Prospects for hard X-ray phase contrast imaging

Ian Robinson
UCL Physics and Diamond Light Source

Garth Williams, Mark Pfeifer, Ivan Vartaniants, Ross Harder
University of Illinois, Urbana, USA

Franz Pfeiffer, Timm Weitkamp, Oliver Bunk, Christian David
Swiss Light Source, Paul Scherrer Institut, Switzerland

Outline

Phase Contrast X-ray Imaging

New methods: DEI and Shearing Interferometer

Coherent X-ray Diffraction

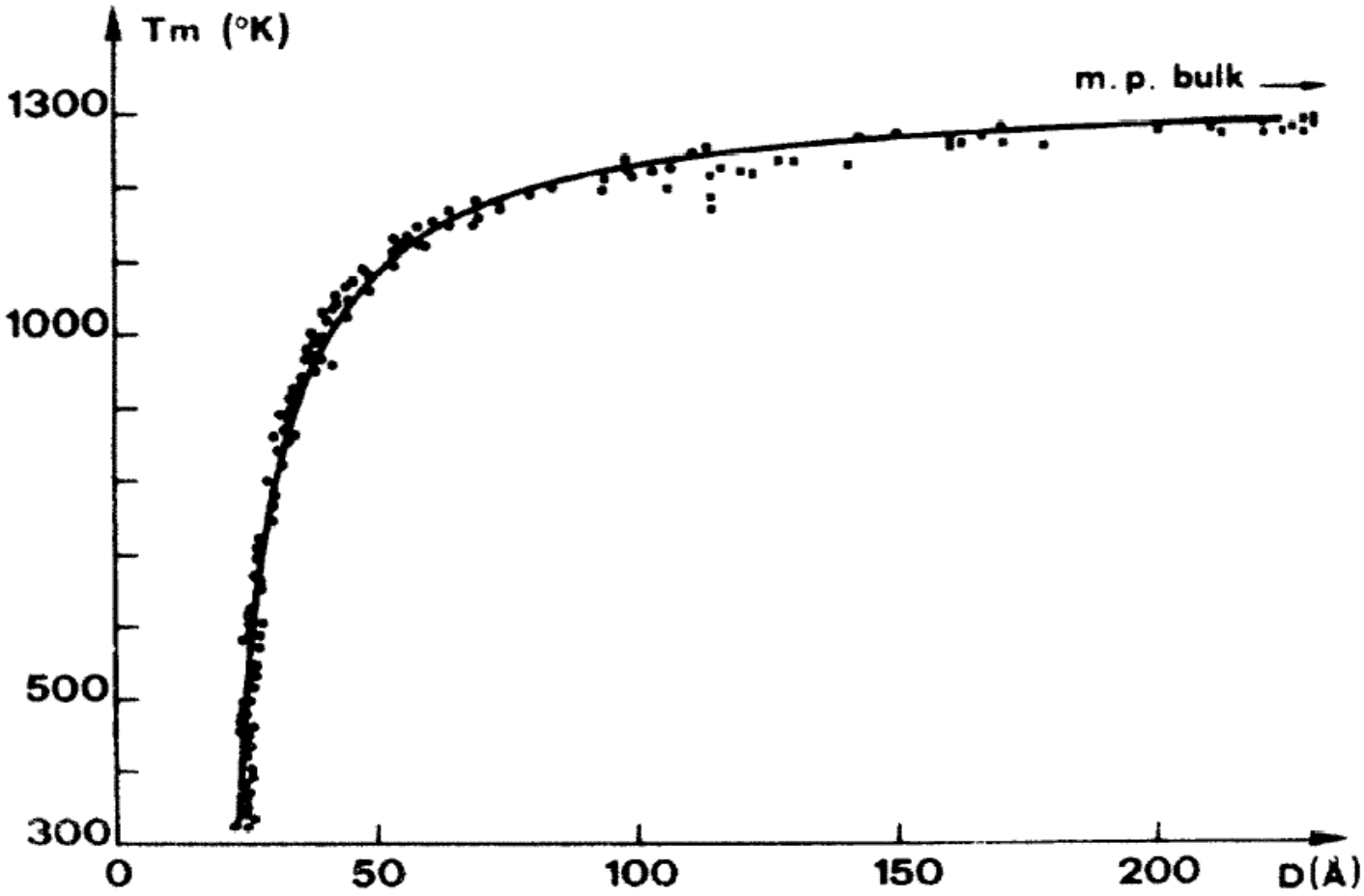
How to Solve the Phase Problem for Nanocrystal Shapes

Extension to Phase Objects

Opportunities at UCL and FELs

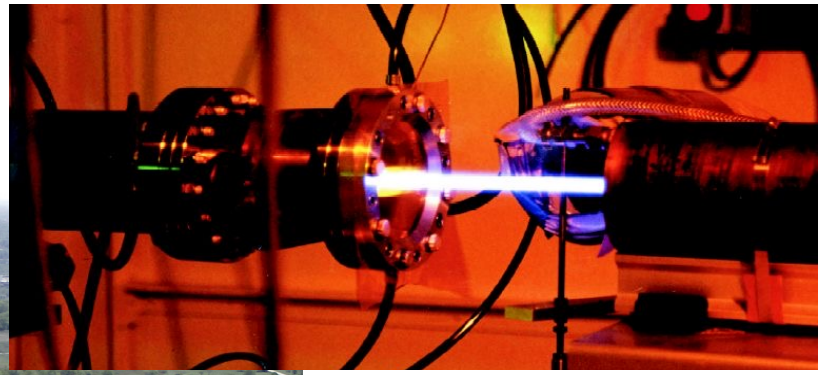
Size-dependent Melting of Au Particles

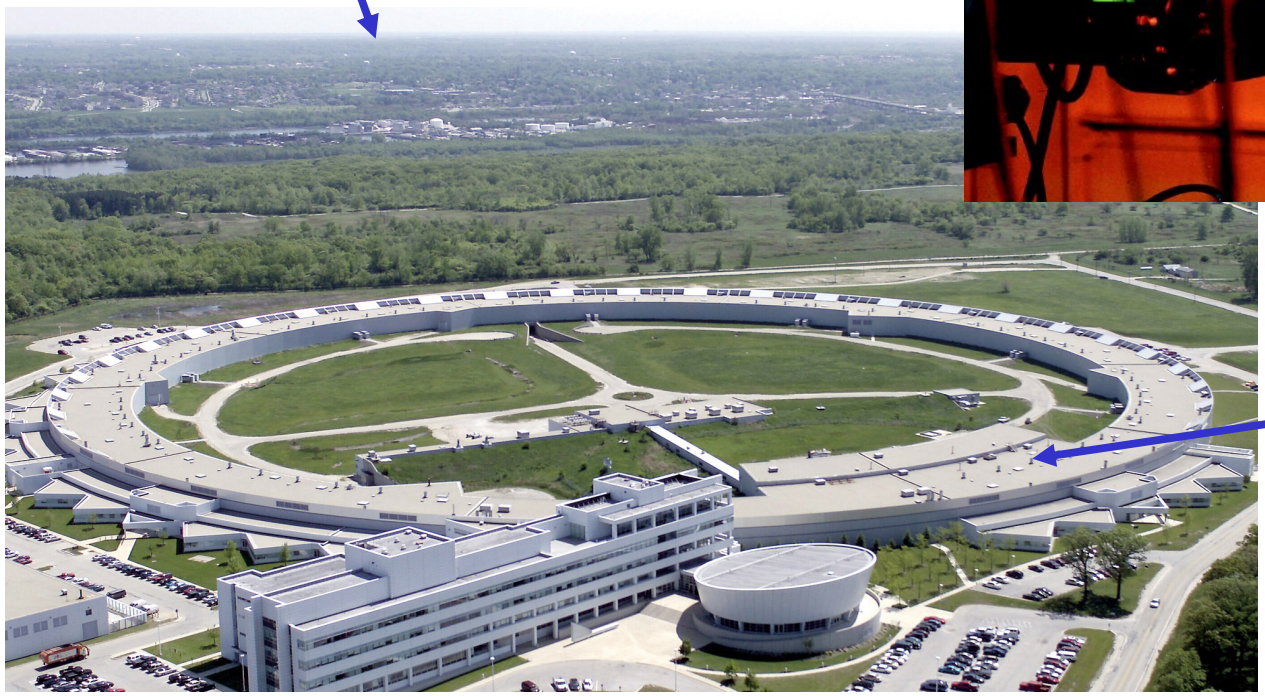
P. Buffat and J-P. Borel, Phys. Rev. A 2287-97 (1975)



