone
Trieste



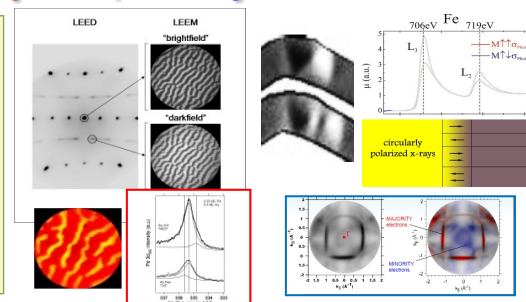
• Microscopy Approaches:

- **X-ray** or **electron optics**; **X-ray** or **electron detection**; **current**

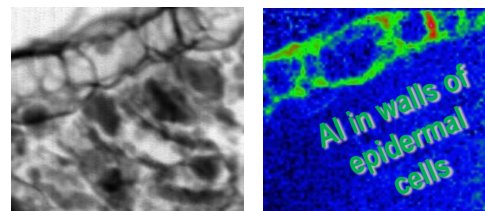
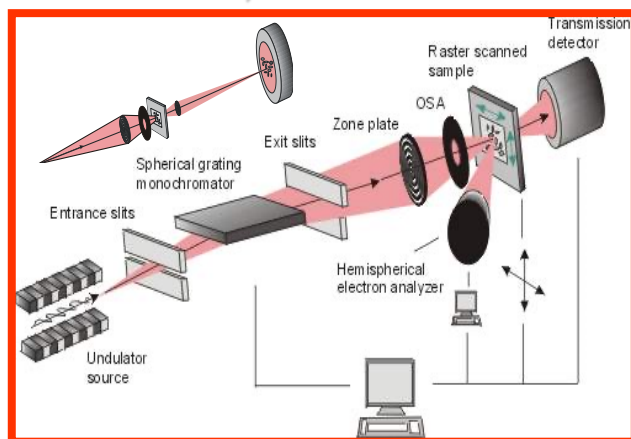
SPEM: Imaging and microspectroscopy



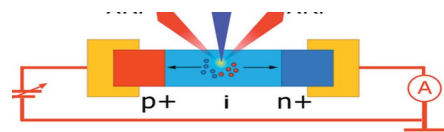
- XRF, XPS, XAS = elemental chemical, spin information
- X-ray transmission and scattering (phase contrast): morphology-XAS
- Topology - Θ , **current (XBIC)**



SPEM, SXM & TXM



SXM: transmission and XRF-XAS



X-ray beam induced current (XBIC)

XPEEM : PES and XAS (+LEEM/μ-LEED)

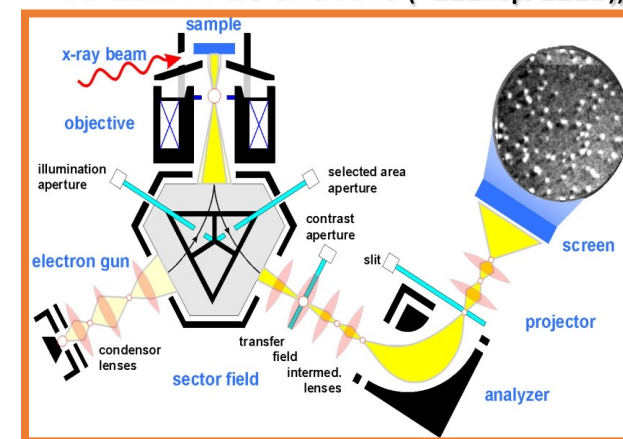
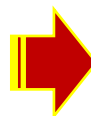


Image contrast

- Density, thickness, morphology (incl. phase contrast and ptychography);
- Element presence and concentration;
- Chemical state, band-bending, charging;
- Magnetic spin or bond orientation.



