Benefit of small, round(ish) and coherent beam for scanning hard X-ray imaging

A. Somogyi, K. Medjoubi, G. Baranton

Nanoscopium, Synchrotron Soleil

Outline

- Why we need a small, round beam for scanning imaging?
- Optical layout of Nanoscopium
- Scanning multitechnique hard X-ray imaging at Nanoscopium today
- What would we gain with a small, round & coherent beam at Nanoscopium? (simple estimation)
- Conclusion

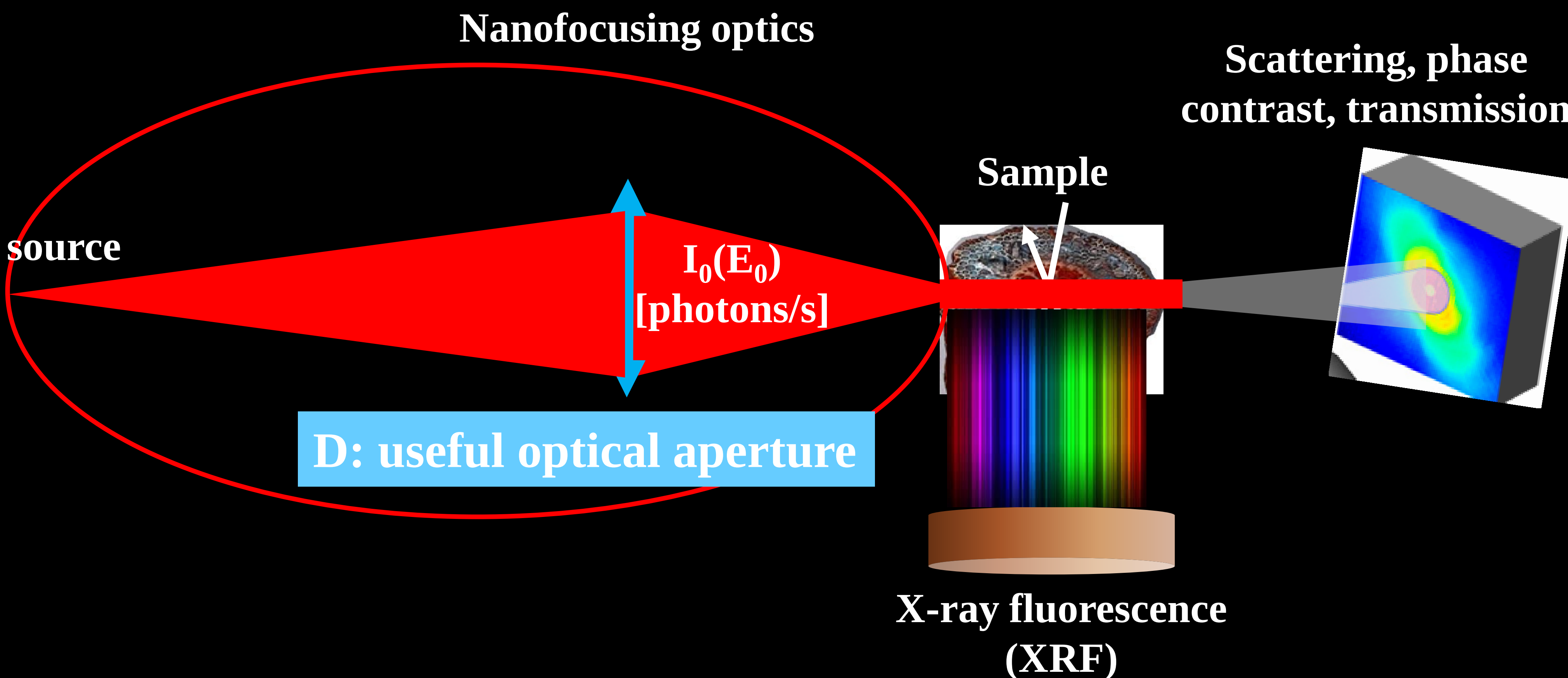
Why we need a small, round beam for scanning imaging?

Scanning X-ray imaging

Today: « slow »

The image is reconstructed pixel by pixel

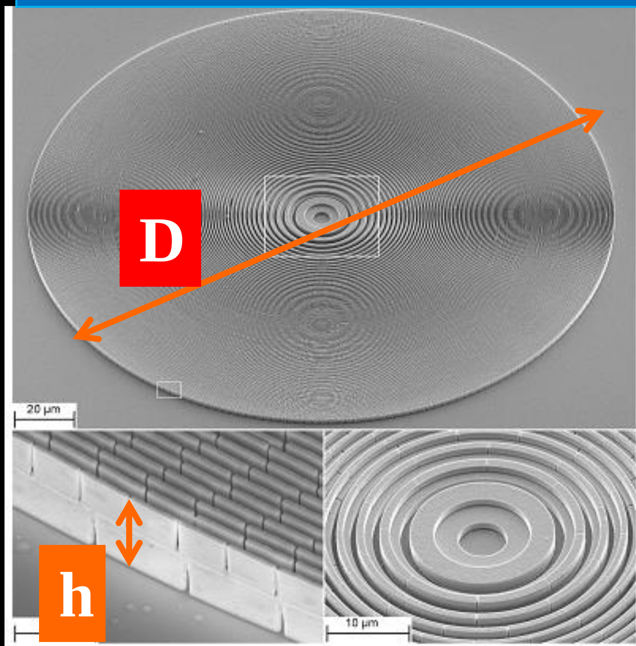
Multimodal



Focused X-ray beam: intensity, size, focal depth, coherence properties influence the obtained image quality