Synchrotron Radiation

Urbana

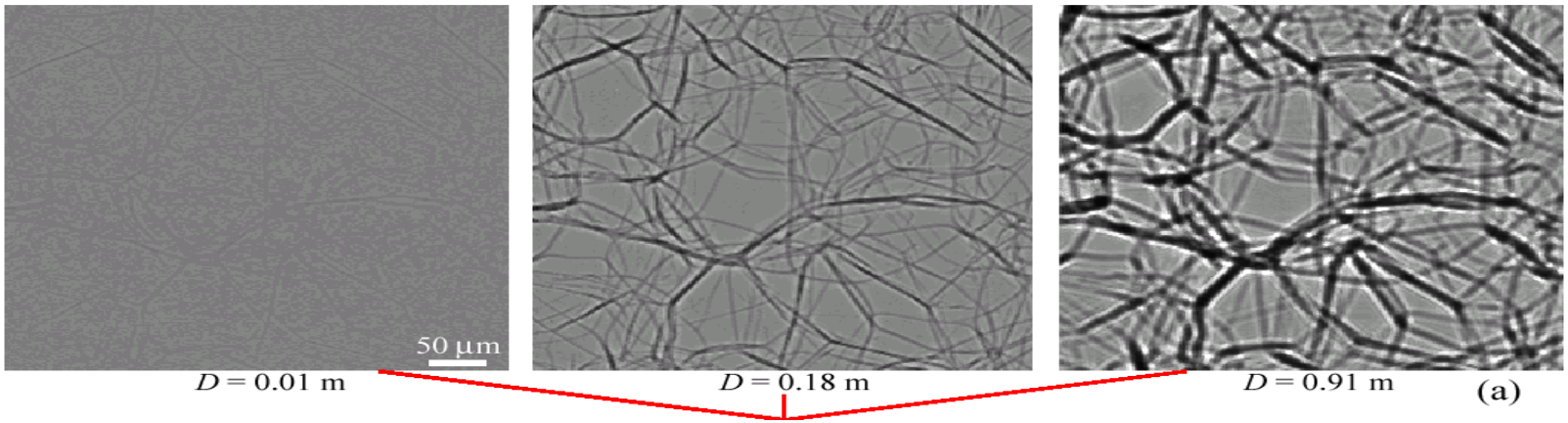




34-ID-C

Phase Contrast by Propagation

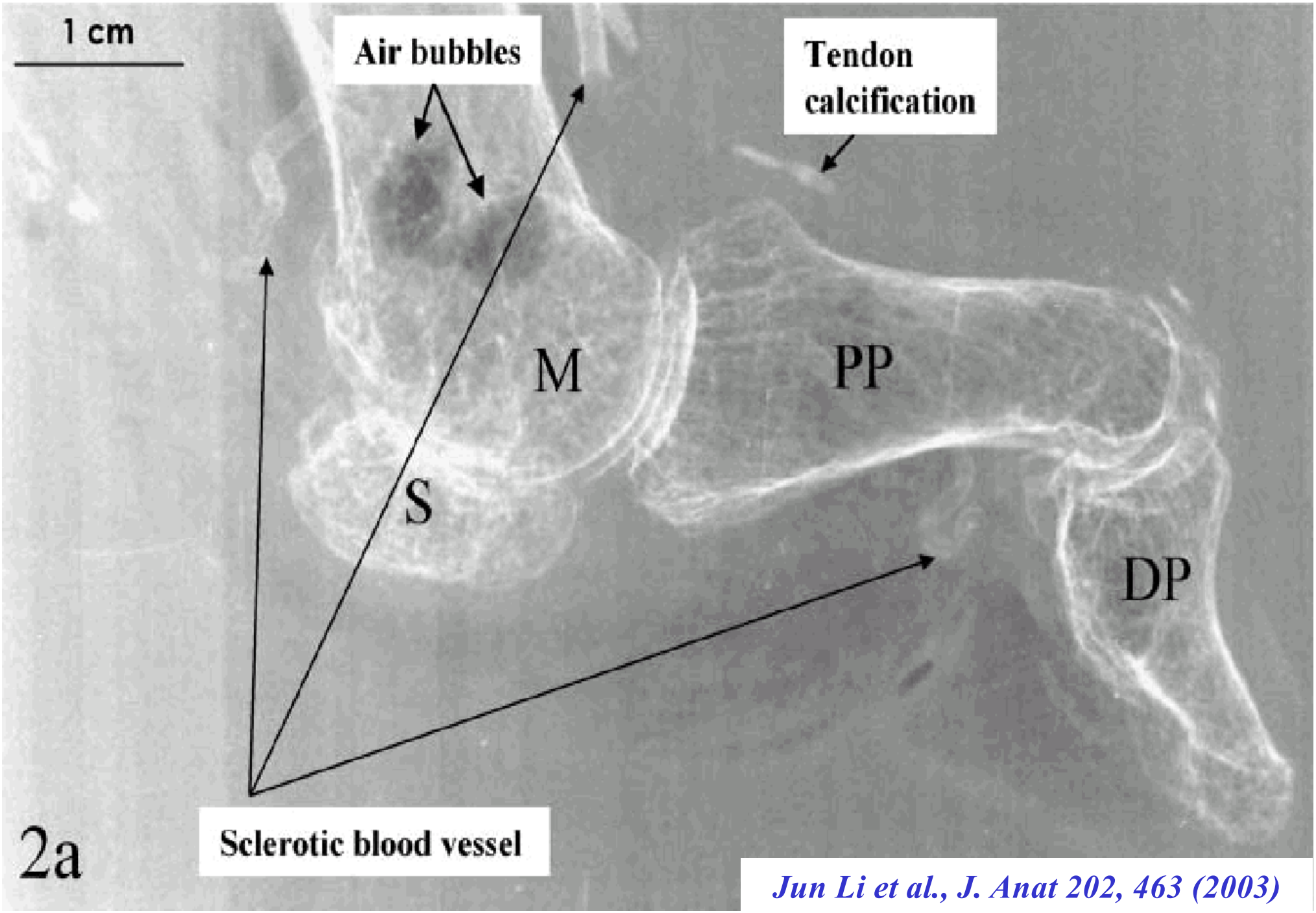
P. Cloetens et al. (1999)



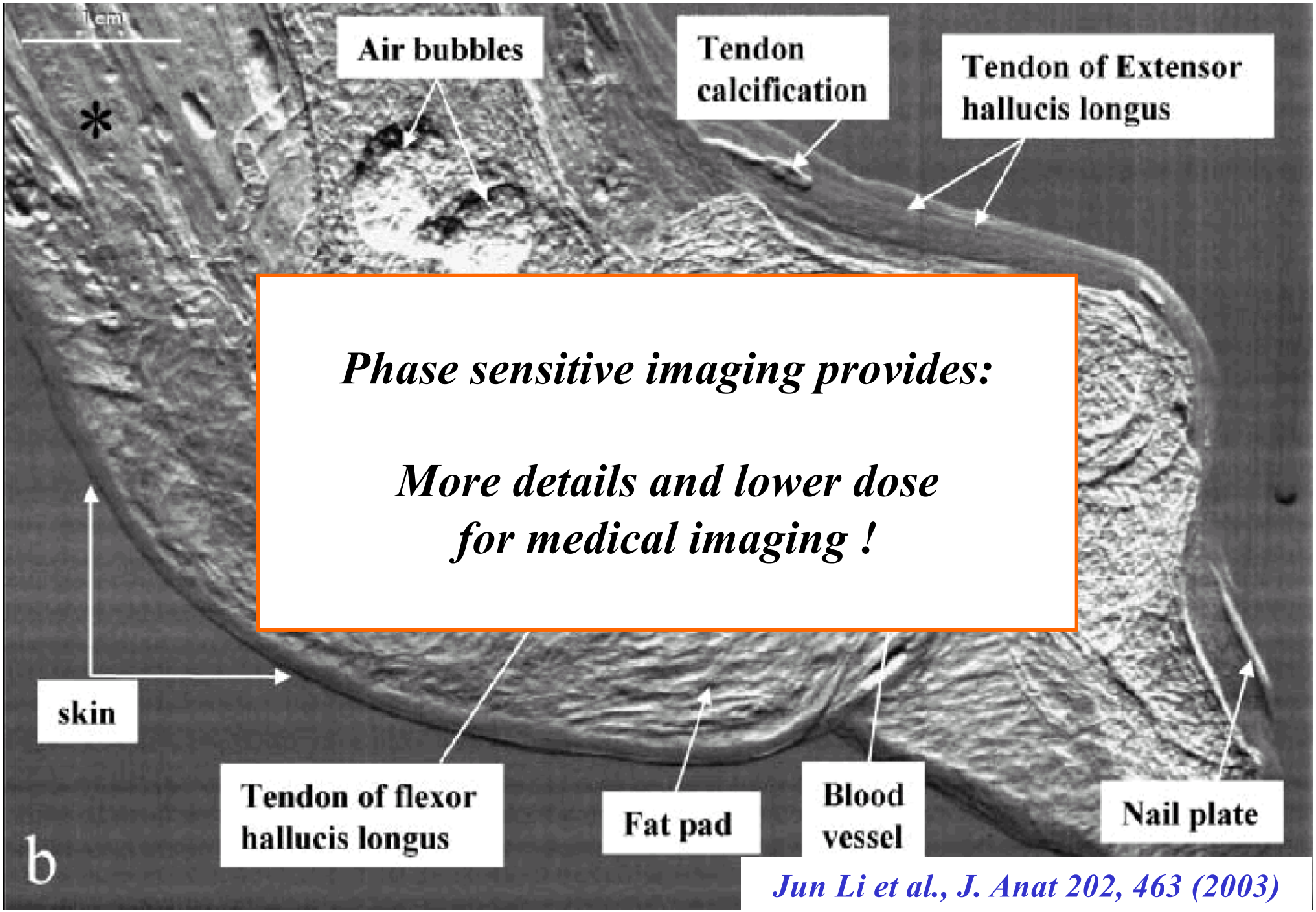
Polystyrene foam,
Propagation images at different distances