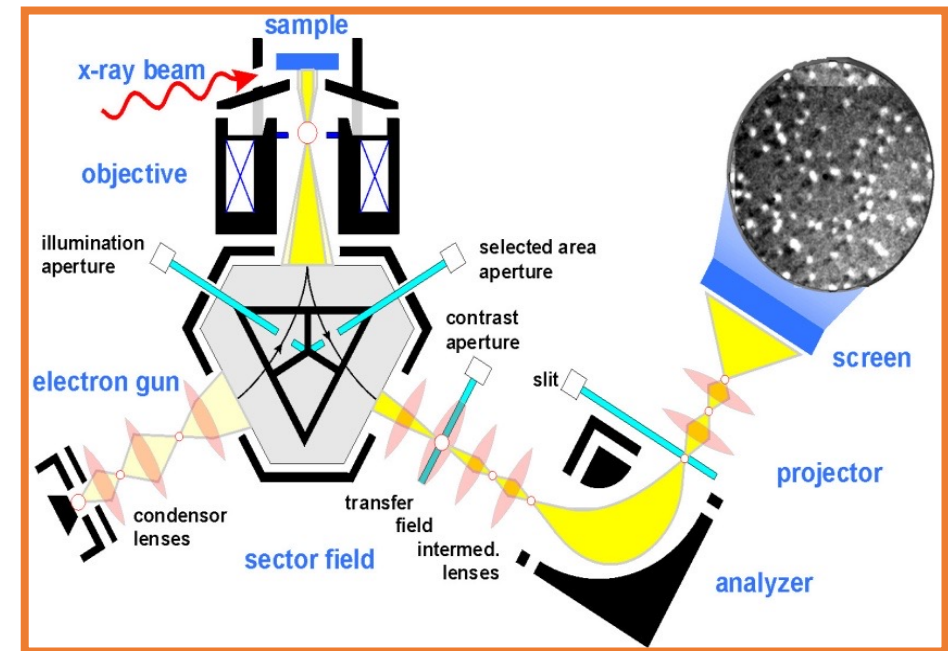
Spectromicroscopy:

μ-XPS, μ-XAS, μ-XRF in selected areas from the images: detailed characterization of the chemical and electronic structure of coexisting micro-phases.

• X-ray Photoemission electron microscope

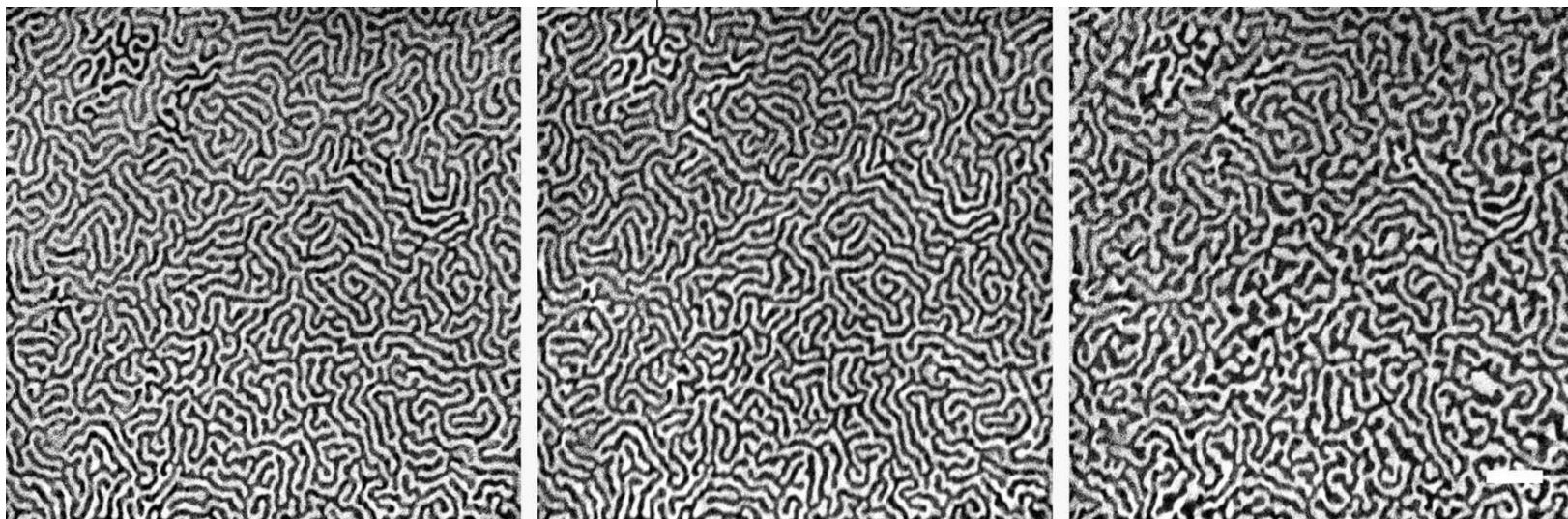
- The photoemission electron microscope images a specimen that is illuminated with soft x-rays or ultra-violet (UV).
- The emitted electrons are accelerated by a strong field in the objective lens.
- The objective produces a magnified image of the specimen, which is further magnified by one or several additional lenses onto a two-dimensional image detector.
- The detector is usually a multi-channel plate image intensifier—phosphorus screen combination and the image on the screen is recorded with a CCD camera.