X-ray optics used at Nanoscopium

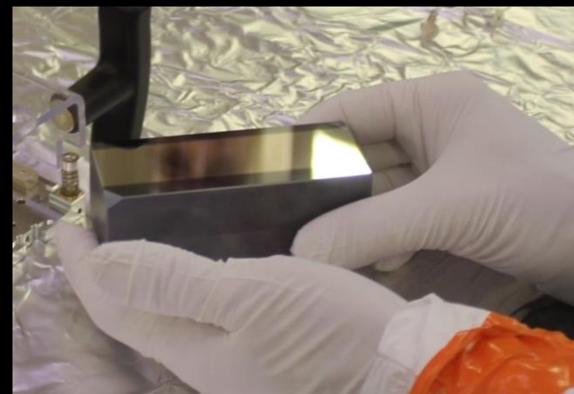
Fresnel Zone Plate lenses

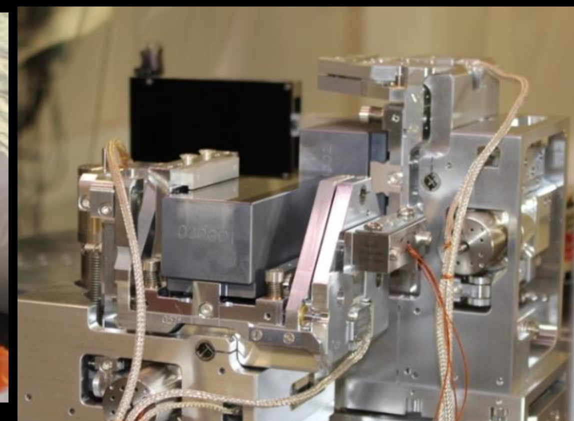


D: useful optical aperture

Chromatic
Circular: simmetric focusing

Kirckpatrick-Beaz mirrors



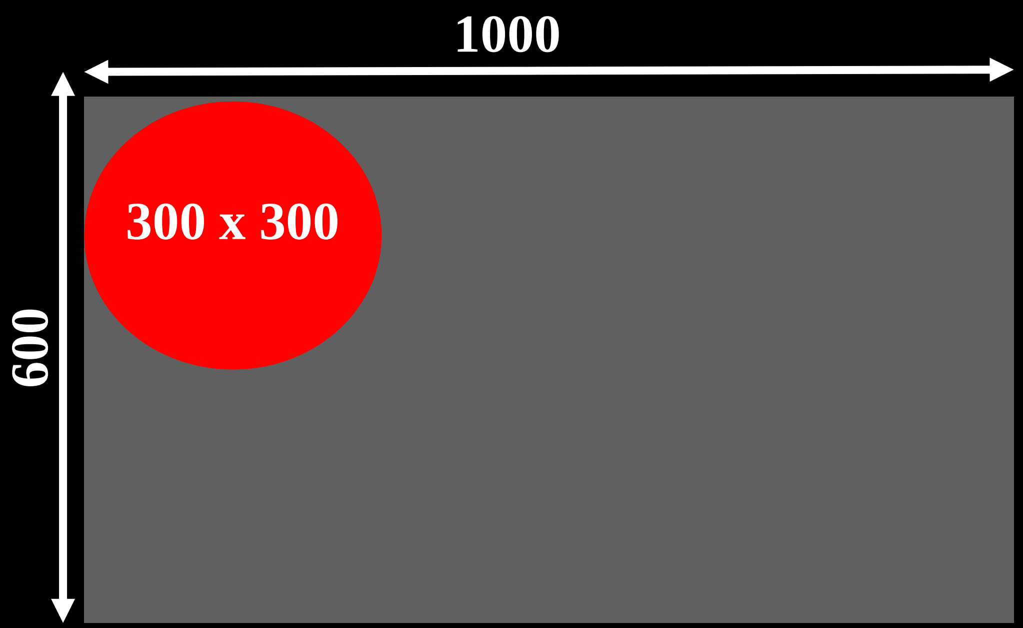


Elliptical mirror shape with
0.2 nm figure error over 10 mm
<nm roughness
achromatic
Slightly assymetric focusing

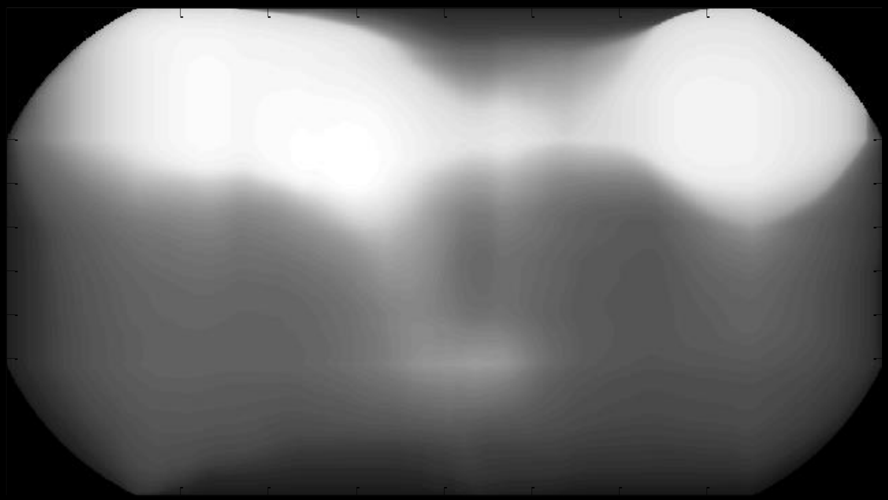
Typical D at Nanoscopium: ~50-500 µm

Why would we like to have « round beam » in imaging?
The beam-size and shape determine the spatial resolution and eventual distortion of the measured image

Let's suppose that the object to measure has a dimensions of ~600 x 1000 (in arbitrary units)



If the dimensions of the probe is: 300 x 300 (arb. units)



« Measured » image

«Dimension» of the object to measure: ~600 x 1000

Let’s suppose a probing beam having a similar H X V dimension ratio of the recent Soleil source

Probe ~10 x 300

Probe ~10 x 150

« Measured » image

Flat, elliptical beam: USEFUL for 1D TEXTURES e.g. surface, layers BUT provides a DISTORTED image of 2D strustures

Let's suppose the same probe flux in the same total probe area, but let's choose different beam dimension ratios

Probe dimensions:

~1 x 100

~10 x 10 round beam

« Measured » image

Optical layout of Nanoscopium

size of the focused beam

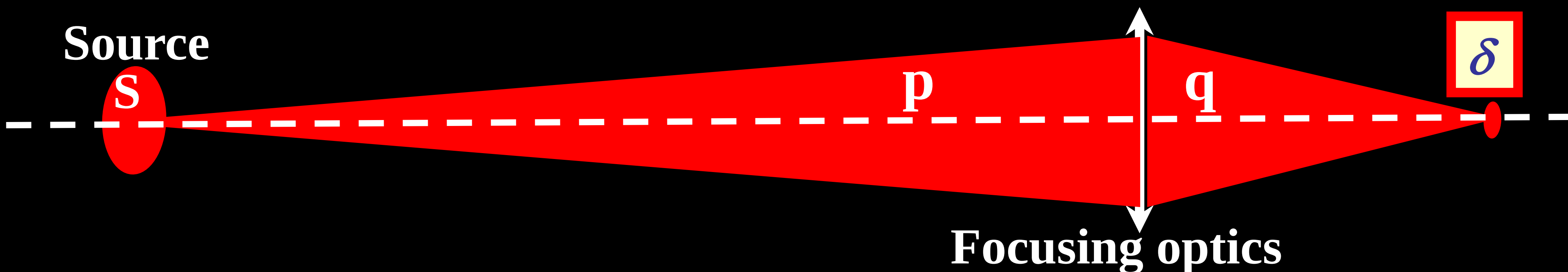
$$\delta = \sqrt{\delta_{DL}^2 + \left(\frac{q}{p}\cdot S\right)^2}$$