Far field ***Lensless Imaging,*** ***Diffraction Microscopy***	***Near field*** ***Phase Contrast*** ***Imaging***

1 nm **1 μm** **1 mm** **1 m**

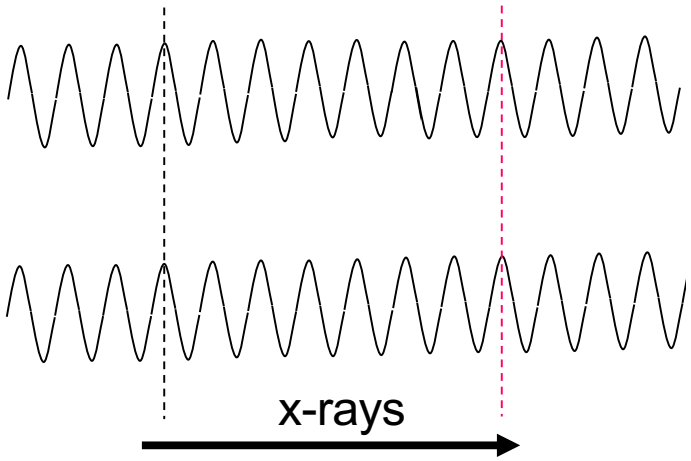


Jun Li et al., J. Anat 202, 463 (2003)



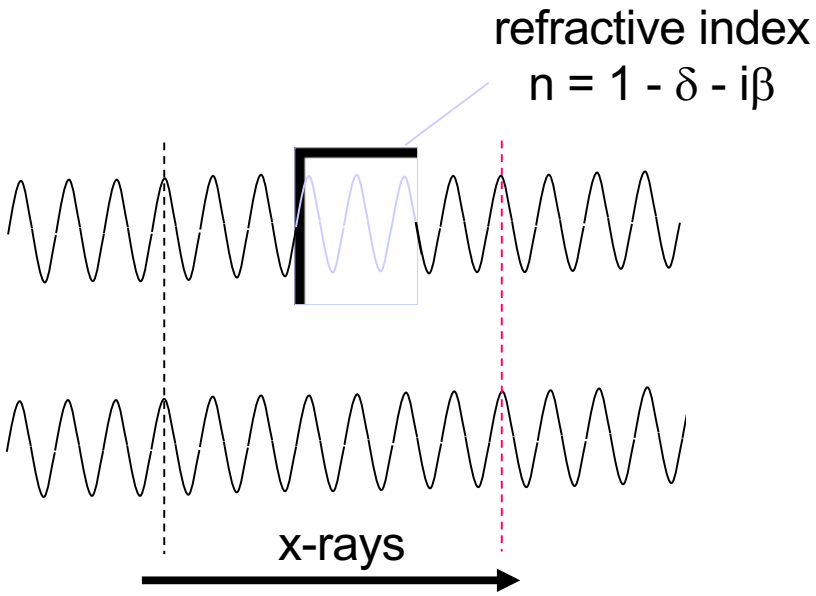
Jun Li et al., J. Anat 202, 463 (2003)