XPEEM : PES and XAS (+LEEM/ μ -LEED))



- What can researchers learn?
- Domain size, shape and distribution, including whether domains form stripes or labyrinthine patterns.
- How magnetic domains respond to applied magnetic fields.
- How interfaces, defects and local chemical composition influence magnetic anisotropy and domain-wall pinning.
- How magnetization changes during switching, and, with suitable time-resolved measurements, how domains move.

- X-ray Photoemission electron microscope



- Investigation of magnetic domains and magnetization reversal in thin films and nanostructures.
- XPEEM combines spatially resolved imaging with chemical and magnetic sensitivity, allowing researchers to visualize how magnetic behavior changes from one region of a sample to another.
- Tune the synchrotron energy to the element absorption edge, where it is absorption is particularly sensitive to its magnetic state.
- Illuminate the sample with circularly polarized X-rays. The absorption depends on the relative orientation of the photon helicity and the local magnetization, through X-ray magnetic circular dichroism (XMCD).
- Acquire PEEM images using opposite photon helicities, or reverse the magnetization, and calculate a difference or asymmetry image.
- Map the magnetic domains. Different XMCD signals reveal regions with opposite magnetization.



• STXM and XPEEM comparison

	STXM	XPEEM
Principle	transmission	photoemission
Detected signal	transmitted X-rays	emitted electrons
Geometry	sample between optics and detector	electrons emitted from sample
Main sensitivity	bulk/through sample	surface/interface
Typical sample	thin samples	surfaces, thin films, devices
Spatial resolution	nm	nm
Chemical sensitivity	X-ray absorption	XPS/XAS
Magnetic imaging	XMCD	XMCD/XMLD
Vacuum	usually not necessarily UHV	UHV essential
Sample thickness	must transmit X-rays	not necessarily transmission geometry
Surface sensitivity	relatively low	very high

STXM scans a focused X-ray spot across the sample.

XPEEM illuminates an area and images the emitted electrons directly.

So XPEEM is essentially a **full-field electron-imaging technique**, rather than a scanning X-ray microscopy technique.



• XPSmicroscopy and XPEEM comparison

	XPS microscopy	XPEEM
Spatial selection	Focused X-ray spot	Electron-optical field of view
Image acquisition	Point-by-point scanning	Parallel imaging
Typical spatial resolution	Tens to hundreds of nm, depending on instrument	Tens of nm, depending on instrument
Spectroscopy	Often full XPS spectra at each point	Energy-filtered imaging or image stacks
Field of view	Set by scan area	Set by objective lens and field of view
Surface topography	Generally less affected by electron-optical projection	Can be strongly affected by surface topography and local electric fields
Magnetic contrast	Possible with suitable polarization and geometry, but not inherent to ordinary XPS mapping	Particularly powerful with XMCD/XMLD
Sample requirements	Often more flexible	Usually requires clean, conductive or suitably prepared surfaces and careful control of charging



• X-ray Diffraction Imaging

- X-ray diffraction is among the most useful phenomena to probe matter at the atomic scale.
- Crystalline materials, which produce sharp diffraction peaks, are especially well suited for in-depth investigation with high-energy x-rays. To date, the large majority of protein structures have been determined using x-ray crystallography.
- Even though x-ray scattering is very well understood and simply described using reciprocal space concepts, the problem of structure determination from x-ray diffraction data remains fundamentally difficult.
- The essence of these problems lies in the very measurement of diffracted radiation, in which only the amplitude is measured while the phase part of the diffracted wave is lost.
- The crystallographic 'phase problem' can be tackled nowadays with a multitude of efficient, though highly specialized, methods.