Source demagnification

Diffraction limited spot-size

Smallest possible beam-size: $\delta \sim \delta_{DL}$

coherent illumination is necessary



Diffraction limited spot-size

Example: Kirckpatrick Baez mirror of Nanoscopium

e.g. source-KB distance: p_2~70 m

Smallest beam-size foreseen at Nanoscopium today: 50 nm

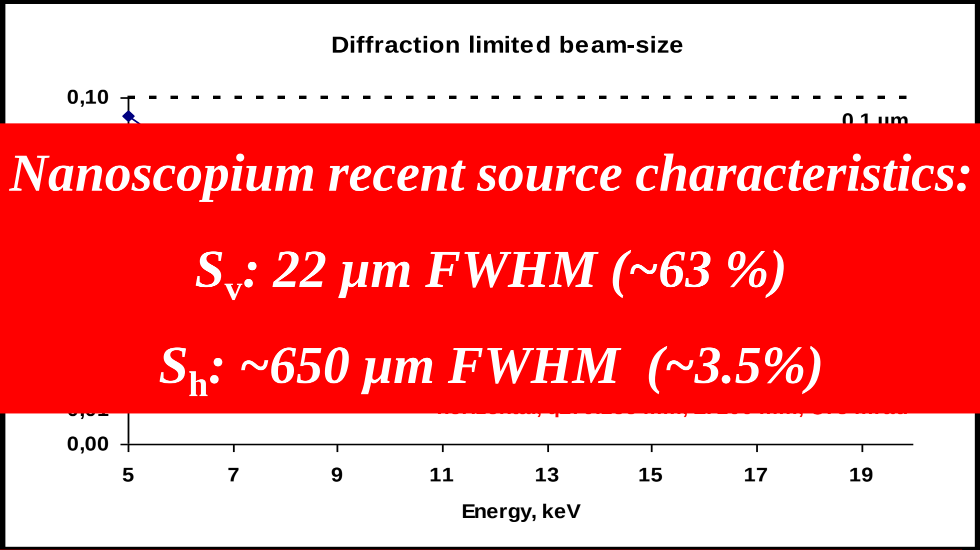
Verical beamsize

q_v=0.255 m (KB mirror1)

M_{vert}~0.0036

<u>Source-size: S_v<14 µm</u>

For obtaining δ_v<50 nm contribution to δ_{DL}



Nanoscopium recent source characteristics:

S_v: 22 µm FWHM (~63 %)

S_h: ~650 µm FWHM (~3.5%)

Horizontal beamsize

q_h=0.155 m (KB mirror2)

M_{hor}~0.0022

<u>Source-size: S_h<23 µm</u>

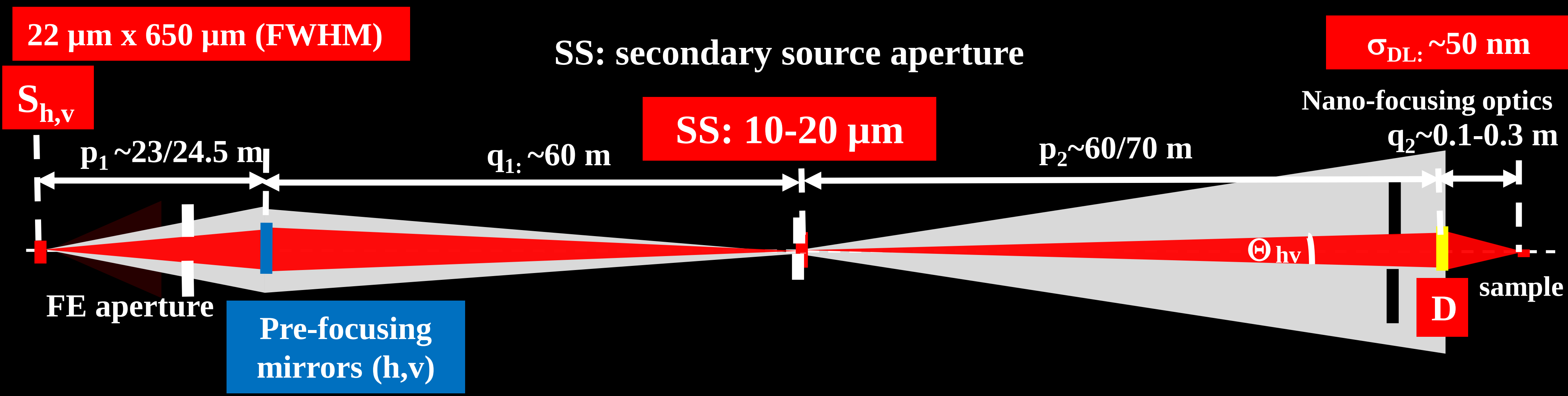
For obtaining δ_h<50 nm contribution to δ_{DL}

<u>Round(ish)</u> source would be optimal

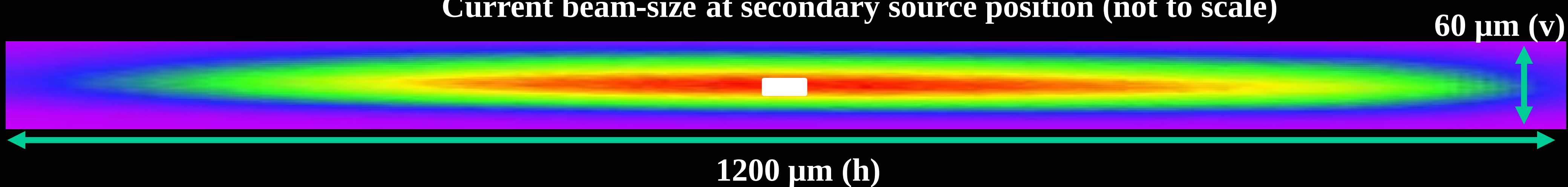
coherent illumination

Optical layout of Nanoscopium: two stage focusing scheme in both directions

S: Photon source size (~10 keV)



Current beam-size at secondary source position (not to scale)



<u>Coherent illumination is required</u> to achieve optic-limited resolution (σ_{DL} diffraction limit)

