X-ray phase imaging with grating interferometers

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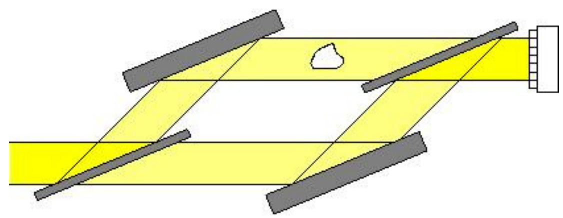
11 July 2005

Motivation

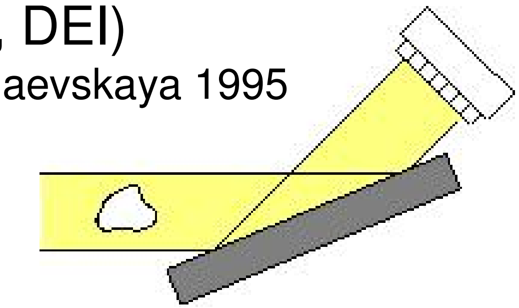
- Hard X rays well suited for radiographic imaging (long penetration depth, negligible refraction)
- General setup uses **absorption contrast:** Area detector behind sample records intensity variations caused by attenuation profile of the sample
- **Tomography:** taking 2D radiographs at different viewing angles yields 3D distribution $\mu(x,y,z)$
- But for **light materials** (biological tissue, polymers...), and **high photon energies**, **absorption contrast is relatively weak**
- Better image contrast would result in
  - **Shorter exposure times** (materials science applications)
  - **Reduced dose deposition** (biology, medical imaging)

Phase radiography methods

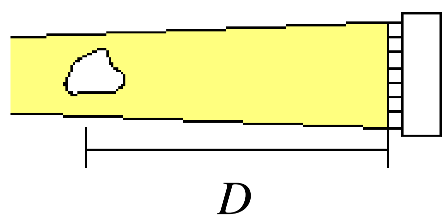
Crystal interferometers
Bonse & Hart 1965



Analyzer-crystal based
("diffraction-enhanced
imaging", DEI)
Ingal & Beliaevskaya 1995



Free-space propagation
("Inline phase contrast")
Snigirev 1995, Wilkins 1995, Cloetens 1996



→ Lots of different schemes already

Why yet another method?

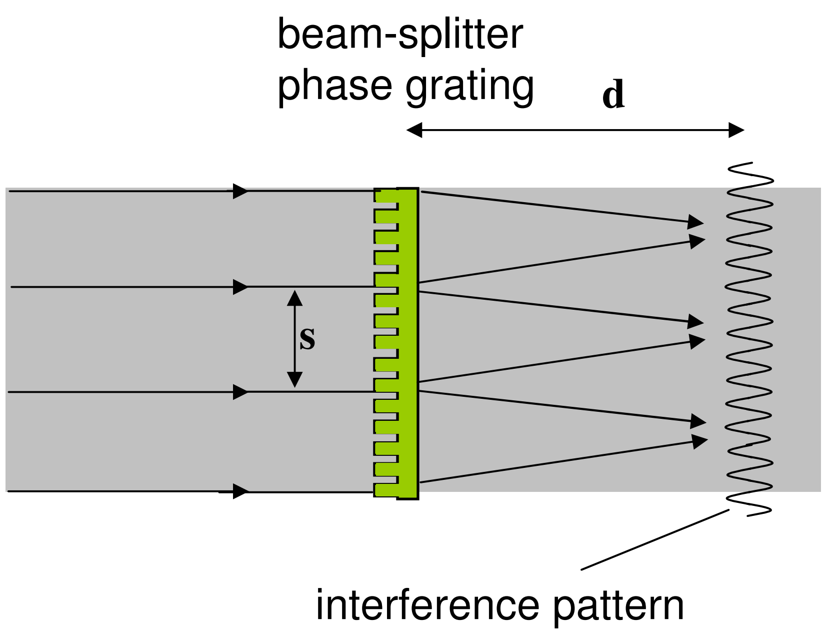
- For the combination of...
  - large field of view (moderate resolution),
  - possibility of use with an X-ray tube source,
- ... the existing methods have problems:
  - Bonse-Hart: crystal size limits FOV
  - DEI: monochromaticity, collimation → needs SR
  - FSP: excellent for high resolution, but at moderate resolution, large distances required
- Grating interferometer: may fill this domain

Grating interferometry

- Phase grating as a beam splitter
- Wavelength ≈ 1 Å, grating period ≈ 1 µm

→ small diffraction angles

→ beams overlap

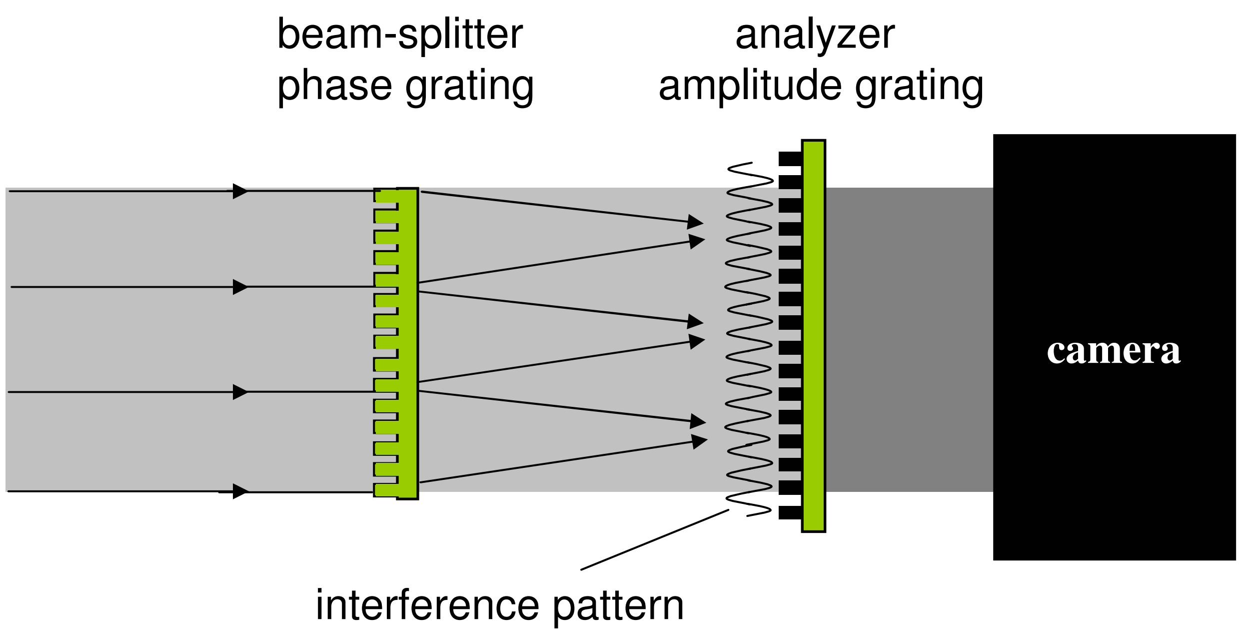


How can we detect the local fringe position?

Grating interferometry

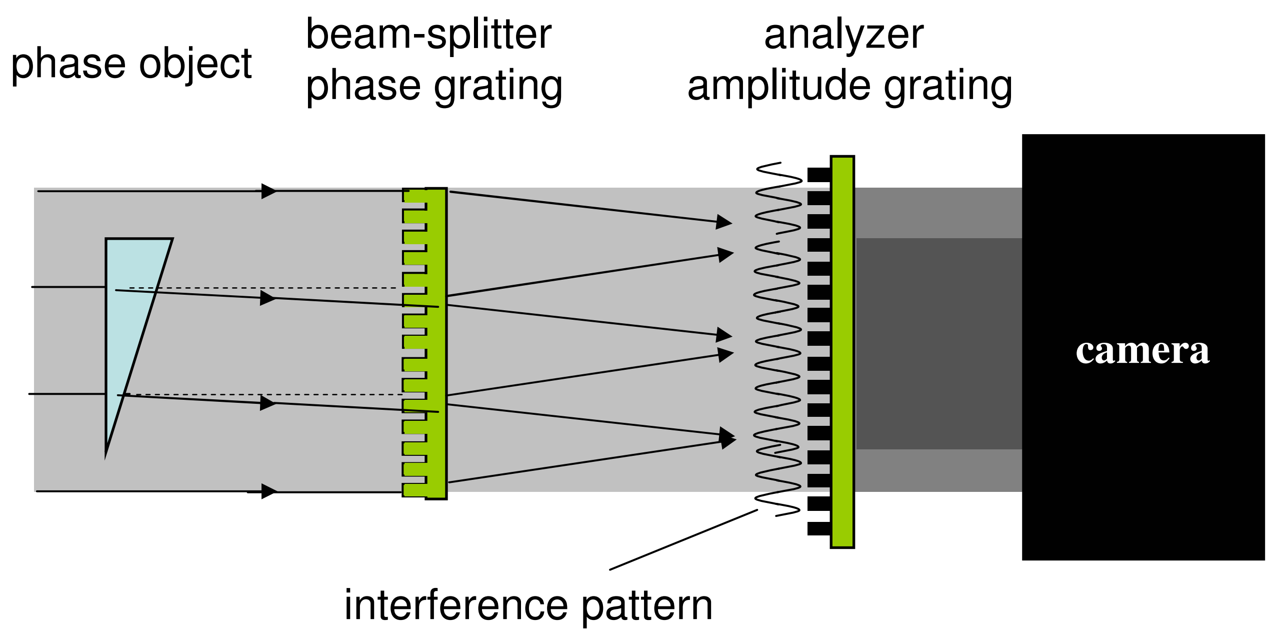
- Absorption grating with same period as fringes
- Acts as transmission mask (not as diffractive element!)
- Transforms fringe positions into intensity signal

  → May use detector with pixels larger than fringe width



Grating interferometry

- Object in beam
- Distorts wavefront, i.e., deflects beam
- Fringes locally displaced
- Different intensity on detector
- Intensity correlated to first derivative of wavefront phase