Phase sensitive x-ray imaging

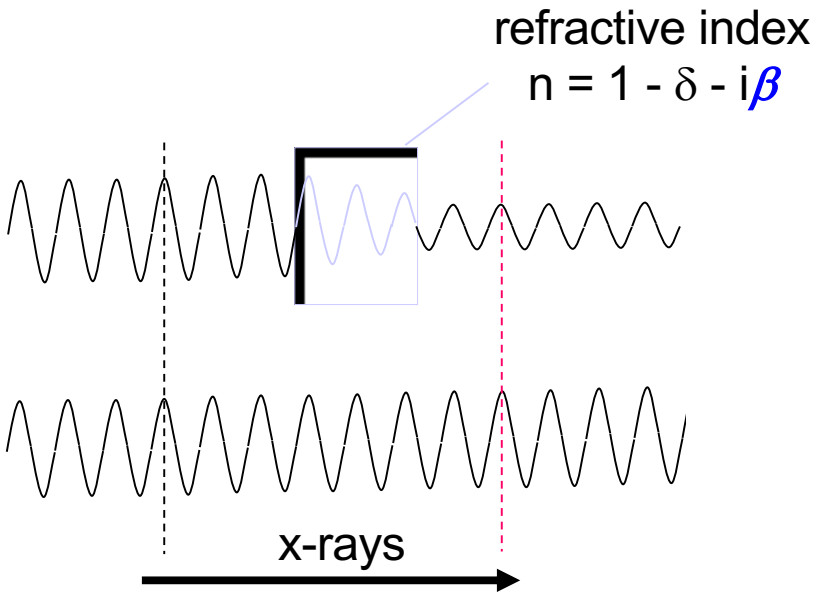


Coherent Beams

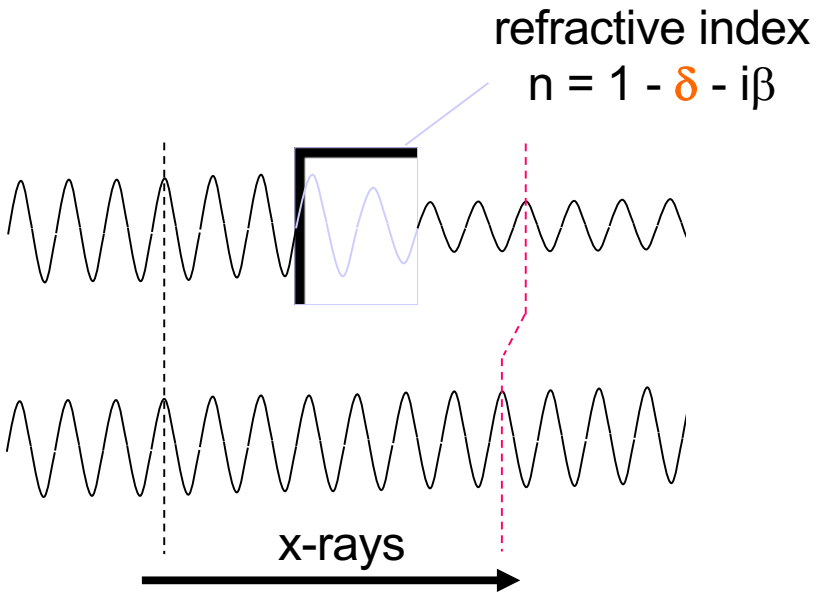
Phase sensitive x-ray imaging



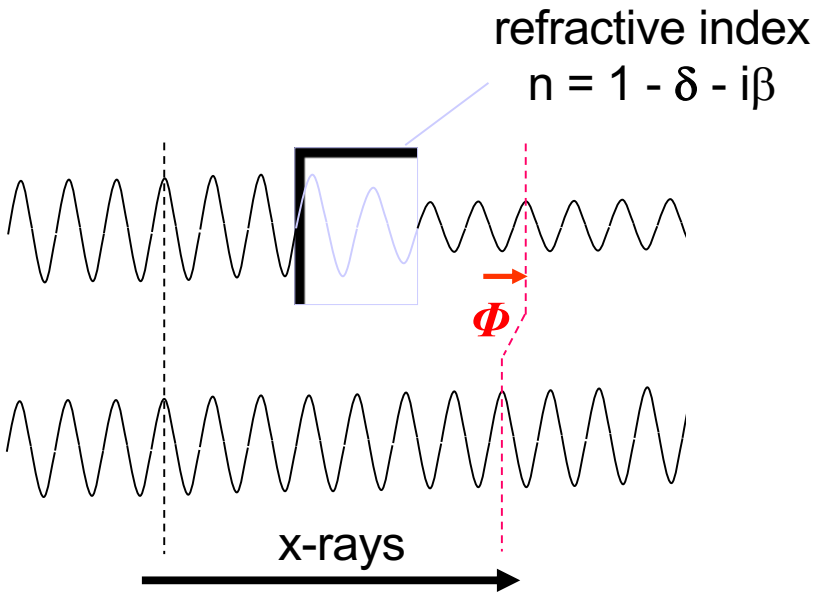
Phase sensitive x-ray imaging



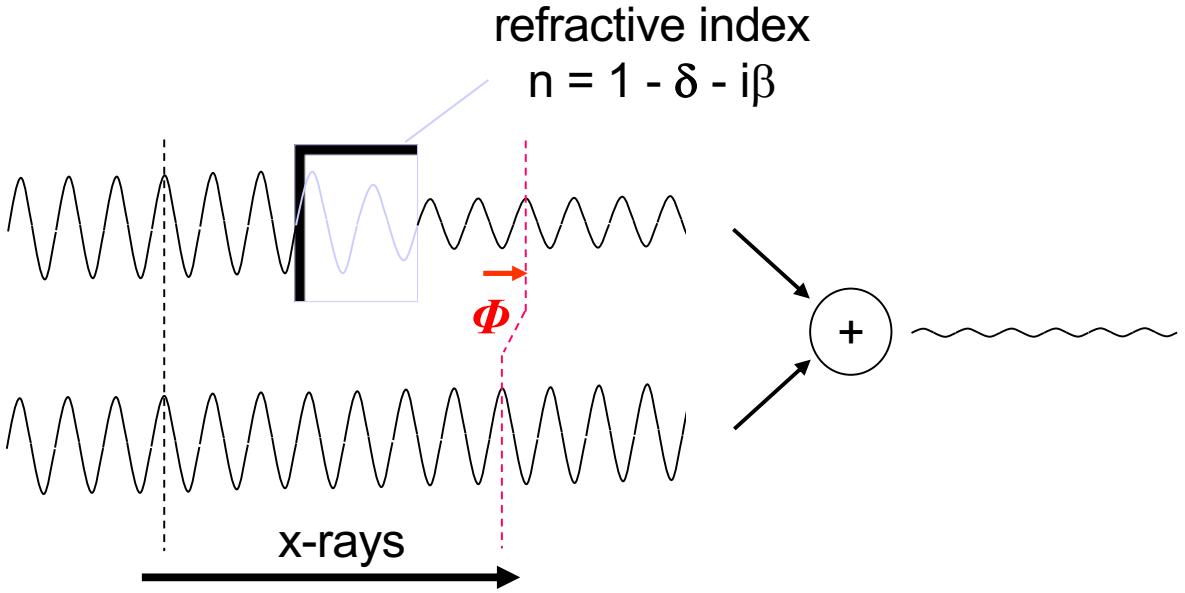
Phase sensitive x-ray imaging



Phase sensitive x-ray imaging



Phase sensitive x-ray imaging

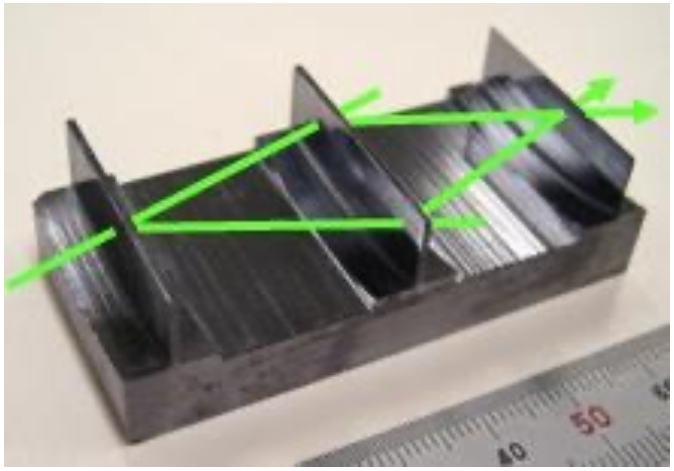


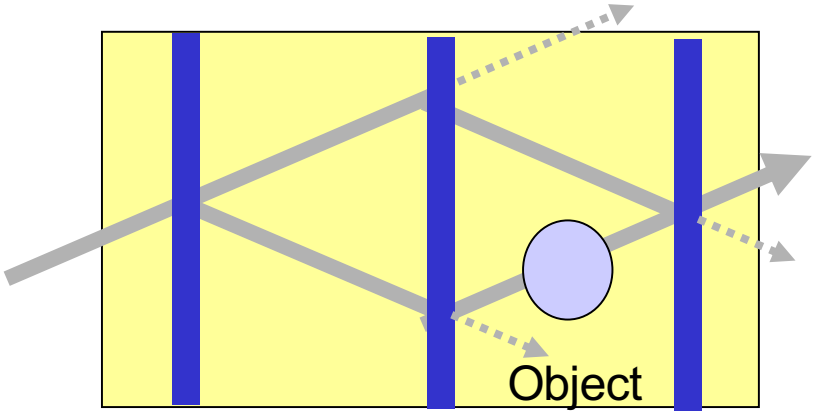
To obtain phase sensitive images, measure:

Φ ***with a crystal interferometer (Bonse & Hart 1965)***

Crystal Interferometers

Bonse & Hart (1965)

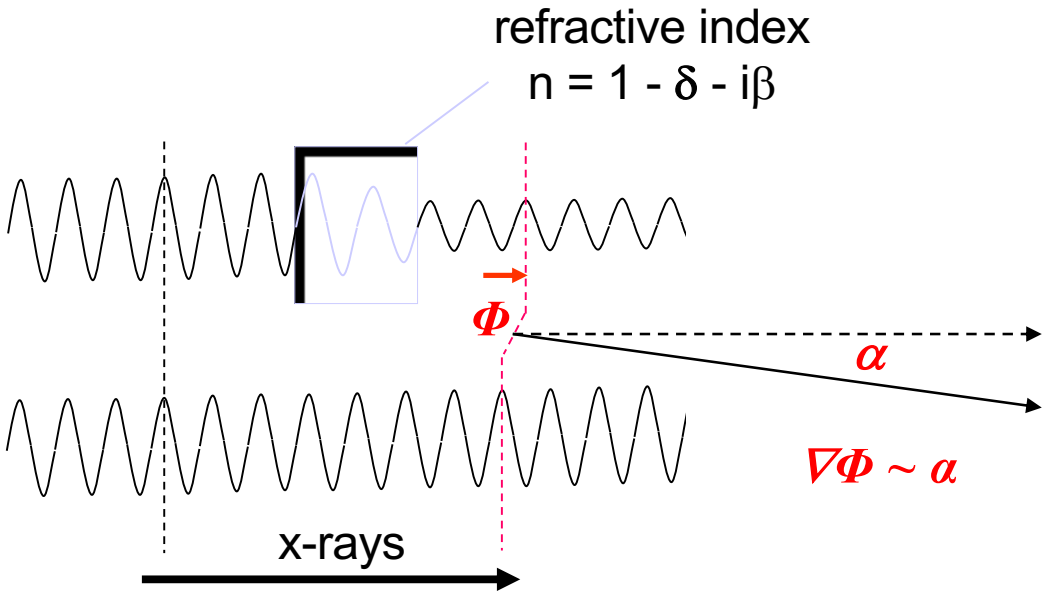




Momose et al. (2005)

PS/PMMA polymer blend
Phase tomography

Phase sensitive x-ray imaging

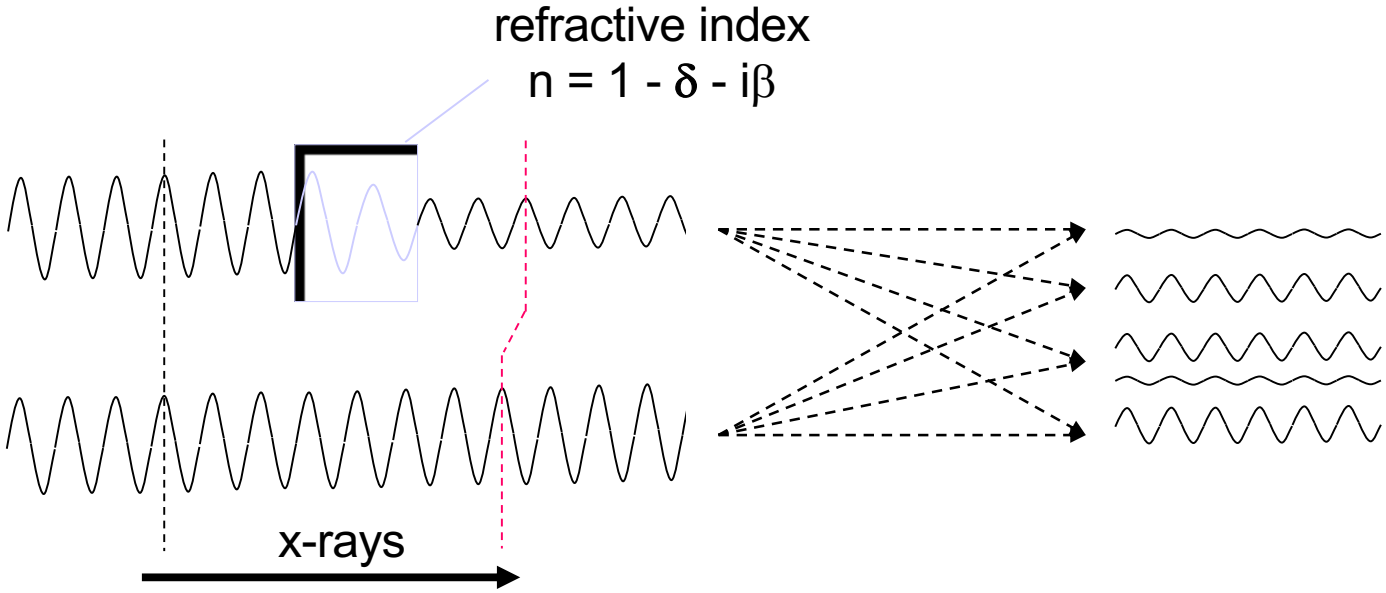


To obtain phase sensitive images, measure:

Φ ***with a crystal interferometer (Bonse & Hart 1965)***

∇Φ ***with diffraction enhanced imaging (Chapman 1997)***

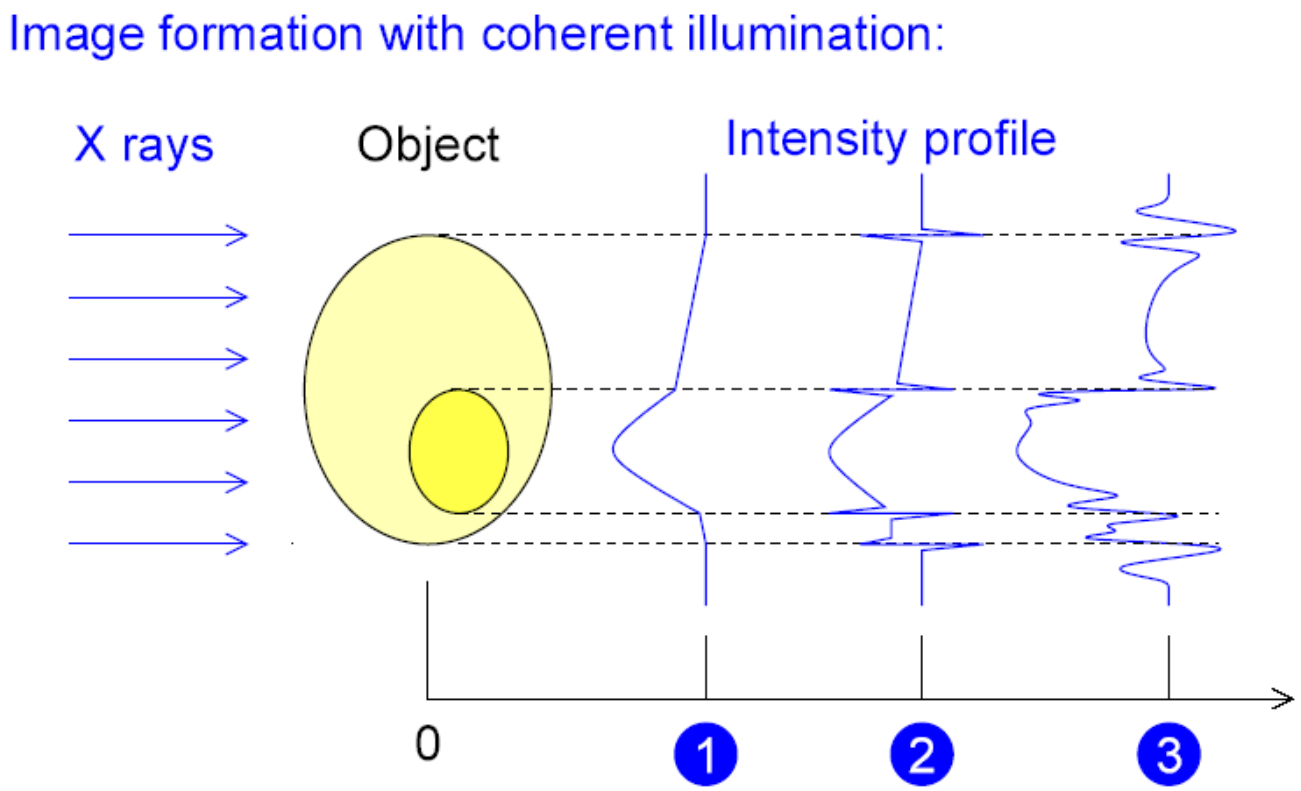
Phase sensitive x-ray imaging



To obtain phase sensitive images, measure:

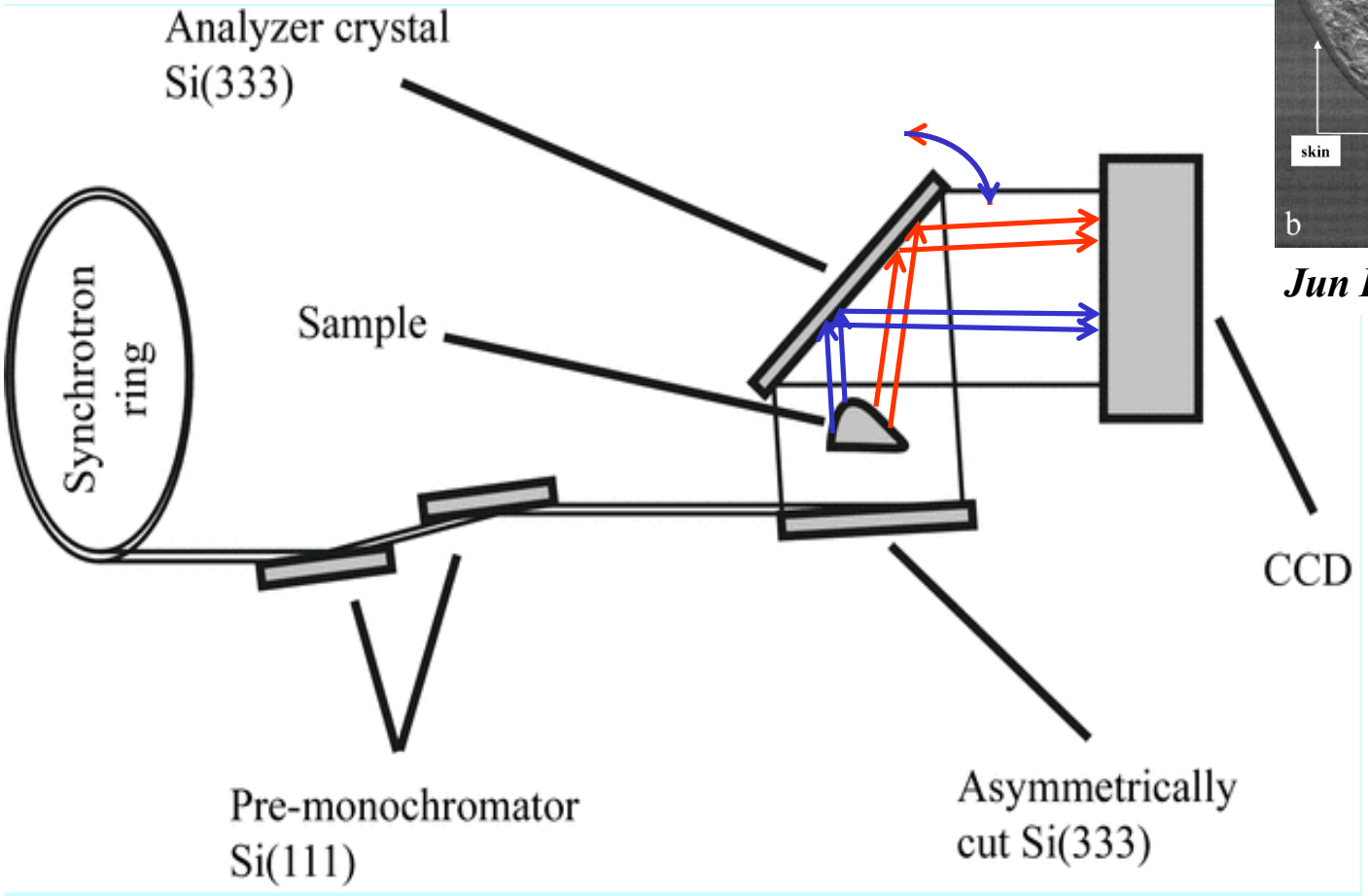
Φ	***with a crystal interferometer (Bonse & Hart 1965)***
∇Φ	***with diffraction enhanced imaging (Chapman 1997)***
ΔΦ	***with in-line holography (Cloetens 1999)***

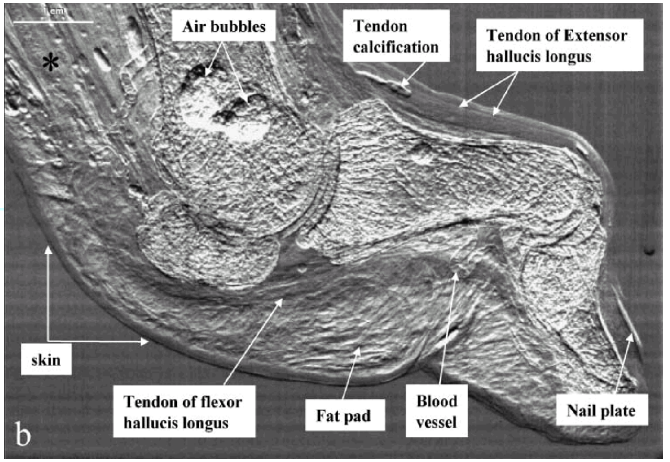
Free Space Propagation



Diffraction Enhanced Imaging (DEI)

Chapman et al. (1997)





Jun Li et al., J. Anat 202, 463 (2003)

Diffraction Enhanced Imaging (DEI)

Good results at synchrotron sources

Highly monochromatic (inefficient)

requires parallel beam

limited field of view (crystals !)