<u>Only the coherent fraction of the X-ray beam</u> is useful for diffraction limited focusing, <u><1% of the beam intensity in</u> the hard X-ray range

Typical flux at the spectro-microscopy (KB mirror) station at E=16 keV:
~300 x 300 nm^2 $1.6*10^{10}$ photons/s (non-coherent beam)
~70 x 100 nm^2 ~ 10^9 photons/s

Trade off between beam-size and intensity

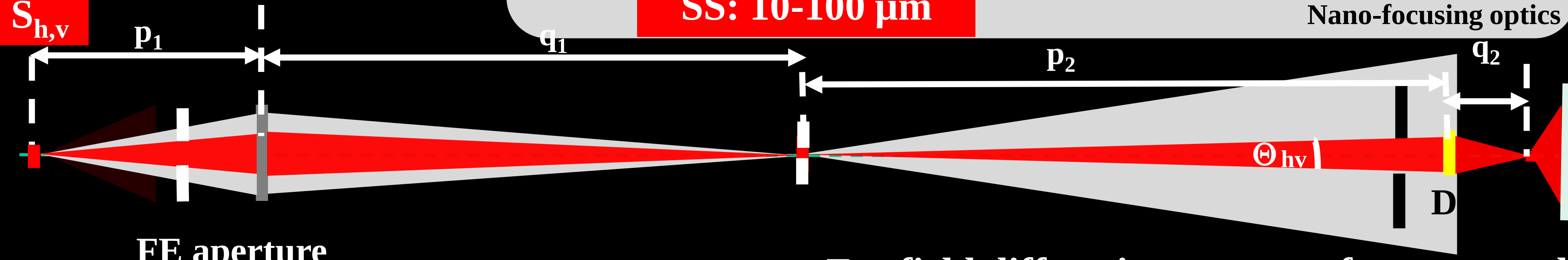
SS: Secondary source aperture

Adjustable µ-/nano-beam size

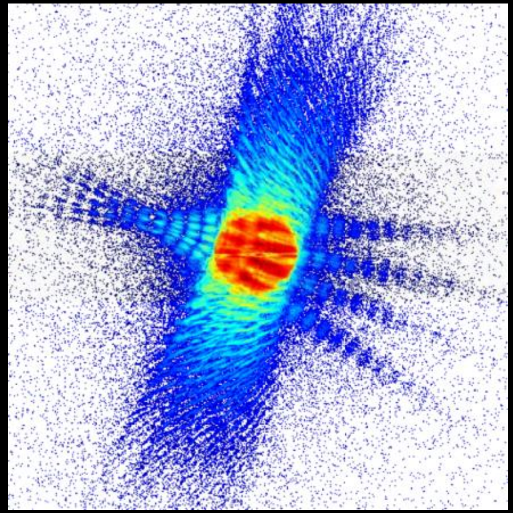
$\sigma_{h,v}$: 70 nm-1µm (FWHM)

SS: 10-100 µm

Nano-focusing optics



Far field diffraction pattern of a test sample



Coherent illumination (<1% of the beam intensity)

Coherent diffraction imaging is readily available

Nanoscopium after upgarde with a round small beam (simple estimation)

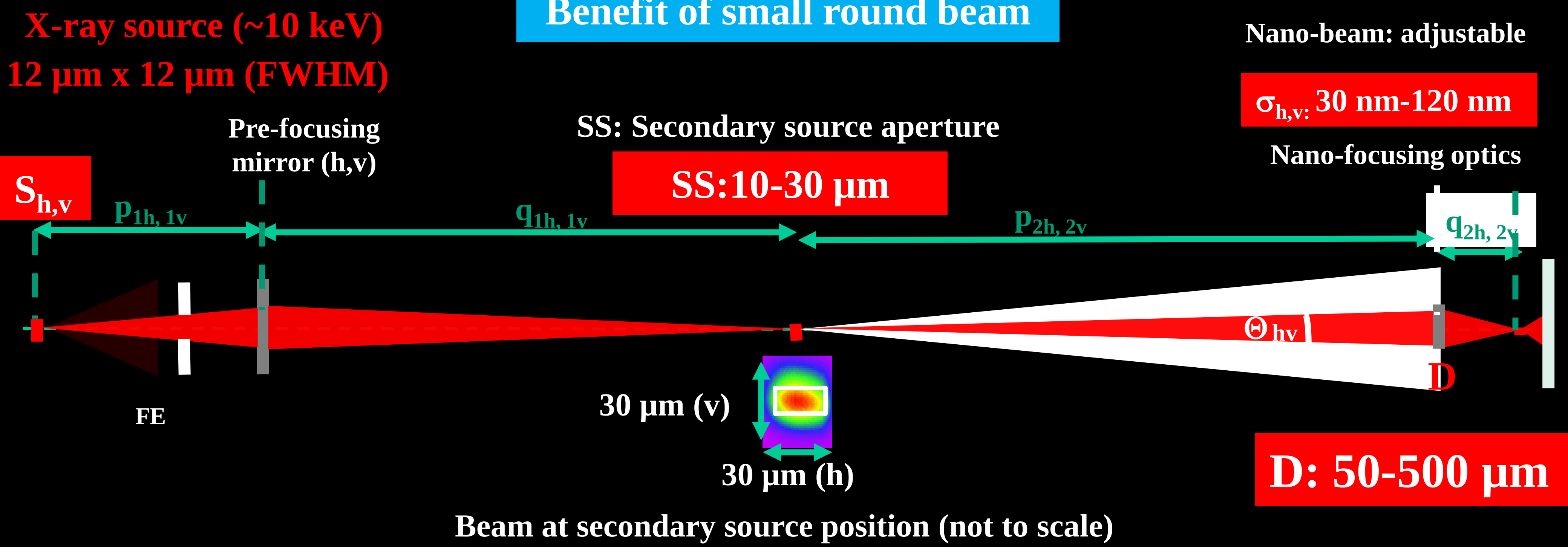
Supposed emittance: 45 pm rad

		actuel	nouveau
	sigmax [µm]	265	5
	sigmaxp [µrad]	25	9
	sigmaz [µm]	9,5	5
	sigmazp [µrad]	4,1	9

Supposed for the estimation: recent optical layout, « perfect » BL optics, no overhead in case of motor motion

Optical scheme of Nanoscopium: two stage focusing scheme in both directions

Benefit of small round beam



Expect nearly direct translation of increased brightness (~60 x) into the focused flux into smaller beam-size.