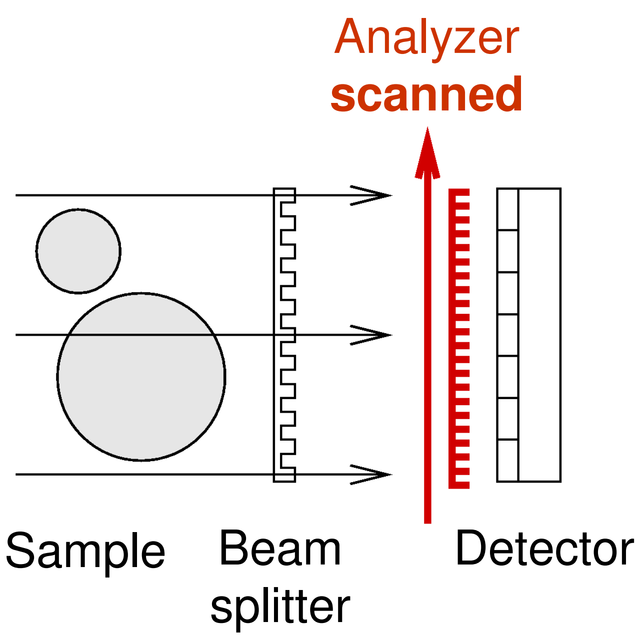


→ Differential phase contrast imaging

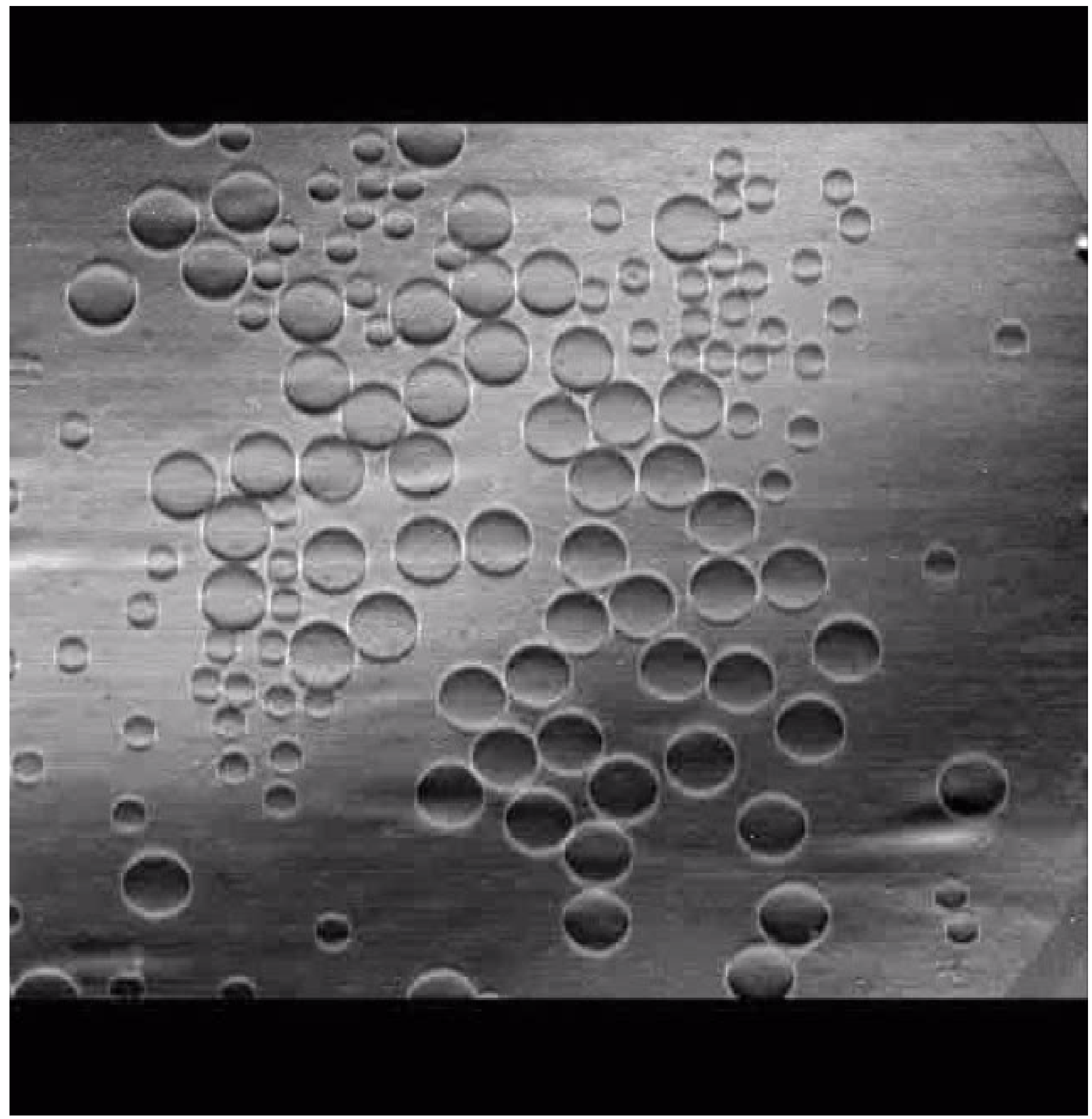
But how to separate phase information from absorption?

Phase-stepping interferometry

Linear transverse scan
of one of the gratings:
→ signal oscillates

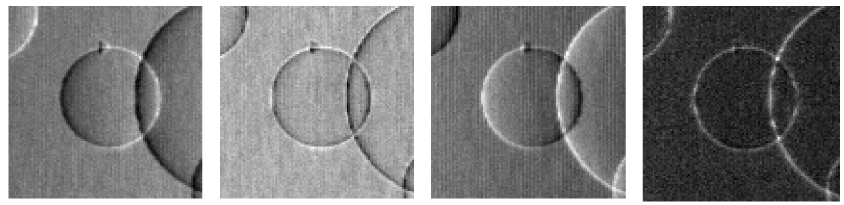


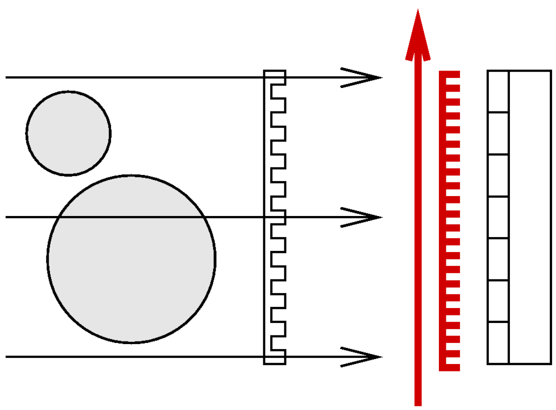
(sample here:
polystyrene spheres
Ø 100 and 200 µm)