• X-ray Diffraction Imaging

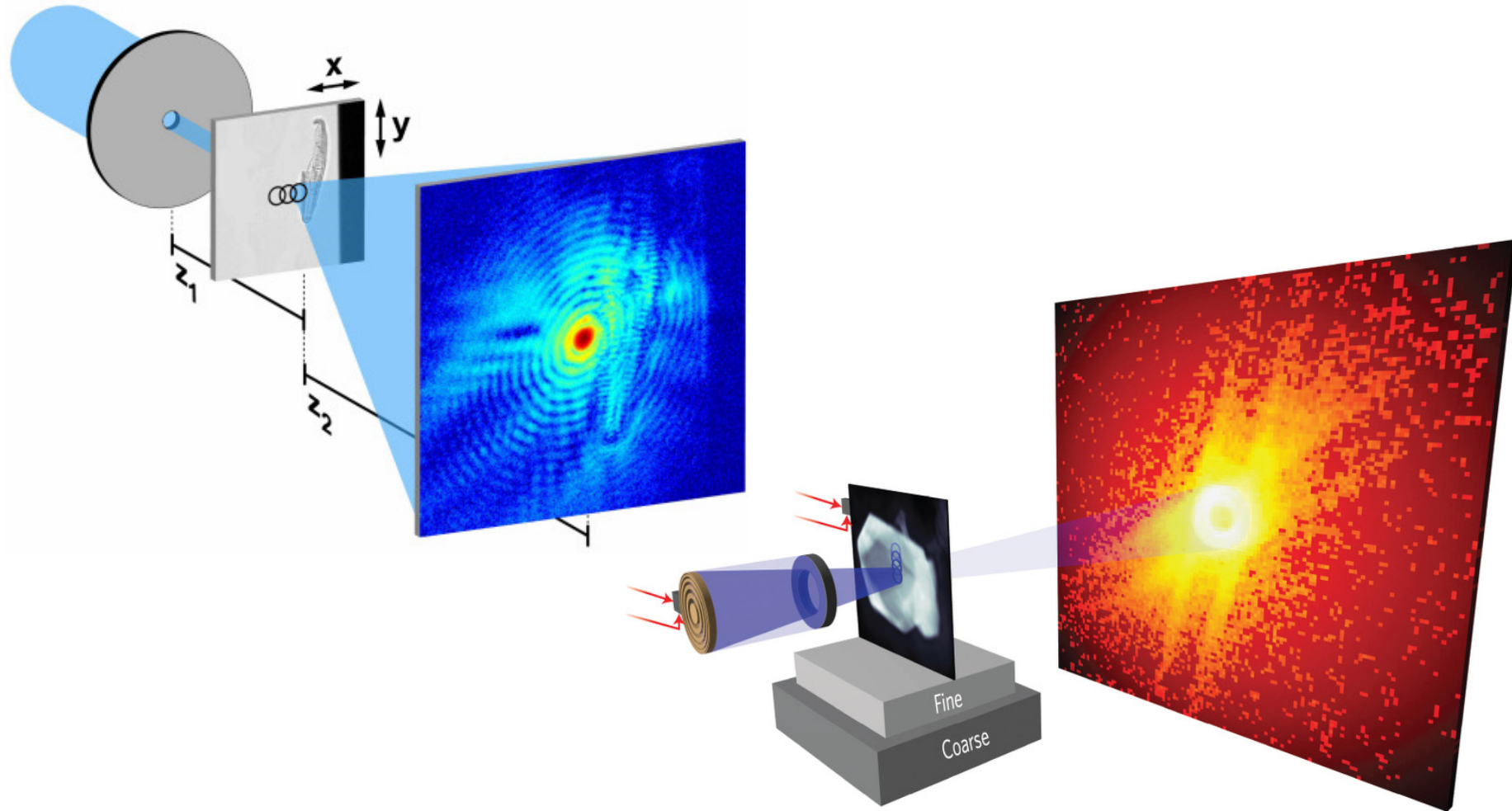
- In the classical form of diffractive imaging, often called diffraction microscopy, a sample is bathed in a planar, monochromatic and coherent wavefield, and the diffracted intensity is measured by a pixel-array detector in the far-field
- The intensity measured in the detector plane is equal to the absolute value squared of the Fourier transform of the exit wave in the image plane.
- The coherence of the incident wave gives rise to a characteristic 'speckle pattern' in the diffraction plane. It is from this speckle pattern that real-space information on the specimen is extracted.
- As in crystallography, the phase problem is the main obstacle to the simple inversion of the diffraction pattern since given only the magnitudes of a Fourier transform, there exists an infinity of possible solutions to the problem, corresponding to all possible assignments of phases to the Fourier components.
- For both technical and fundamental reasons, the diffraction pattern has to be sampled on a grid fine enough to satisfy Nyquist's criterion (Shannon 1949). Satisfying this so-called 'oversampling' condition ensures that the smooth diffraction pattern is known at all points within the detector area, provided that it is band-limited. 'Band-limited' means that the sample has to occupy a sufficiently compact region of space (called the support), thus imposing the critical experimental constraint that the sample be isolated. The fact that most of the field of view is empty, as a result of the sample isolation, provides the required additional constraint to make the phase problem approachable.