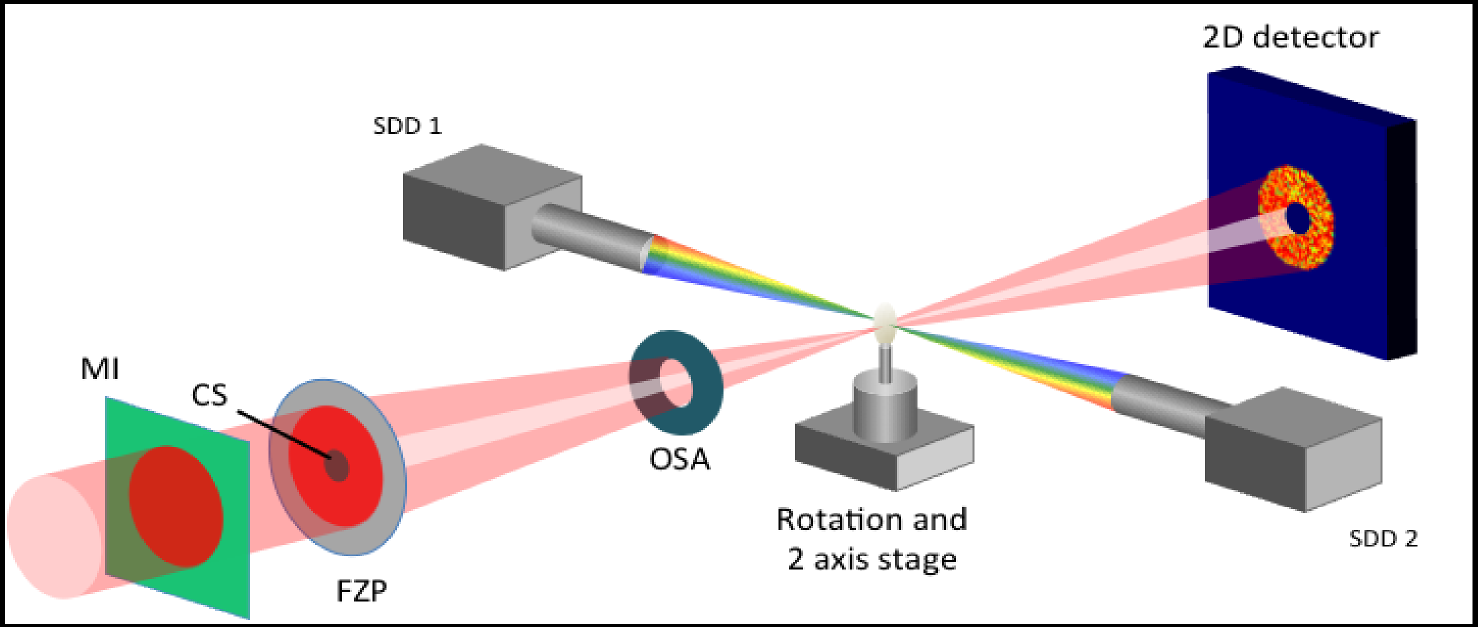
Expected flux at the spectro-microscopy (KB mirror) station at E=16 keV: in 120 x 120 nm^2 ~10^{12} photons/s

With the recent optical scheme

Scanning multitechnique hard X-ray imaging at Nanoscopium

Experimental techniques:

Simultaneous measurement of X-ray Fluorescence (XRF)/Differential Phase (DPC), Scattering and Absorption contrasts coherent scatter imaging (ptychography)



Parallel and fast acquisition

"FLYSCAN": fast detection scheme, down to 1-2 ms dwell time/pixel

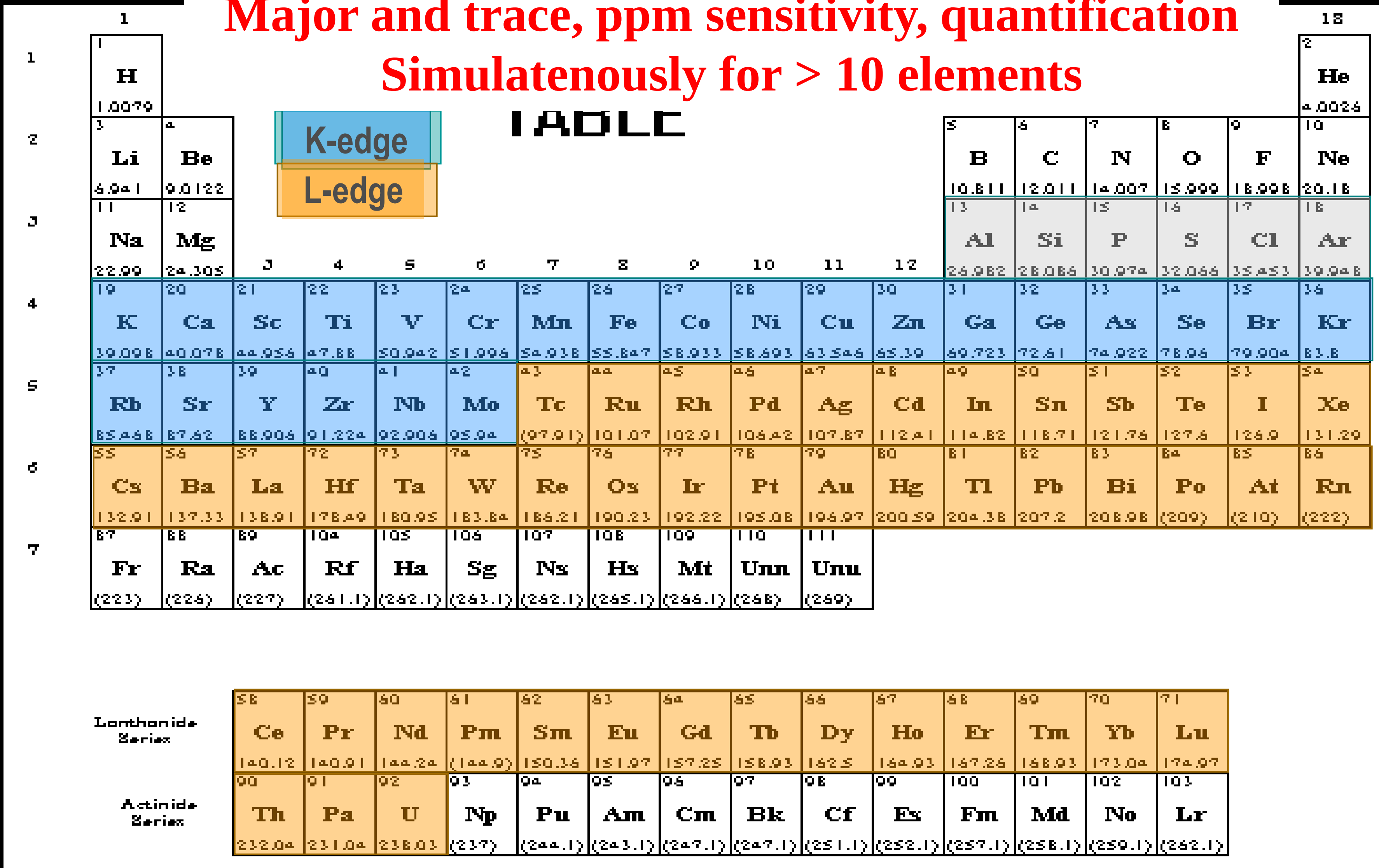
Nanoscopium: scanning hard X-ray nano-probe