ESRF BM5, E=12.4 keV, p_1=4 µm, p_2=2.004 µm

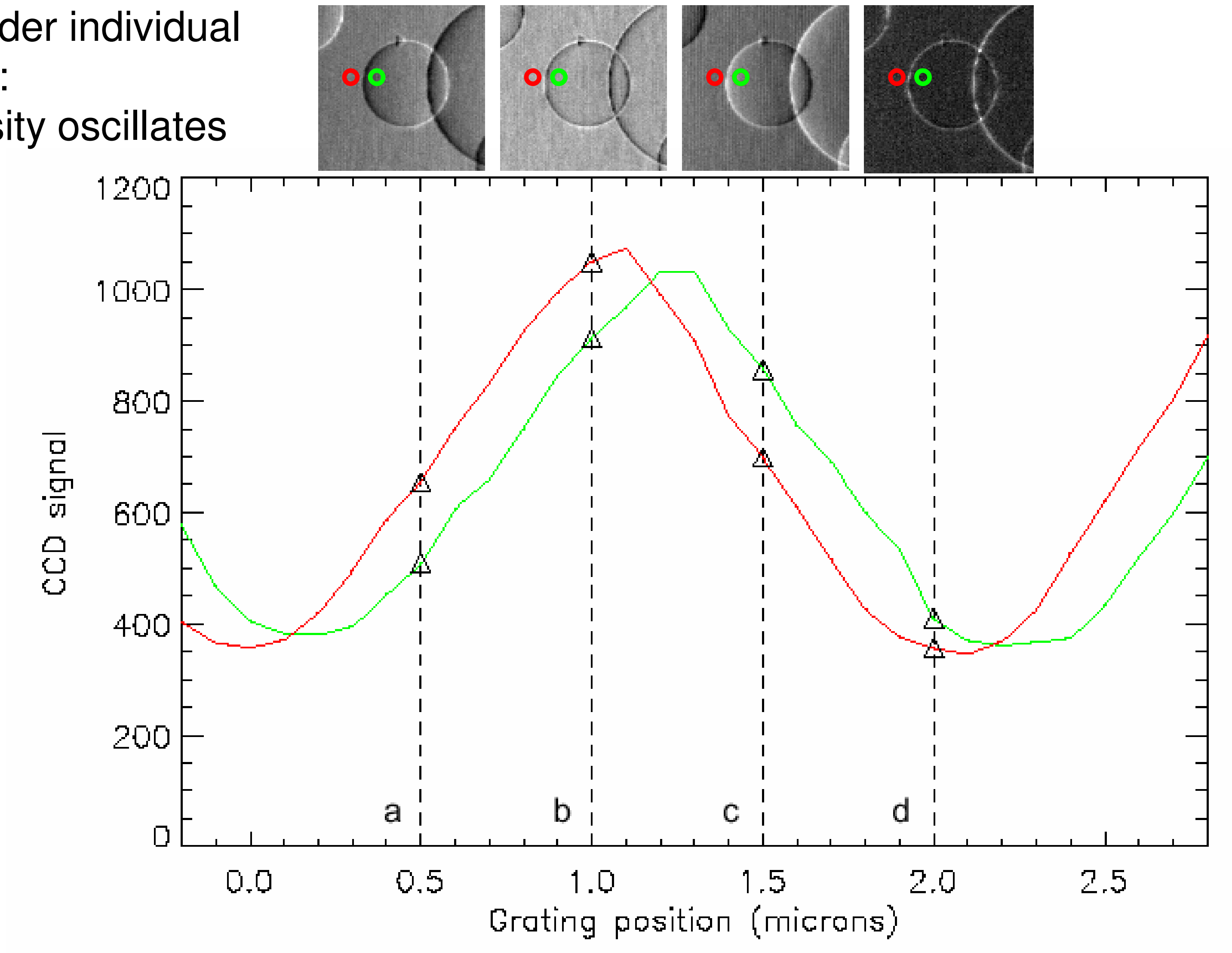
Phase-stepping interferometry



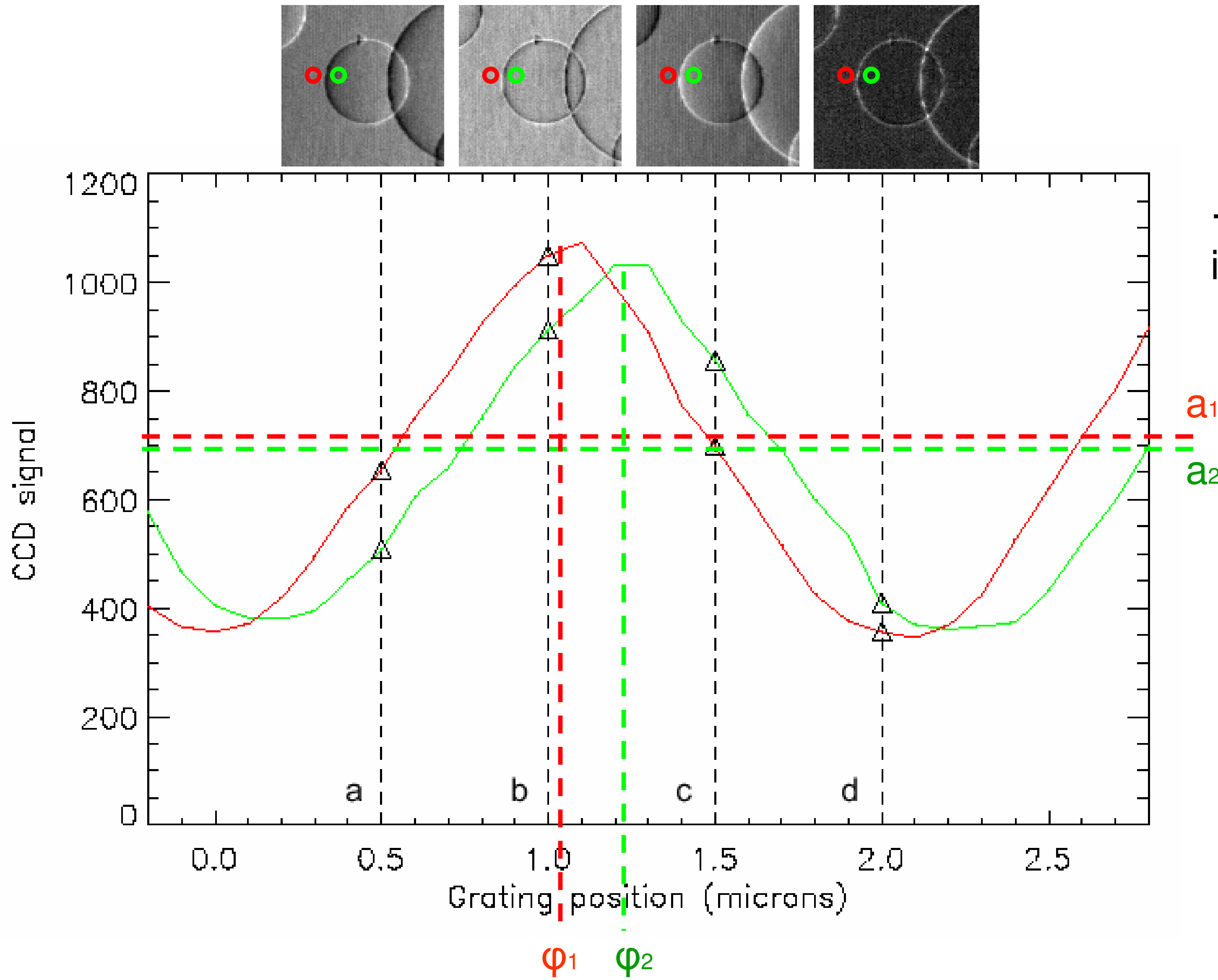


Phase-stepping interferometry

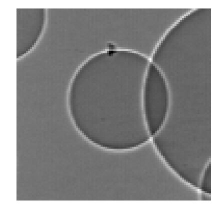
Consider individual pixels:
Intensity oscillates

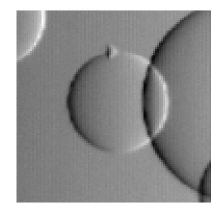


Phase-stepping interferometry

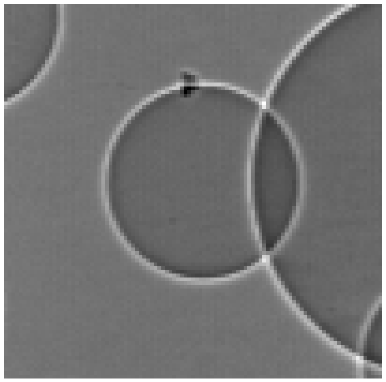


→ Processed images:



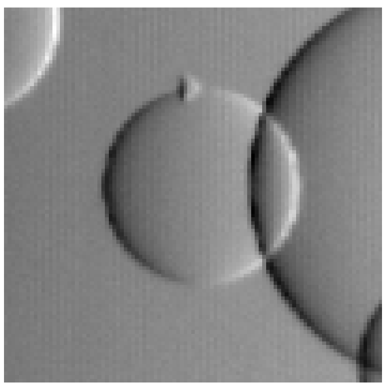


Phase-stepping interferometry

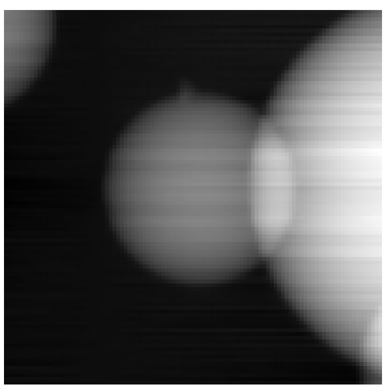


a_{ij} Mixture of absorption and inline phase contrast
--- **the same image that would be observed without the interferometer in the beam**

(suited for tomographic reconstruction)



φ_{ij} **Phase gradient image** (perpendicular to grating lines)
--- all absorption contributions eliminated

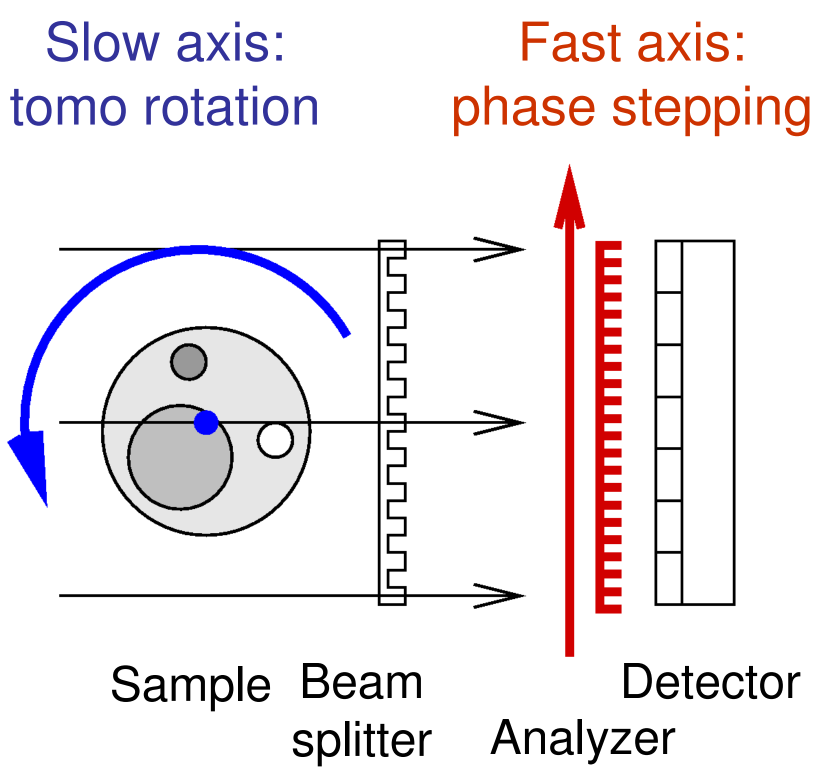


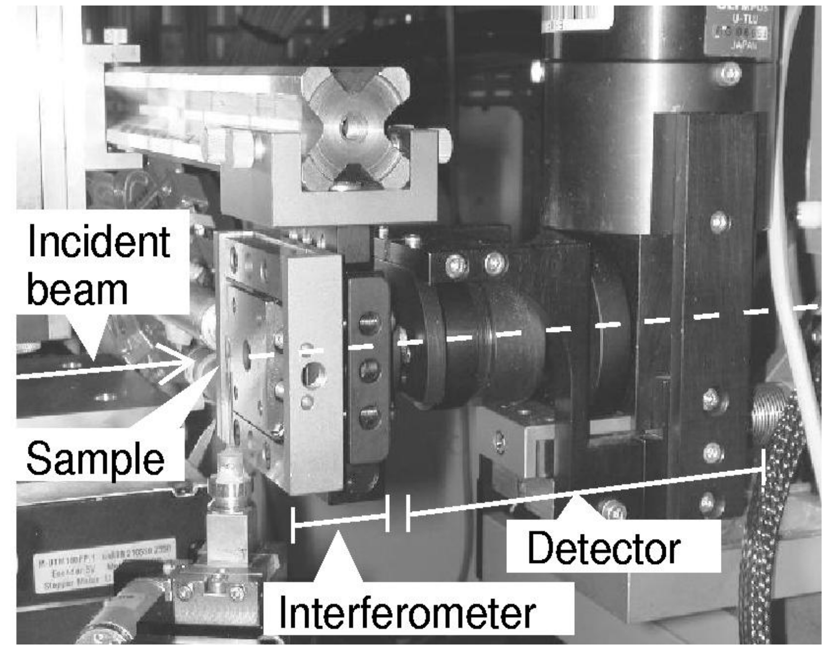
Can be integrated to yield projected phase shift of sample