Not suitable for hospital based medical imaging systems (e.g. x-ray tubes) !

Free Space Propagation

Simplicity

Polychromatic

Non-interferometric method (no phase-stepping)

Limited FOV (high resolution detector required) or very large distances

Low sensitivity at low spatial frequencies

Requires spatial coherence

Not suitable for hospital based medical imaging systems (e.g. x-ray tubes) !

Grating Interferometer

Polychromatic

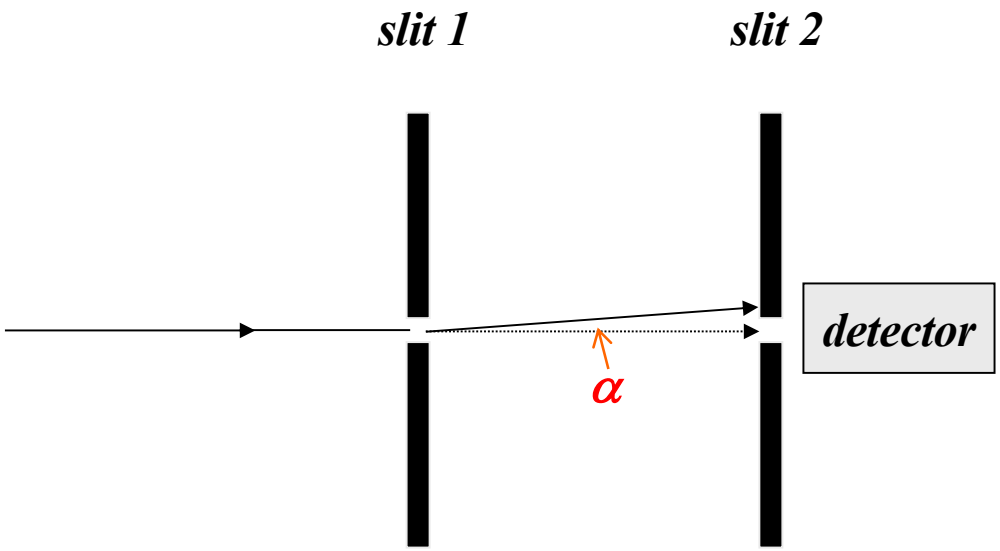
Large FOV possible

Suitable for spherical waves (x-ray tubes)

Requires gratings

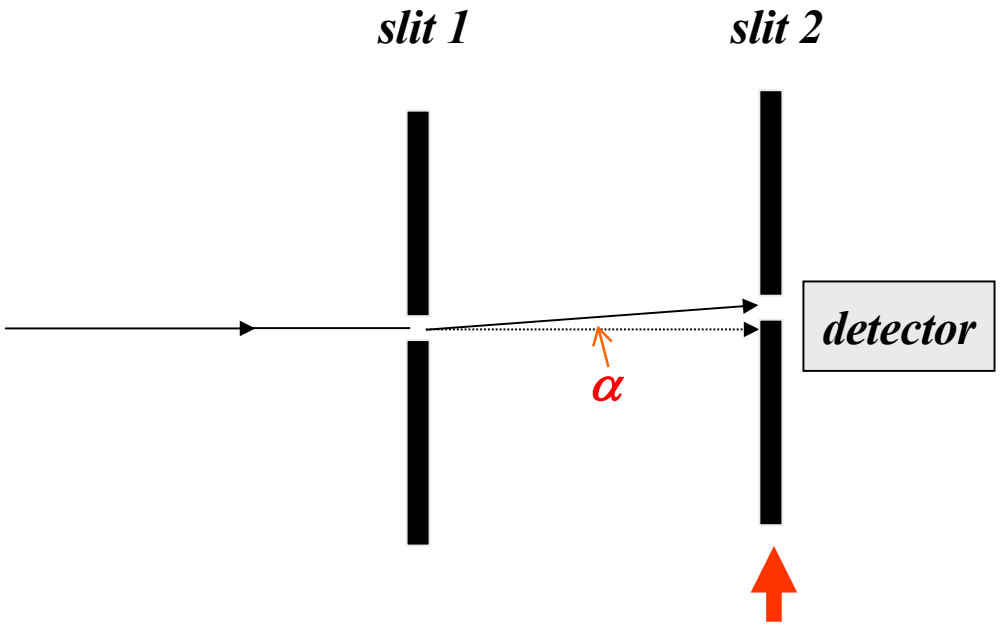
Suitable for hospital based medical imaging systems (e.g. x-ray tubes) !