Energy range: 5-20 keV

XRF: K-edge: Al-Mo, L-edge: Mo-U

Major and trace, ppm sensitivity, quantification

Simulatenously for > 10 elements



Main scientific user communities of the beamline

- Earth sciences, paleo-geobiology
- Biology, medical sciences

Complex heterogeneous systems

Buried structures

Hard X-rays: sample thickness >10-100 µm

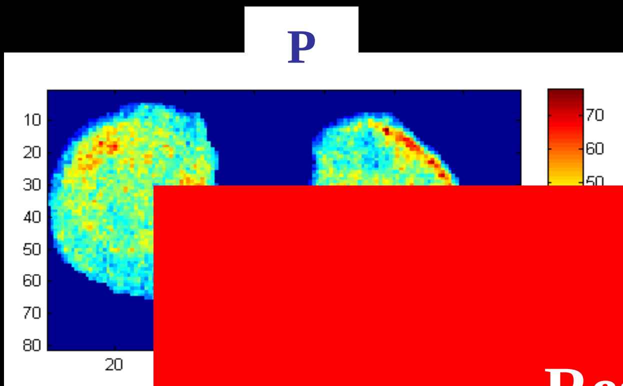
An important challenge is to study the relationship between morphology and chemical composition

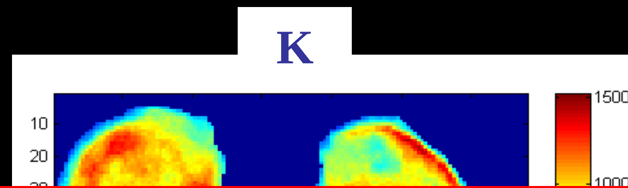
Biology, medical sciences

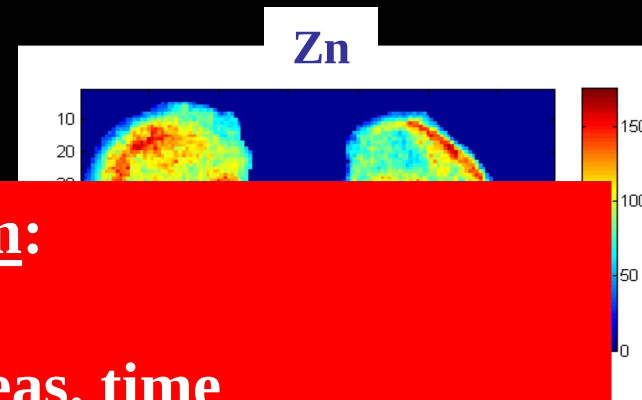
single cells

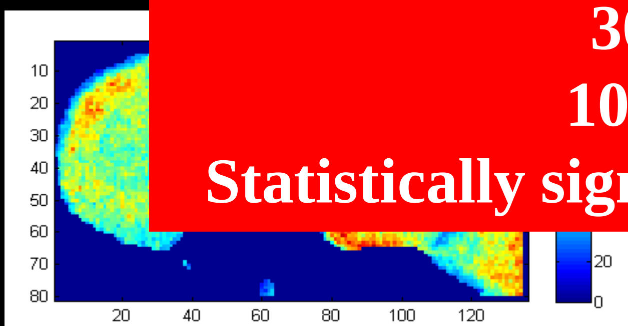
Sensitivity for ultra-trace trace metals is crucial

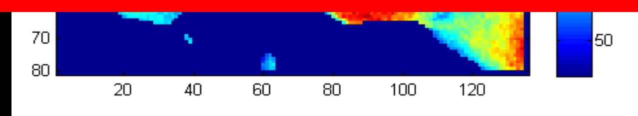
User proposal:
beam-size: 300 x 300 nm^2











<u>With small round beam</u>:

40 ms per pixel

Resolution	Total meas. time
300 x 300 nm^2	7 min
100 x 100 nm^2	1 hours

Statistically significant measurements will be readily available

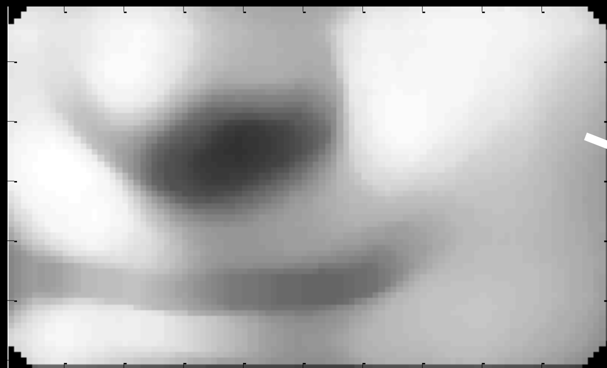
Now, dwell time: 2.4 s/pixel, total measurement time: 7 hours
<u>sensitivity for trace trace metals: in the atto-gramm range</u>