→ Suited for tomographic reconstruction

→ Quantitative: $\frac{\partial \Phi(x,y)}{\partial x} = \frac{p_2}{\lambda d}\varphi(x,y)$

Phase-stepping tomography



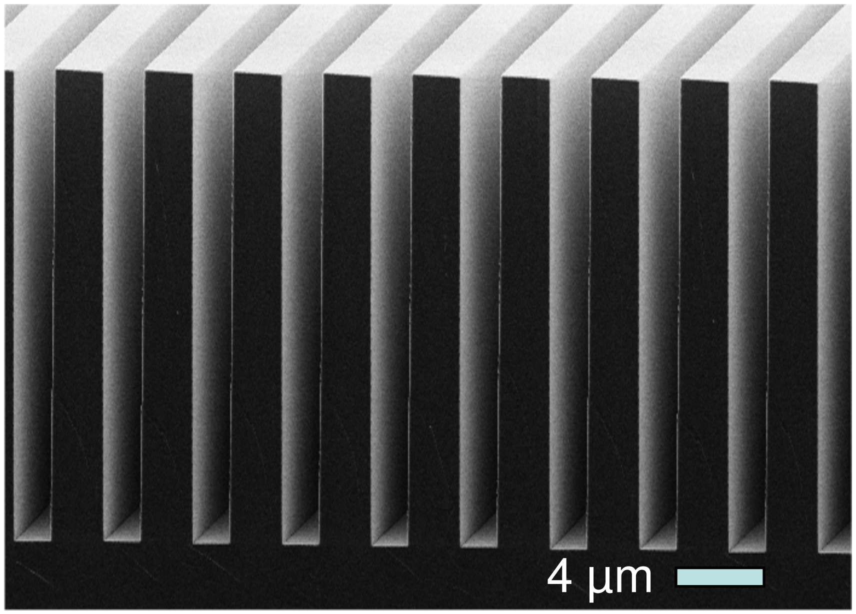


ESRF ID 19, June 2004
E=12.4 keV, p_1=4 µm, p_2=2 µm, d=23 mm

- Two scan axes: projection angle and interferometer phase
- Number of projection angles: 100…1000
- Number of phase-stepping points per angle: 4 or more
- Results: 3D distributions $\delta(x,y,z)$ and $\mu(x,y,z)$

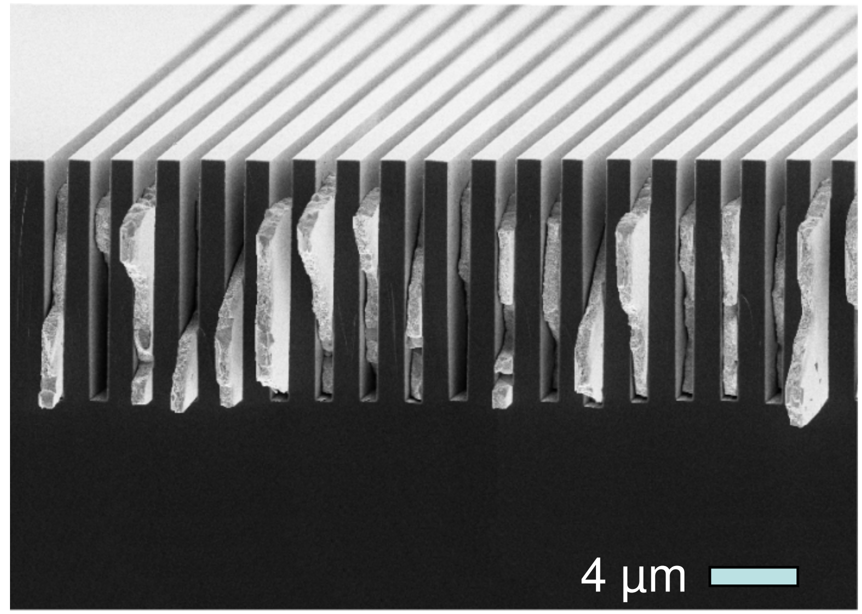
Beam splitter phase grating (p = 4 µm) and analyzer absorption grating (p = 2 µm)

Phase grating (Si)



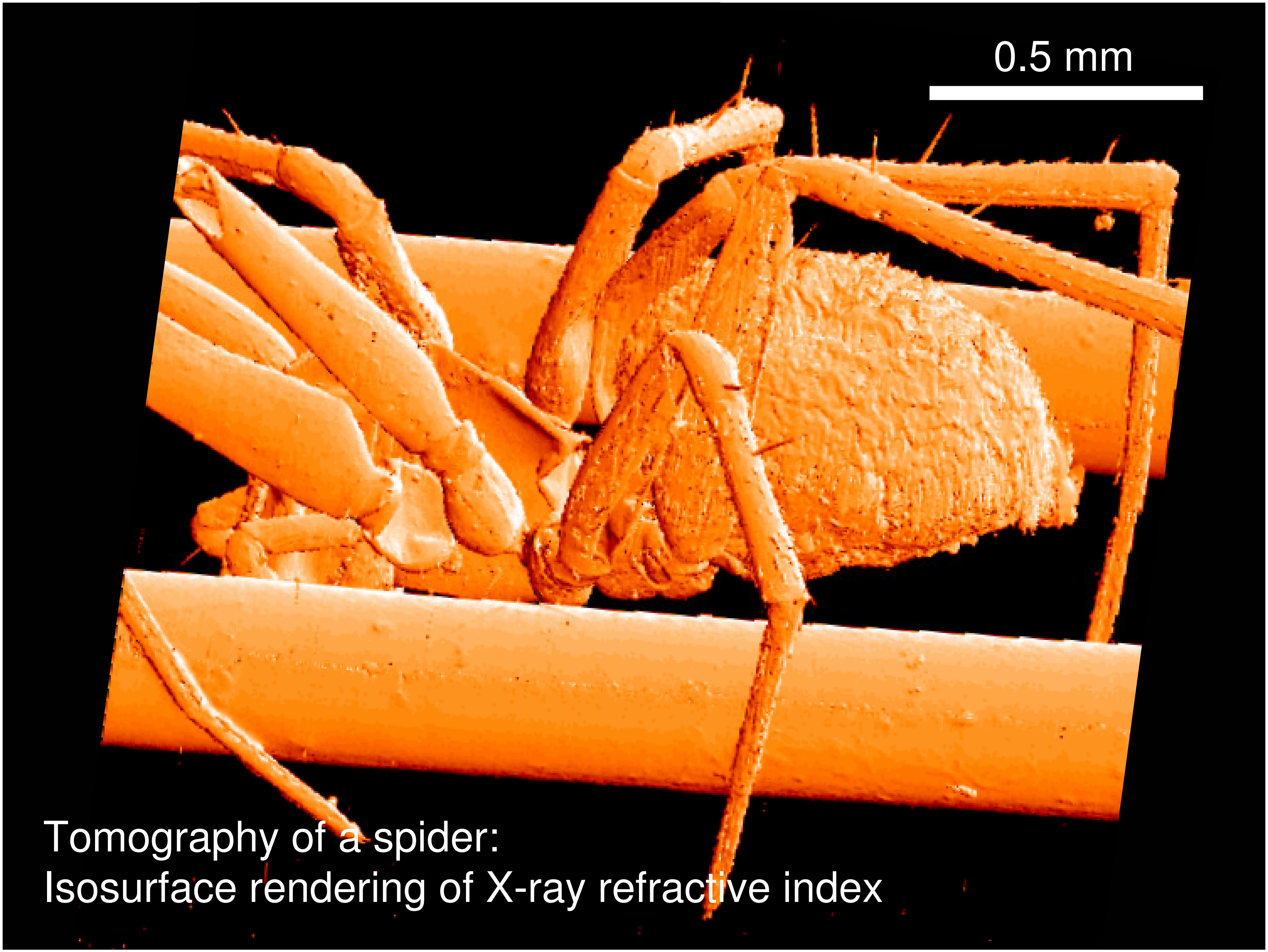
- Silicon wet-etched
- Depth of structures chosen so that phase shift is π → no zero order
- → Efficiency limit: 80 % (fraction of useful photons)