Grating Interferometer



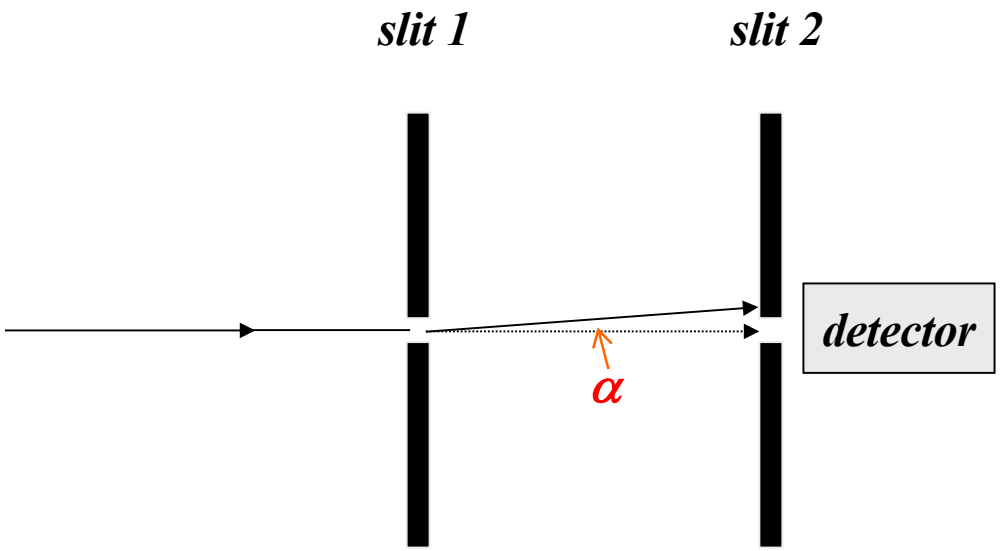
Idea: polychromatic detection of angles

Grating Interferometer



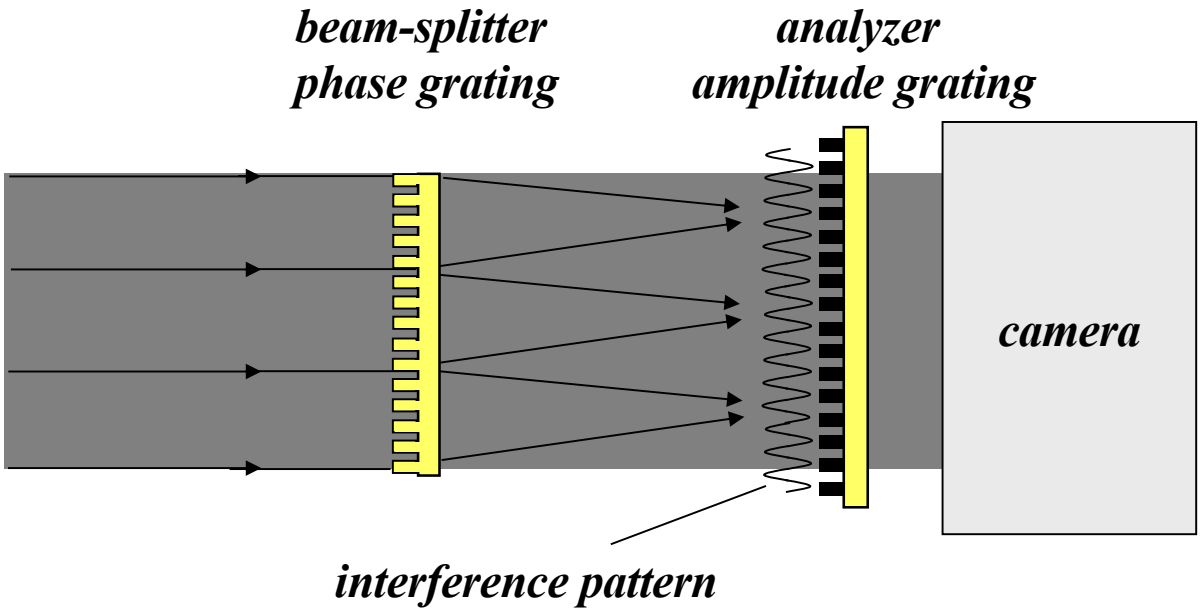
Idea: polychromatic detection of angles

Grating Interferometer



Idea: polychromatic detection of angles

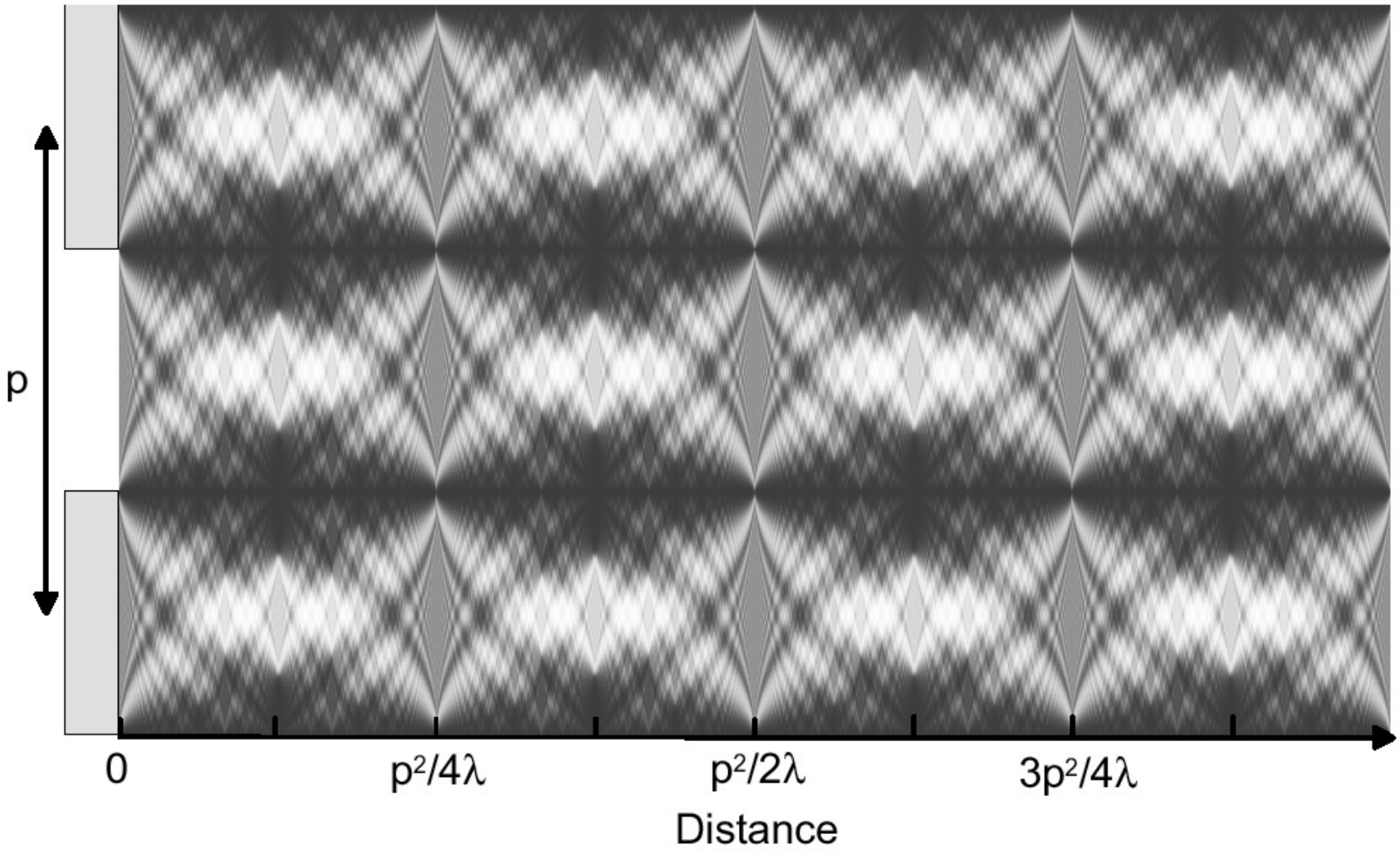
Grating Interferometer



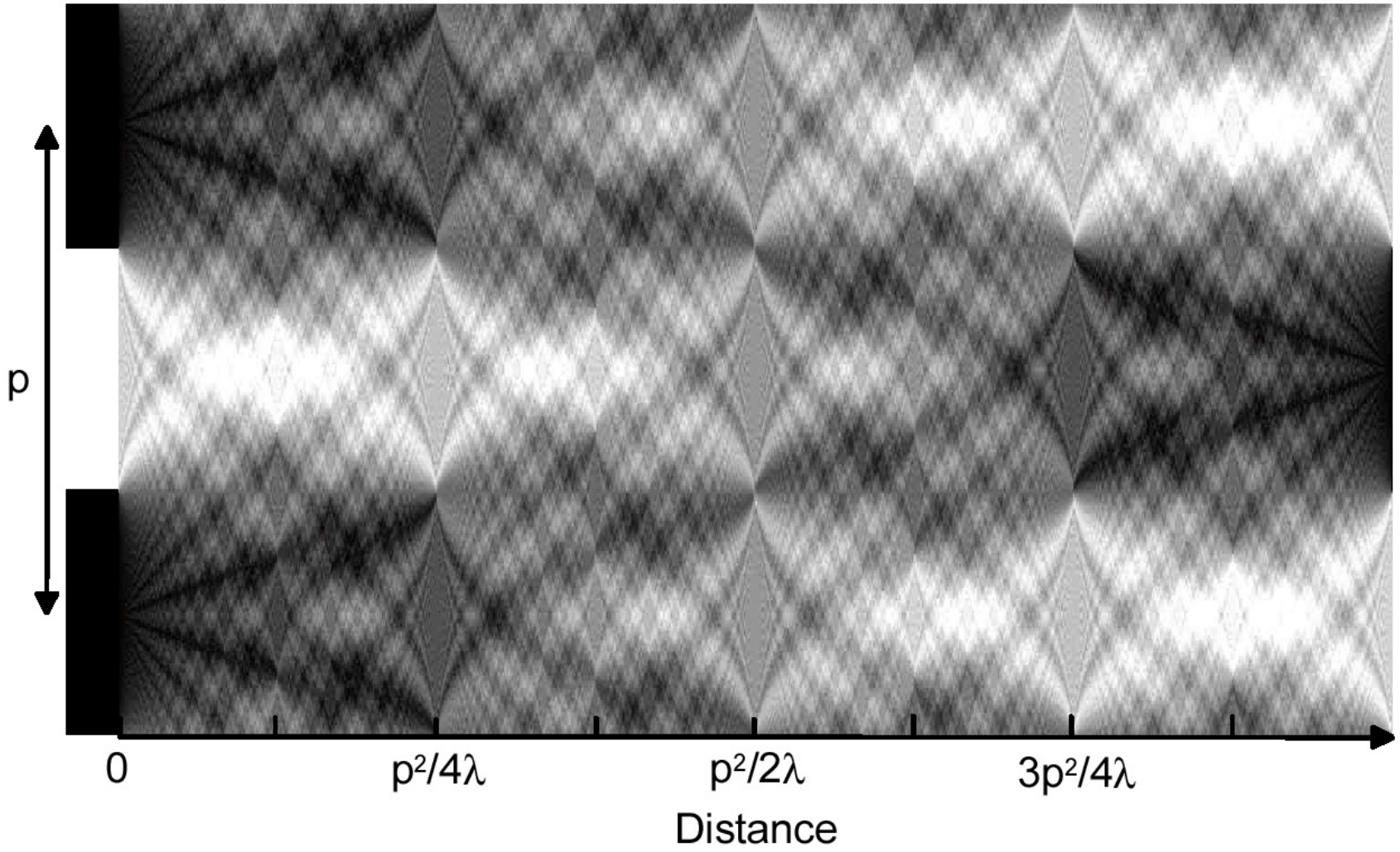
- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