Data analyzis and interpretation is in progress

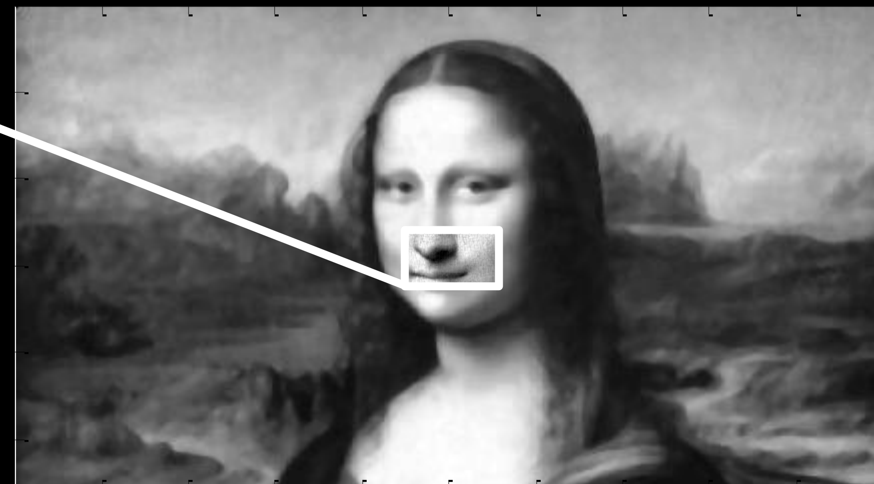
Hierarchical length-scale imaging

Intense Round beam, moderate resolution

~10 x 10



Total object : 600 x 1000



Measured image

High resolution region: 60 x 100

~1 x 1

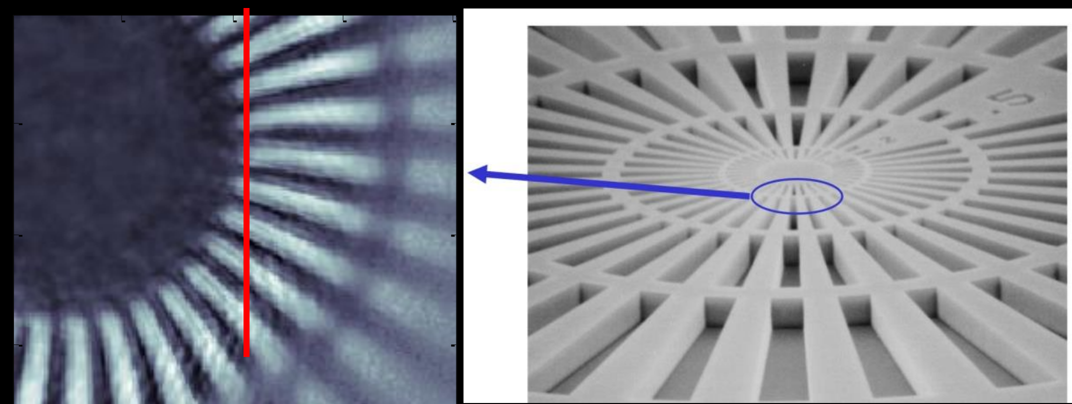
Small Round beam with reduced intensity

We can improve the probe dimension (by pinhole) in trade of with « flux »,
longer measurement time/pixel, in a smaller region

Highly coherent beam today: we spatially filter a partially coherent beam

Ptychograpghy: scanning coherent diffraction imaging

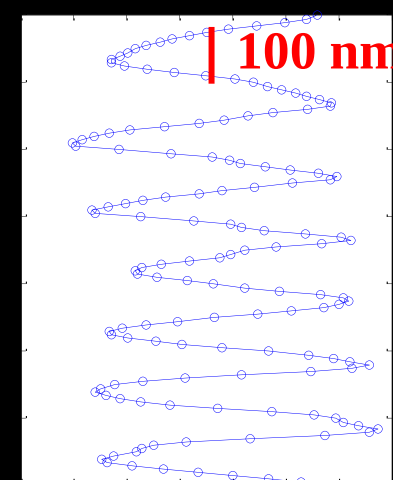
Reconstructed phase Test sample: Siemens star



~500 nm beam size at sample position
50 nm motor steps, 1 s/image,
spiral scan with 4000 sampling points
Total measurent time: 1.2 hours
Reconstructed image size: 3.5 x 2.8 μm^2
Reconstructed pixel size: 14 nm

<u>Resolution: ~35 nm</u>

<u>After upgrade</u>:
16 ms per pixel
Total: 1.2 minutes
3D ptychraphy becomes available for users

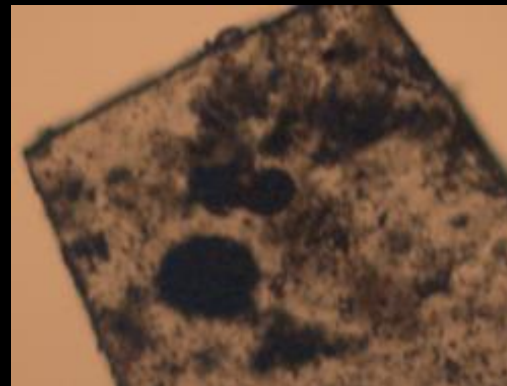


<u>increased data rate and spatial resolution</u>

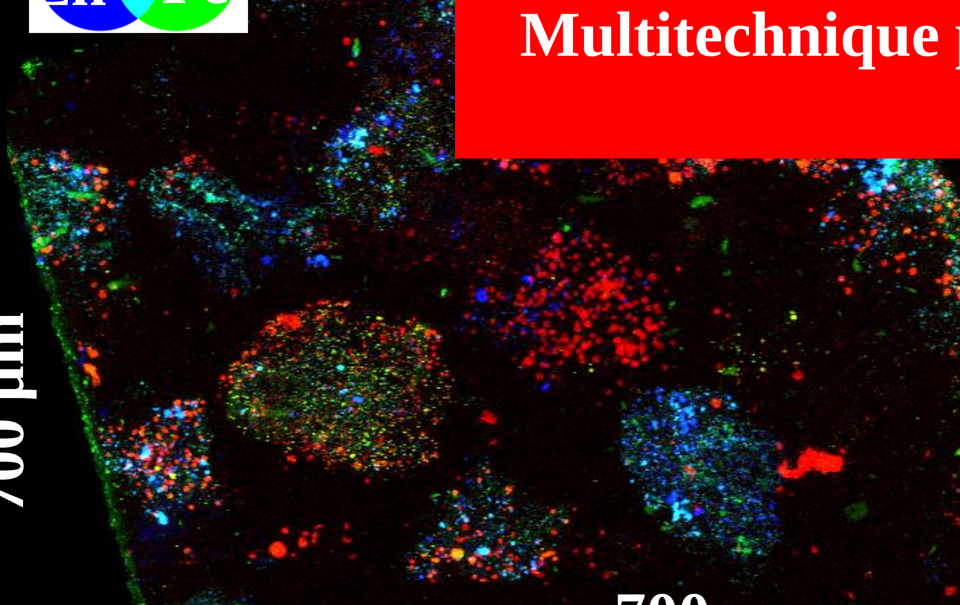
DLSR: high degree of transverse coherence