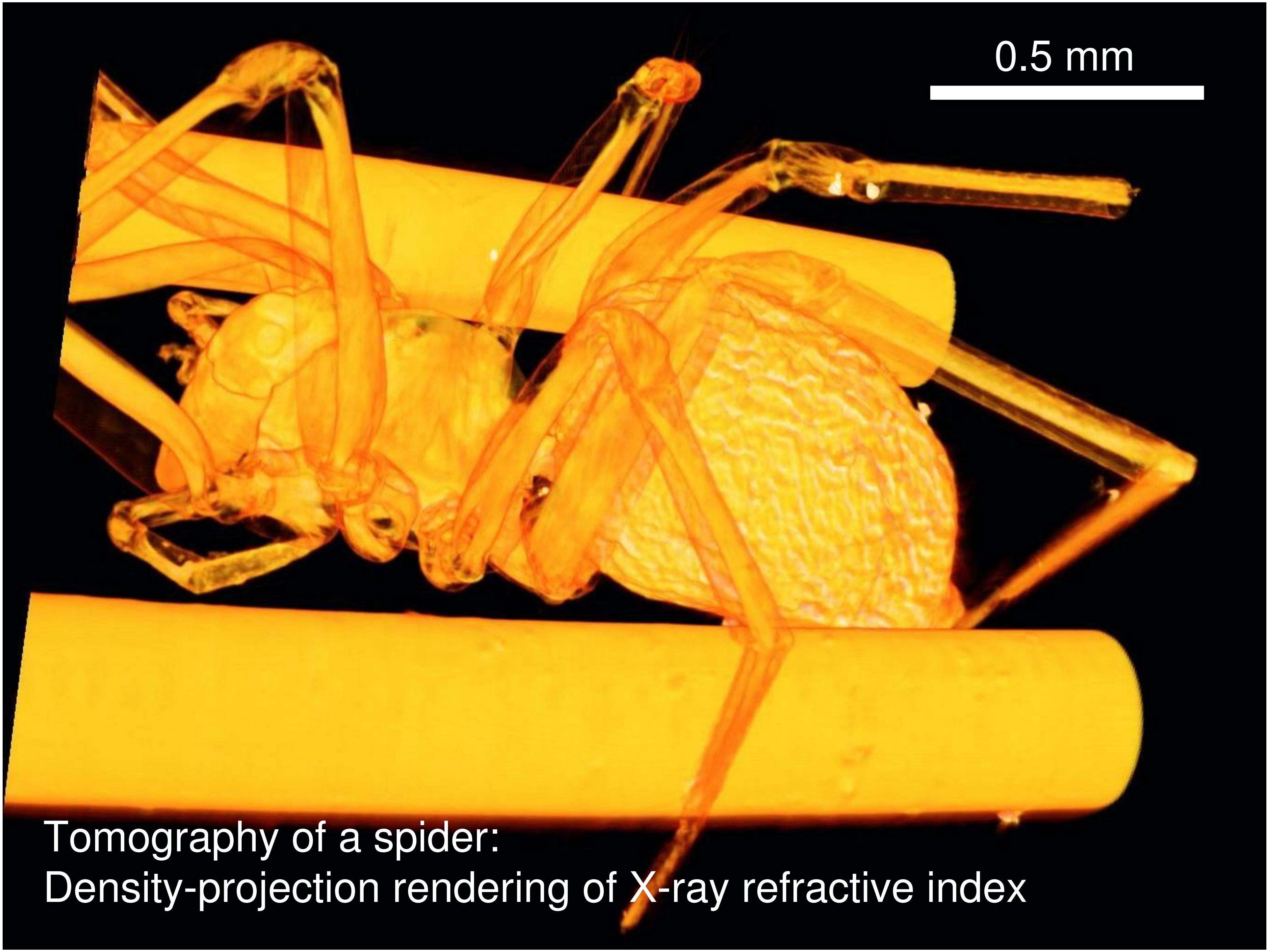
Absorption grating (Au in Si)

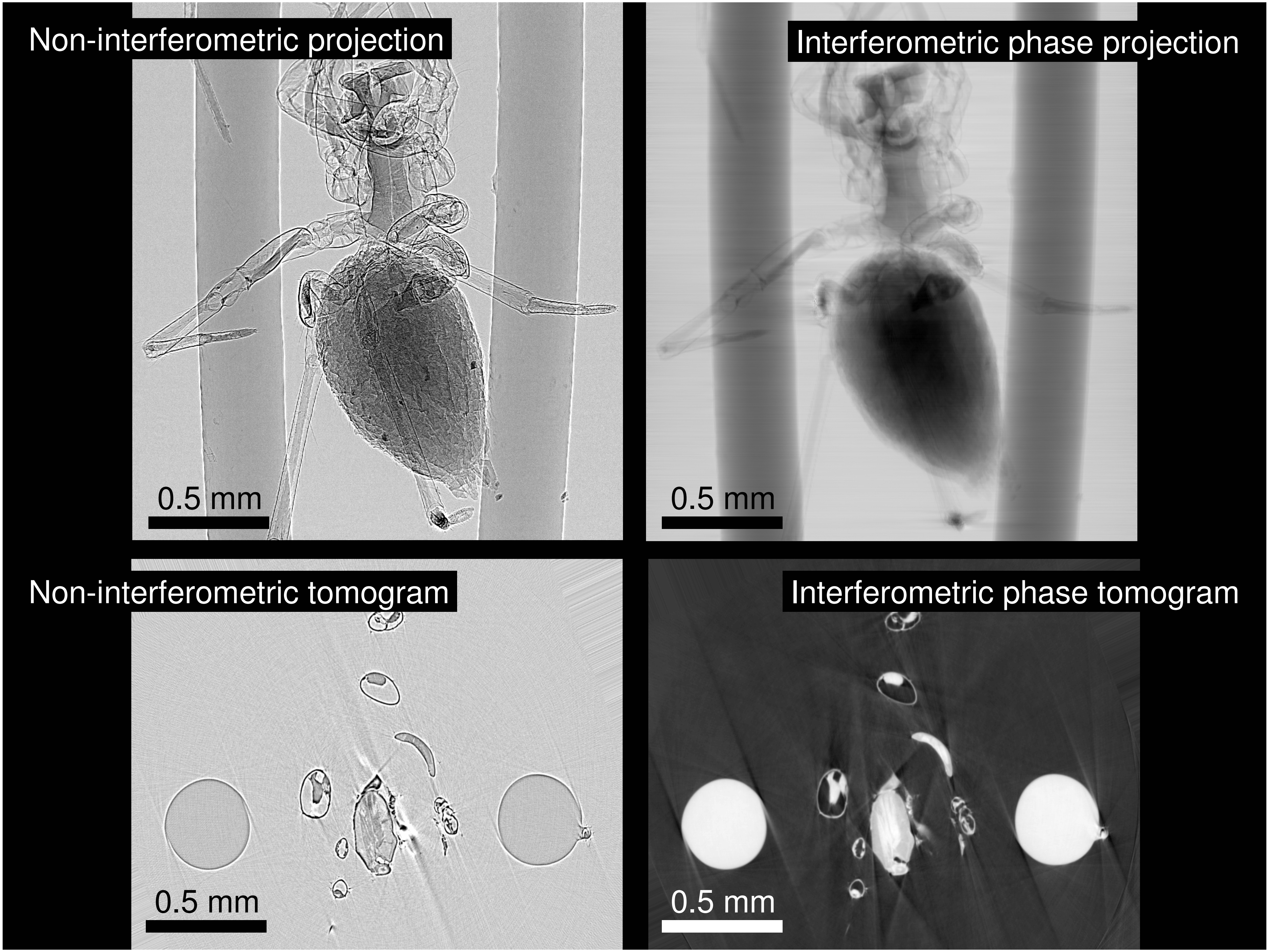


- Gold in gaps of silicon grating
- Grown electrochemically
- Period is half that of Si grating
- Efficiency limit: 50 % (fraction of transmitted intensity)

→ Poster P9, A. Diaz et al.

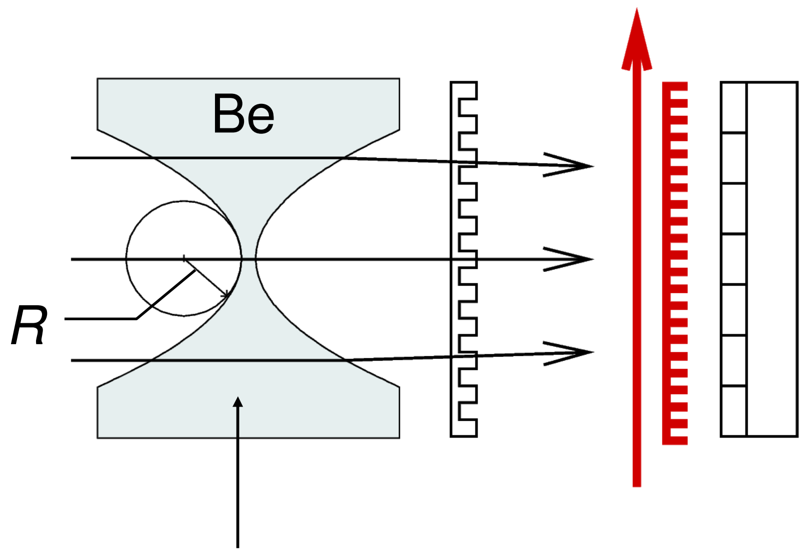

0.5 mm
Tomography of a spider:
Isosurface rendering of X-ray refractive index


0.5 mm
Tomography of a spider:
Density-projection rendering of X-ray refractive index

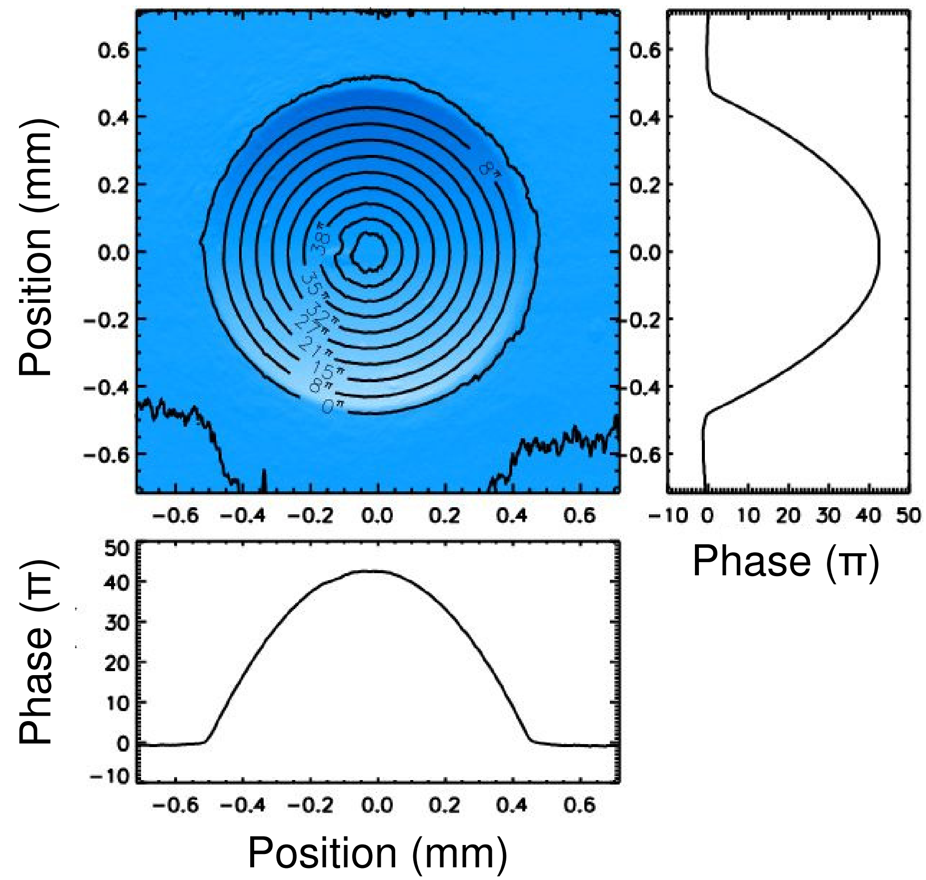

Non-interferometric projection
0.5 mm
Interferometric phase projection
0.5 mm
Non-interferometric tomogram
0.5 mm
Interferometric phase tomogram
0.5 mm