• Ptychography (CDI)

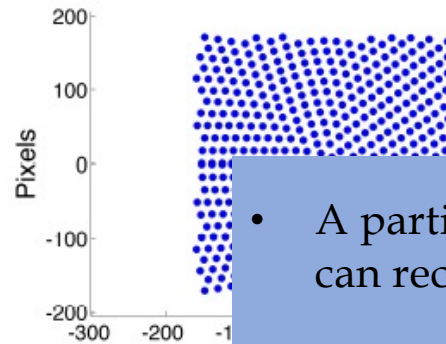
- Ptychography is rapidly developing into an important imaging tool in X-ray microscopy.
- It doesn't require X-ray Optics
- The technique involves successively illuminating overlapping regions of a specimen with a coherent probe and recording the resulting diffraction patterns.
- It is important that the illuminated areas overlap significantly since those common regions provide duplicate information that allows computer algorithms to reconstruct reliably both the sample transmission function and the illuminating probe from the measured diffraction patterns.

Ptychography (CDI)



- K. Giewekemeyer, M. Beckers, T. Gorniak, M. Grunze, T. Salditt, and A. Rosenhahn Optics Express Vol. 19, Issue 2, pp. 1037-1050 (2011)
- D. A. Shapiro, Y.-S. Yu, T. Tyliczszak, J. Cabana, R. Celestre, W. Chao, K. Kaznatcheev, A. L. D. Kilcoyne, F. Maia, S. Marchesini, Y. Shirley Meng, T. Warwick, L. Lisheng Yang, H. A. Padmore Nature Photonics 8, 765-769 (2014)

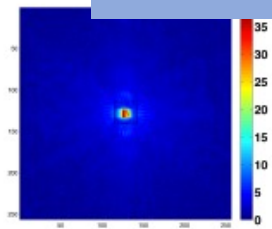
Ptychography Algorithms



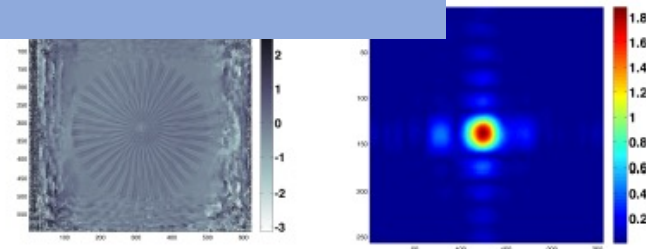
Scan

Start Guess Object

- A particularly useful feature of these algorithms is that they can recover the amplitude and phase of both these signals.
- The lateral resolution of the reconstructed image is not limited by the probe size, overcoming the limitation of X-ray microscopy imposed by the focusing optics



Processed Data



Probe from test object



Elettra
Sincrotrone
Trieste



www.elettra.eu