Scanning hard X-ray multitechnique tomography

Sample thickness:
100 µm



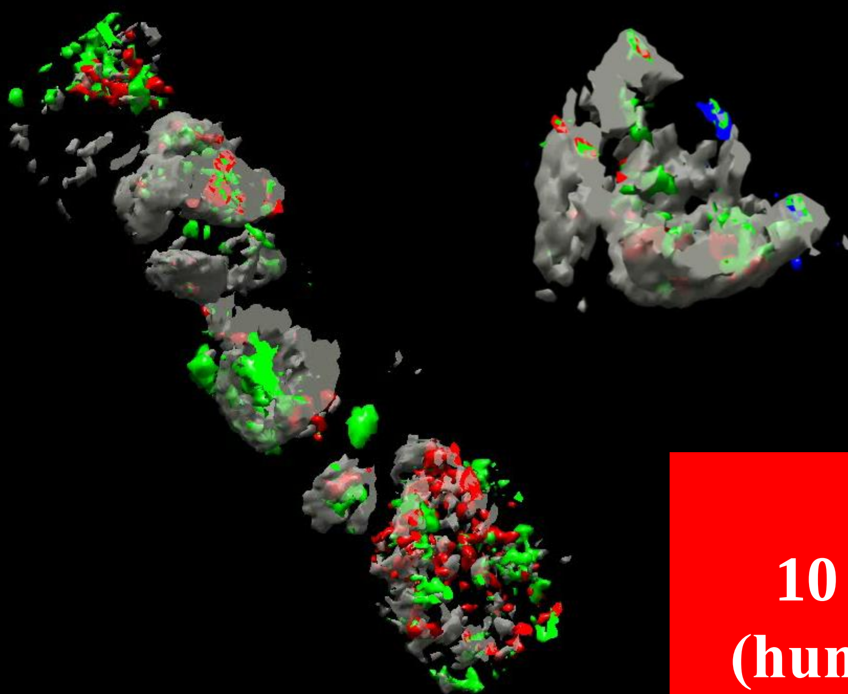
Multitechnique projection today: 10 ms/pixel



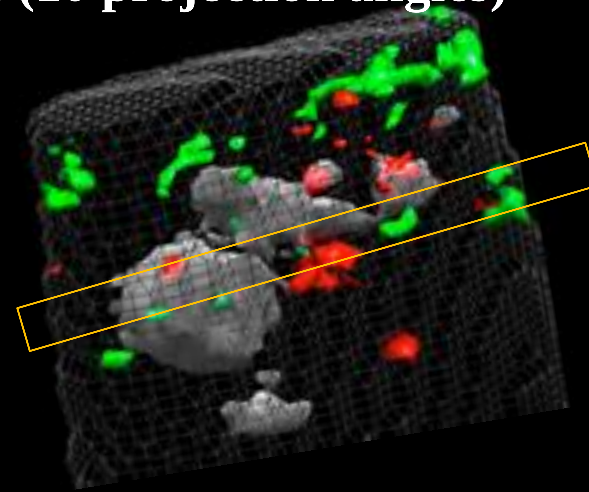
Multitechnique projection image: 0.17 ms/pixel after upgrade

Scanning hard X-ray multitechnique tomography

Dark-field: strongly scattering material



Draft 3D reconstruction of the whole sample (10 projection angles)



As

Fe

Zn, Cr

<u>After upgrade</u>:
10 slices of 2 μm resolution of a similar (hundreds μm's size) sample: in 4 minutes

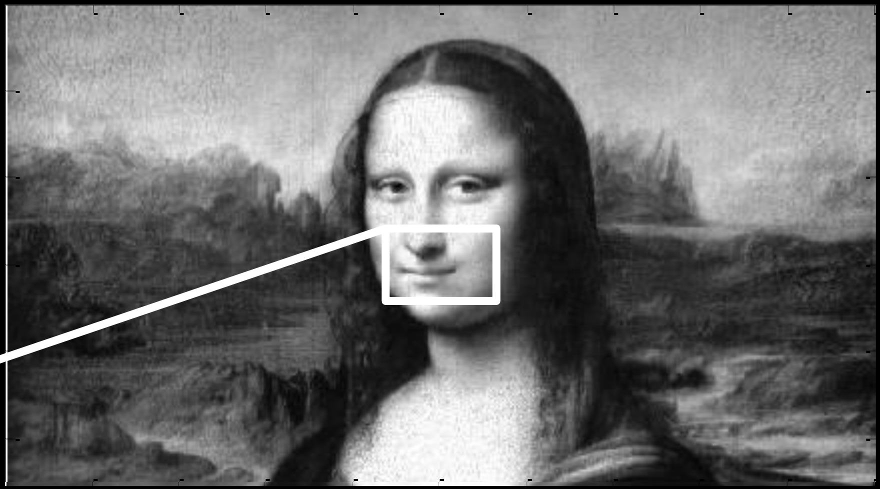
the whole 3D image can be obtained with μm resolution in some hours

Today, total: in 4 hours 10 slices
Moderate (2x2x2 μm^3) resolution due to the large sample size

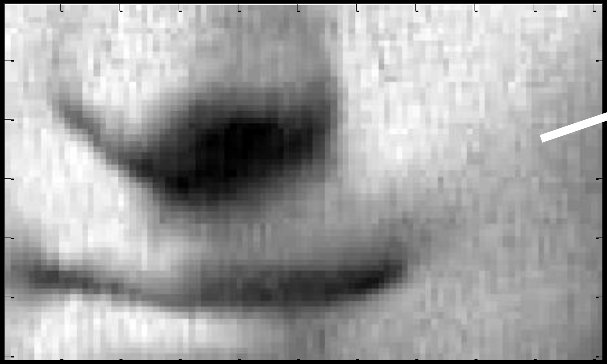
Conclusion

With a new 60-100 x brighter round probe: we could measure the whole object with high resolution within the same time

Total object : 600 x 1000



High resolution area: 60 x 100



~1 x 1

Measured image

Hierarchical length-scale imaging

With a new 60-100 x brighter round probe:

With chemical (XANES) contrast
3D tomography

Beautiful technical challenges (detectors, sample positioning, stability, optical quality, data treatment, automatic sample preparation and handling, radiation damage)

Thank you for your attention !

Scanning tomography on time scales of minutes

Speed…. Field of view, statistics

Large 2D samples at simultaneous high resolution

Visualizing nanoscale structure across macroscopic fields of view

to increase spatial, temporal, compositional and chemical resolution/contrast

ICA

ECA

Gr. Vide

Gr. Mechanique

Gr. Det.

Gr. Optic

Gr. Alignment

Bat./Infra

Gr. Eng.

Collaborators

Merci pour le support, aide et contribution des colleques de Soleil