Quantitative phase reconstruction I

Example: phase profile of parabolic refractive lenses

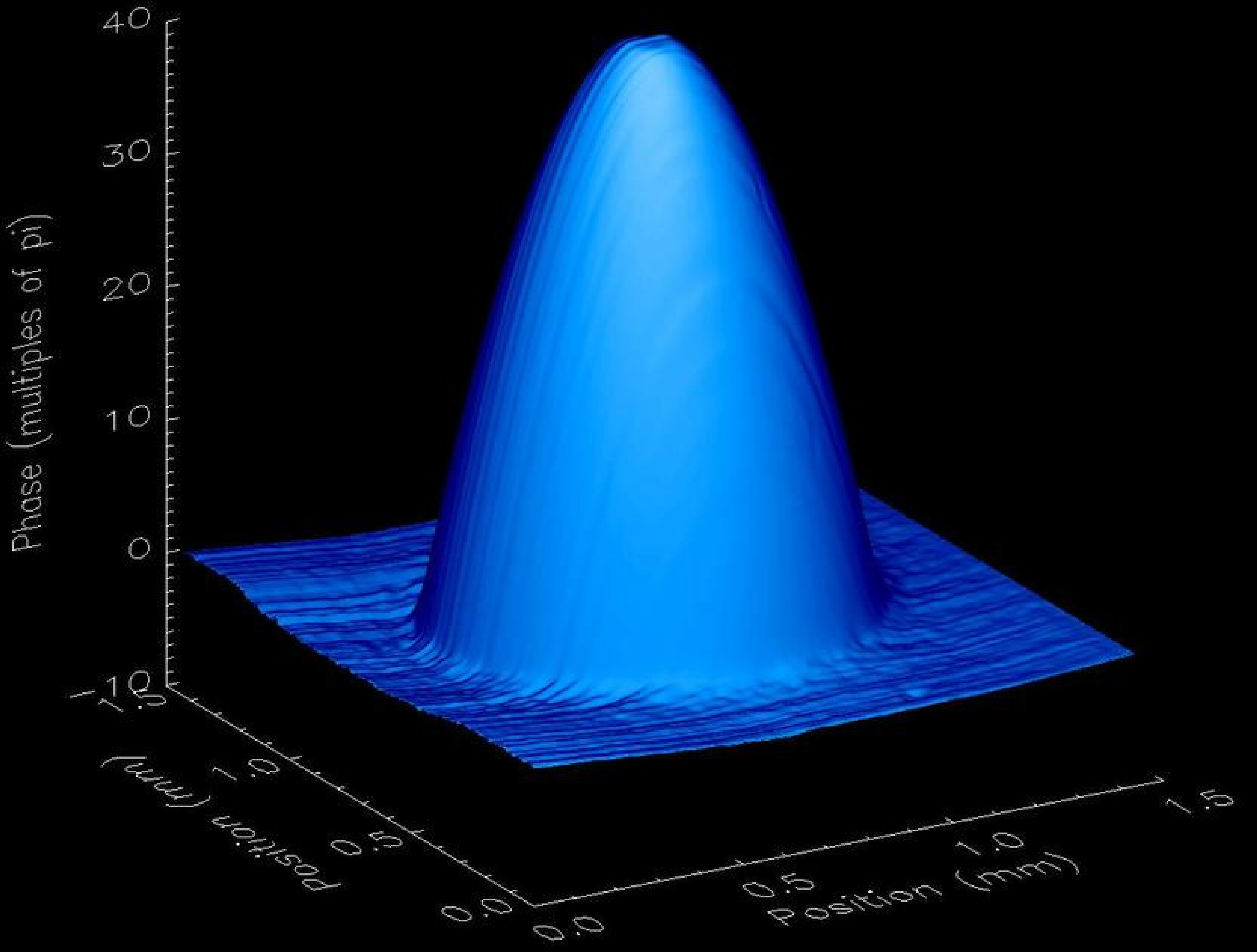


Beryllium refractive lens,
R=0.2 mm
→ *f*=61 m at 14.4 keV



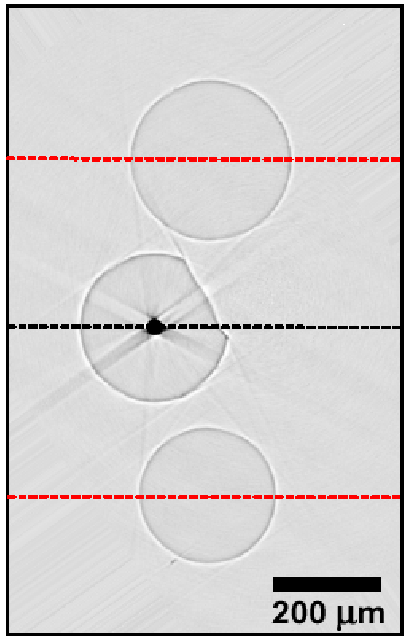
ESRF BM5, 9 June 2005
Collaboration with J. Patommel, B. Lengeler (RWTH), C. Schroer (HASYLAB)

Quantitative phase reconstruction I

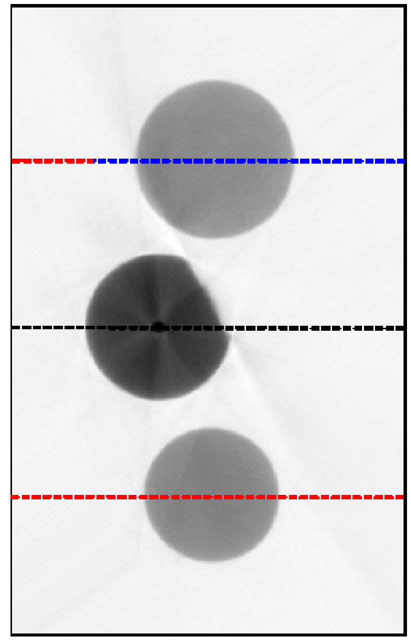


Quantitative phase reconstruction II: pink-beam tomography

Non-interferometric tomogram

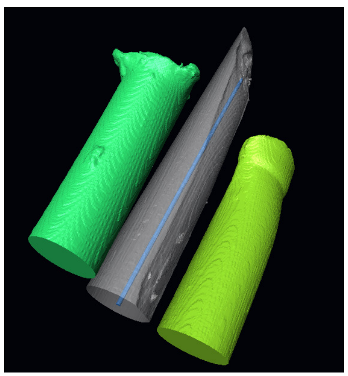


Interferometric phase tomogram

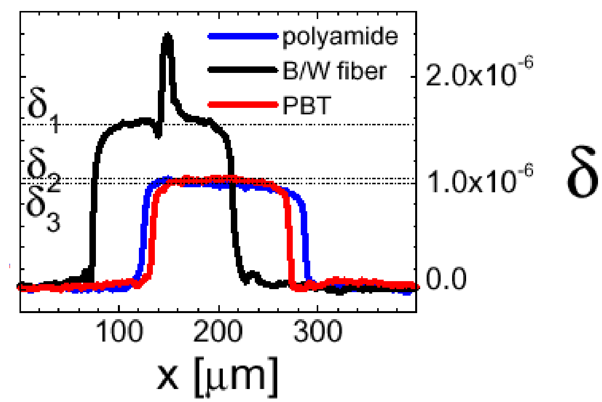


E = 17.5 keV, ΔE = 1 keV

Sample:

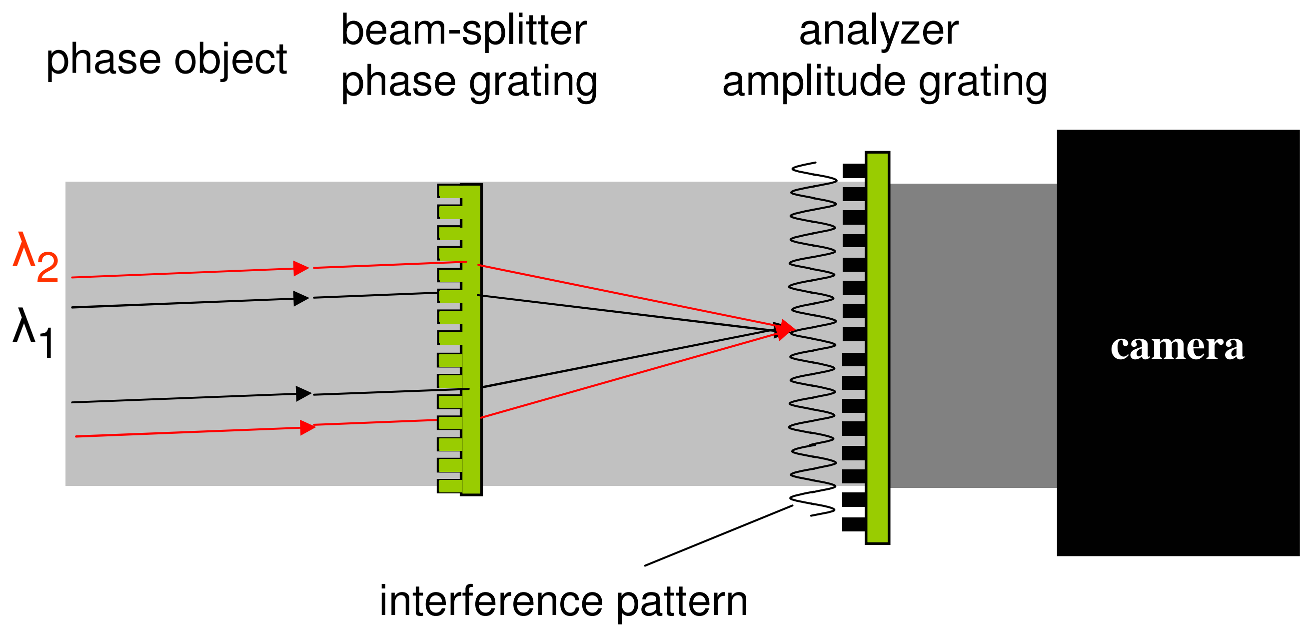


Three fibers
- Polyamide Ø 225 µm
- Boron Ø 200 µm, core: W Ø 10 µm
- PBT Ø 190 µm



SLS Materials Science beamline
July 2004

Polychromatic radiation



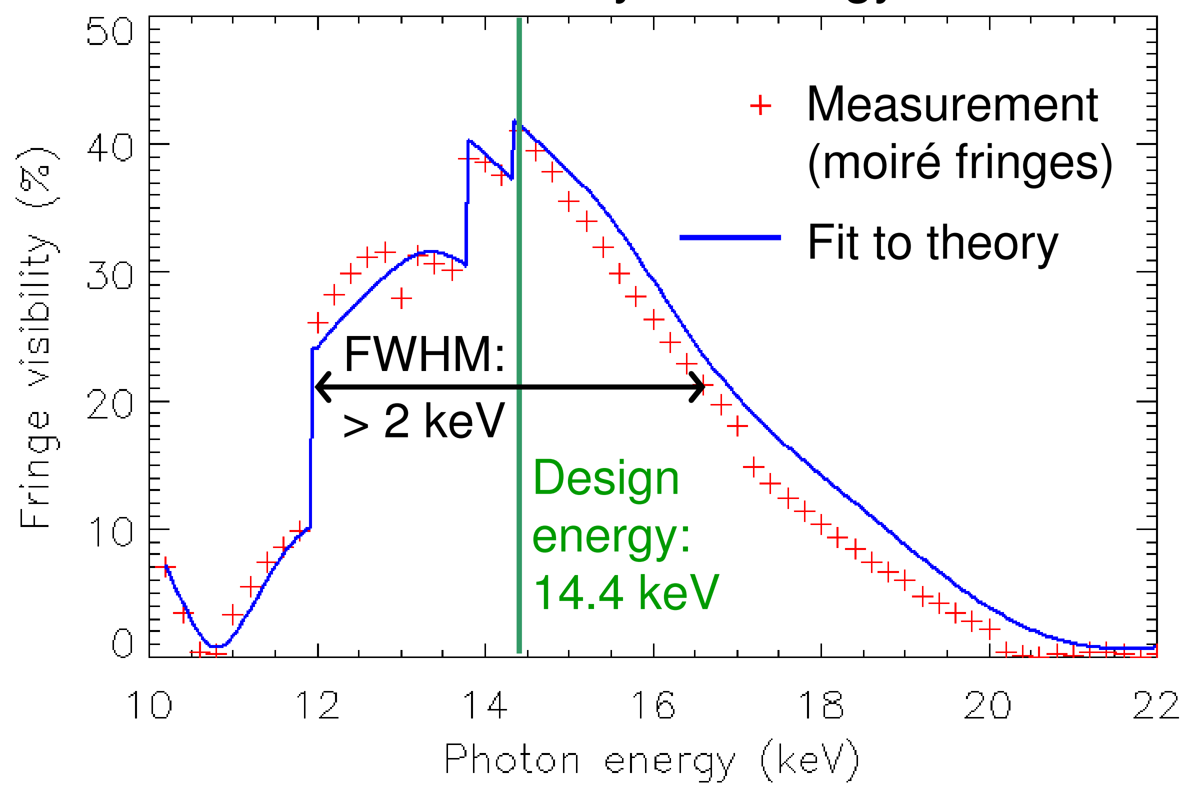
→ Quasi-achromatic instrument

Limits of achromaticity

Effects of energy change (away from design energy) on efficiency of a given setup:

- Inter-grating distance:
  deviates from Talbot condition,
- Beam splitter:
  phase shift deviates from π,
- Analyzer:
  changes absorption.

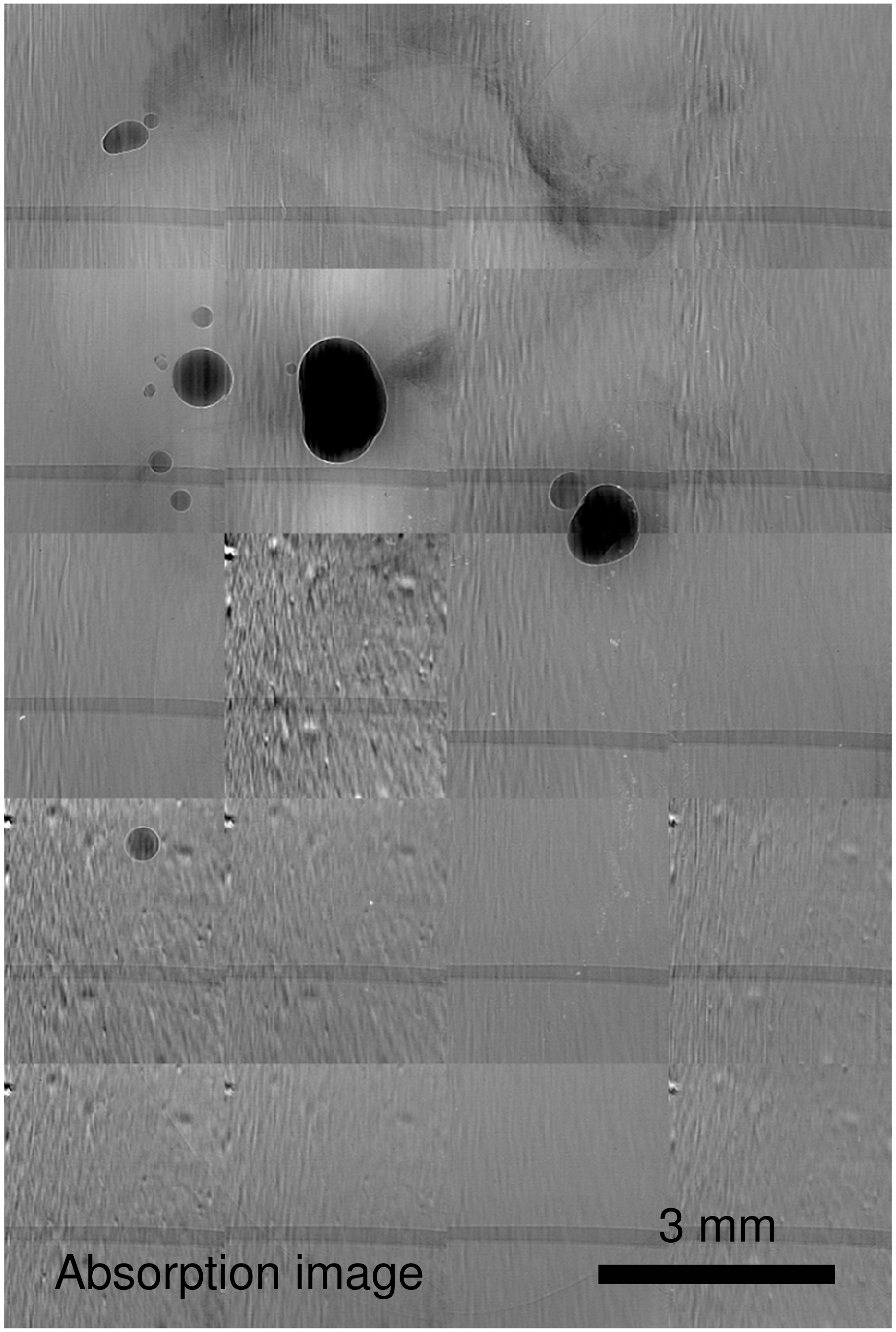
Efficiency vs. energy



(Grating periods p_1=4 µm, p_2=2 m, 3rd Talbot distance d_3=69.7 mm)
Data taken at ESRF BM5, 11 June 2005

Biological tissue samples in aqueous environment

- Conditions similar to natural environment, i.e., to *in-vivo* imaging
- Contrast between tissue and water is very weak, i.e., a real challenge
- Large object, moderate resolution enough → test case
- Our first sample:
  the heart of a rat, in formalin

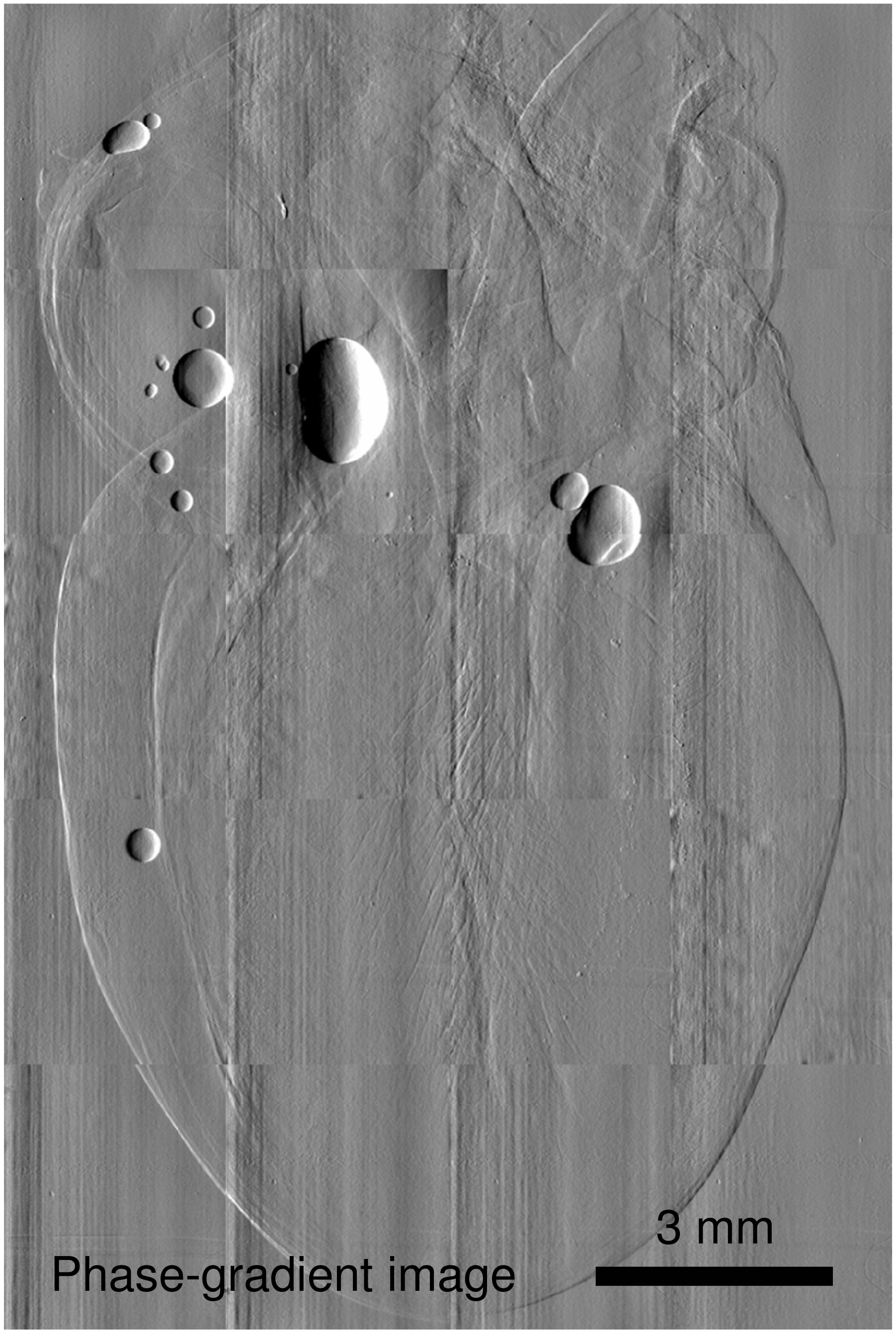


Rat heart in formalin

- Walls of vessels clearly visible in the phase-contrast image
- … but not in the absorption image acquired with the same dose

Pixel size 14 µm
Image stitched from 5x4 detector frames
SLS beamline 4S, 29 Jan 2005

Sample by T. Khan, Univ. hospital Zürich



Rat heart in formalin

- Walls of vessels clearly visible in the phase-contrast image
- … but not in the absorption image acquired with the same dose
- Field of view here only limited by synchrotron beam size
  --- not by the interferometer

Pixel size 14 µm
Image stitched from 5x4 detector frames
SLS beamline 4S, 29 Jan 2005

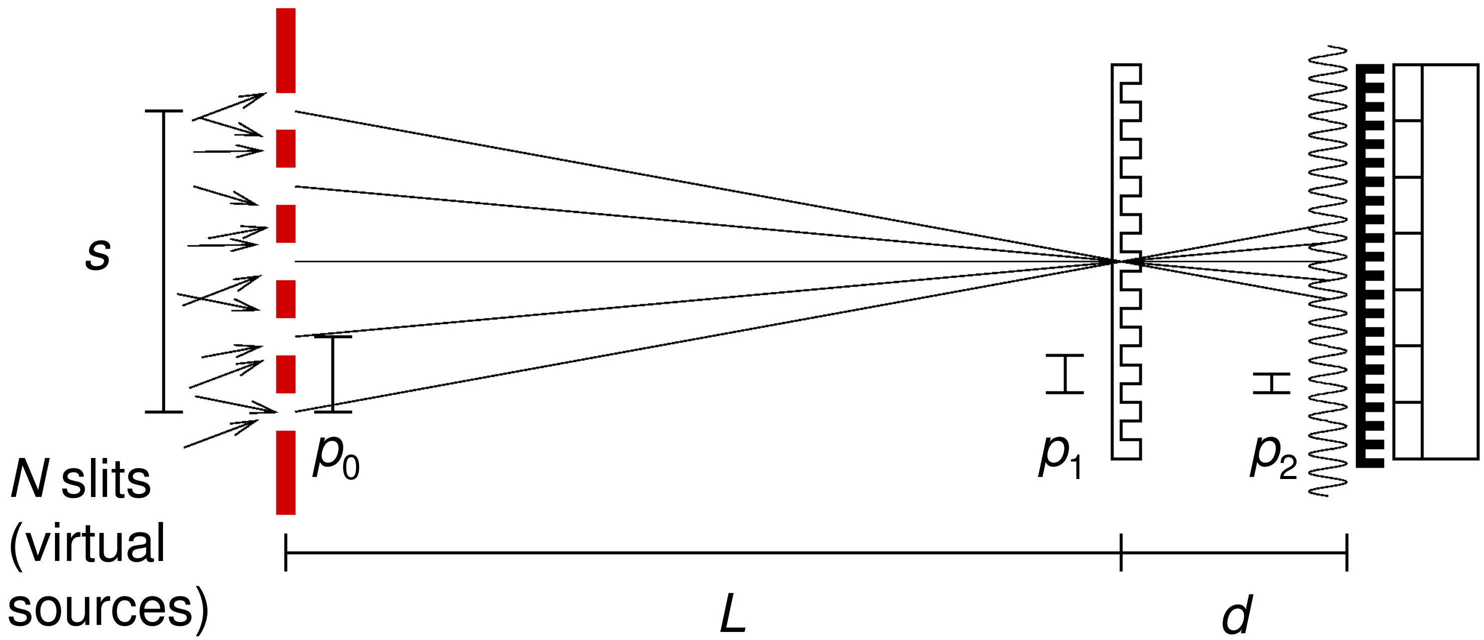
Sample by T. Khan, Univ. hospital Zürich

X-ray tube?

- Problem: coherent flux
- Have to use microfocus source
  or slit a usual source down
- No better solution?
  (i.e., higher flux) – we don’t need the high
  resolution of a micro focus
- Maybe using … another grating?

Arrayed source

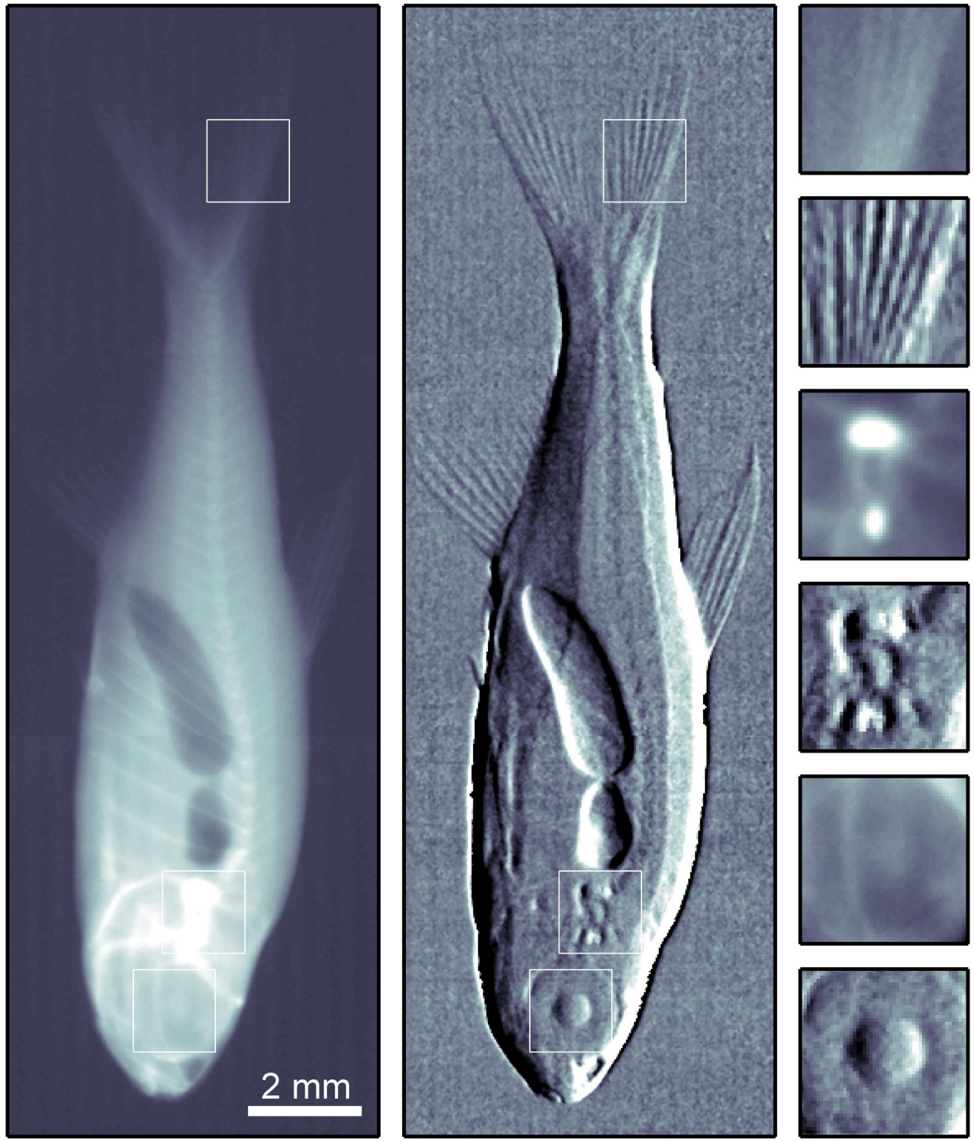
Trade resolution for flux, keeping coherence



- Fringe patterns from the different virtual sources superimpose incoherently, but constructively.
- Spatial resolution degrades to ($s\ d\ /\ L$).
- But flux is increased by a factor of N.

C. David, F. Pfeiffer, T. Weitkamp, patent pending

X-ray tube results



Summary

- Grating interferometer gives differential phase contrast ($d\Phi/dx$)
- Phase stepping separates absorption from phase, yielding both phase Φ and transmission signal
- Phase-stepping tomography yields refractive index $\delta(x,y,z)$
- Results are quantitative
- Instrument is largely achromatic
- Stable, robust, almost no alignment
- Better contrast than in absorption imaging with the same dose
- With an arrayed source, efficient use with X-ray tube
- Can be scaled up to higher energies and larger fields of view

→ Suitable for radiography and tomography applications with large fields of view, moderate resolution

Posters:

- Wavefront sensing with moiré interferometry (P8, Christian David et al.)
- Fabrication of gratings (P9, Ana Diaz et al.)
- Coherence characterization (P44, Franz Pfeiffer et al.)