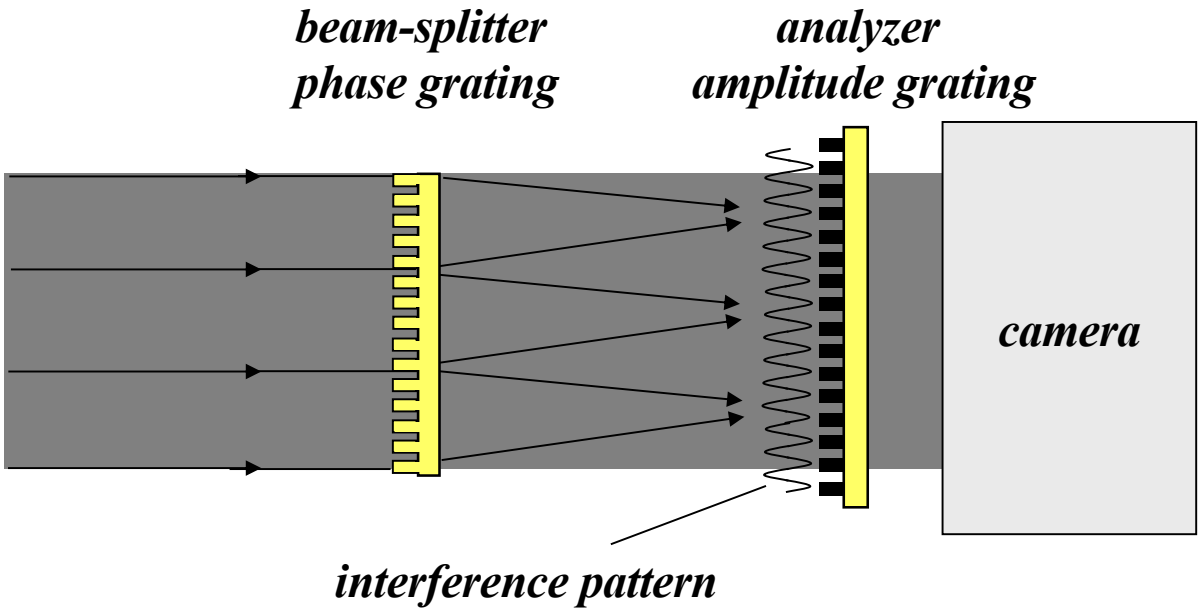
The Talbot effect



The Talbot effect



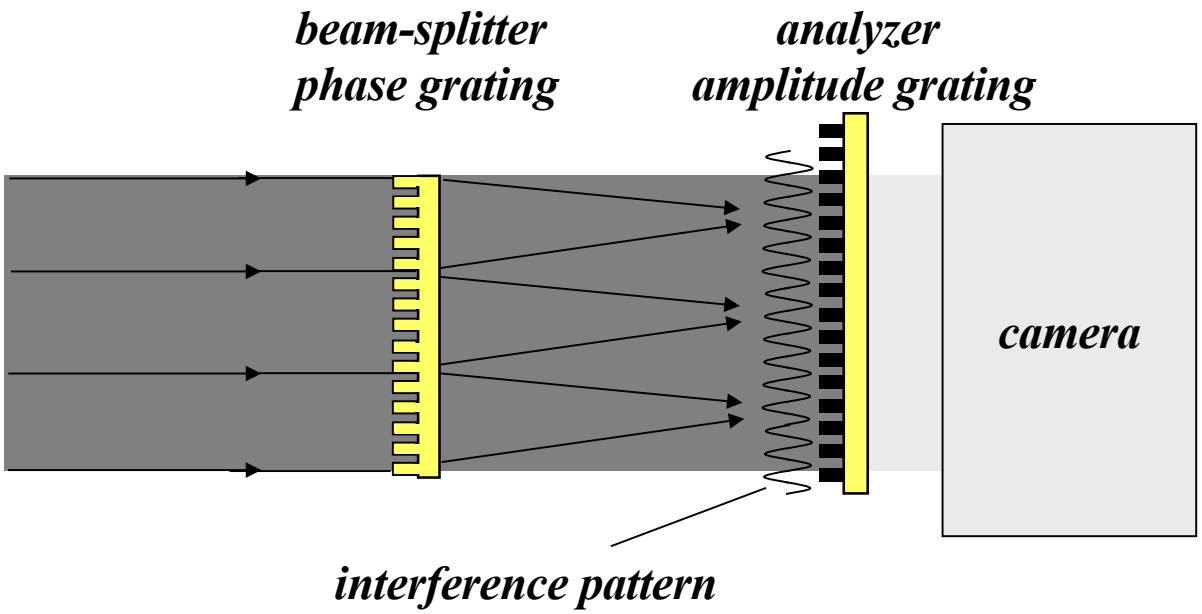
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

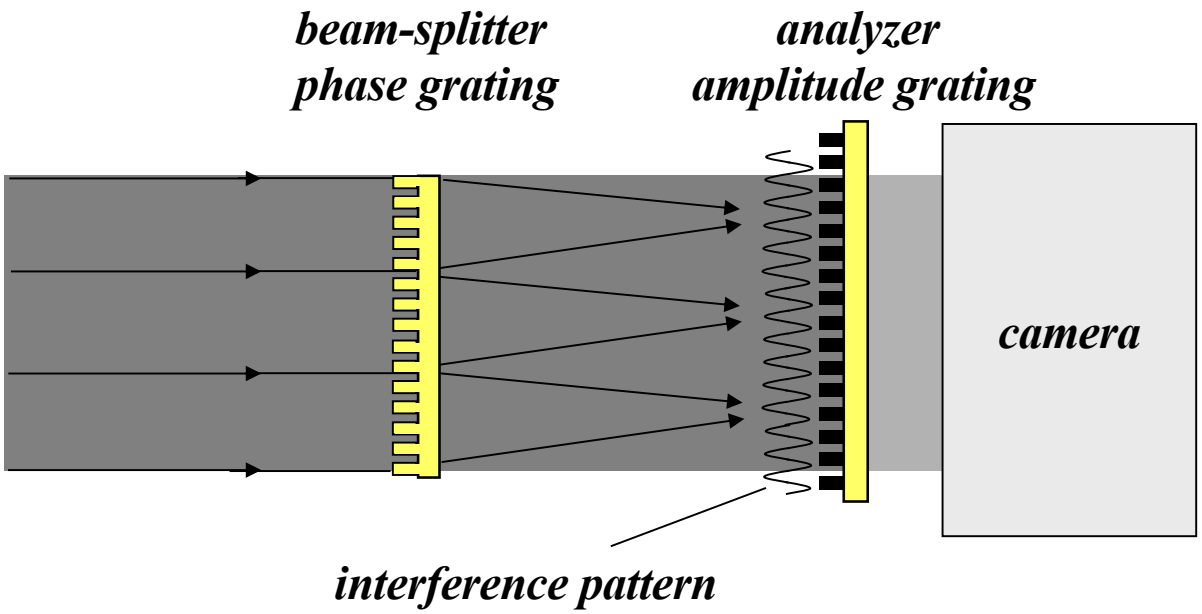
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

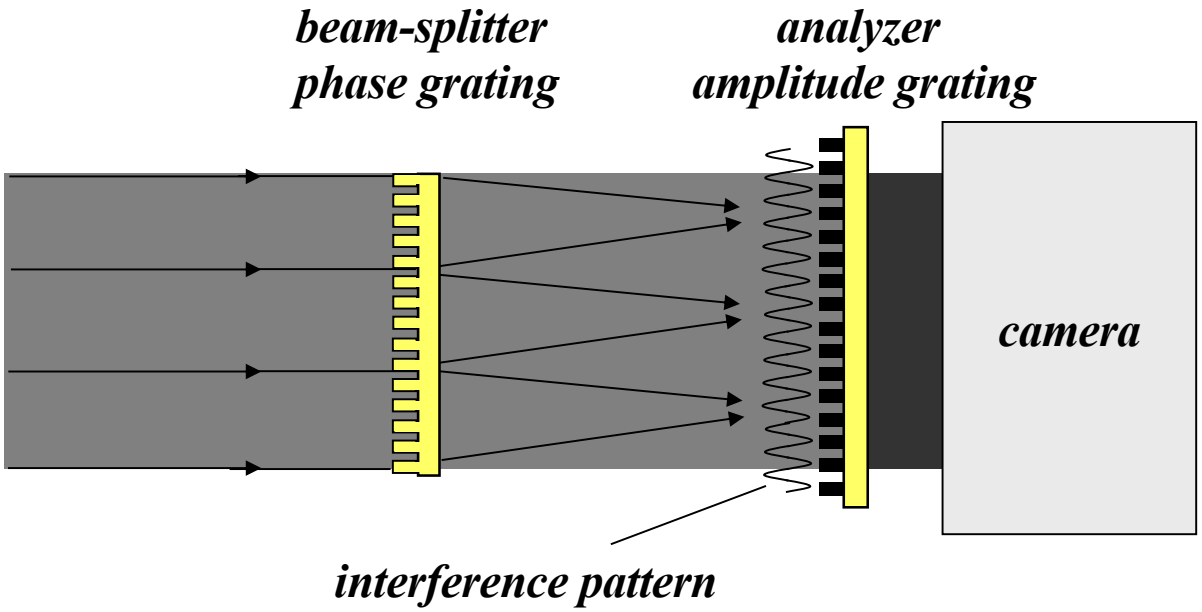
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

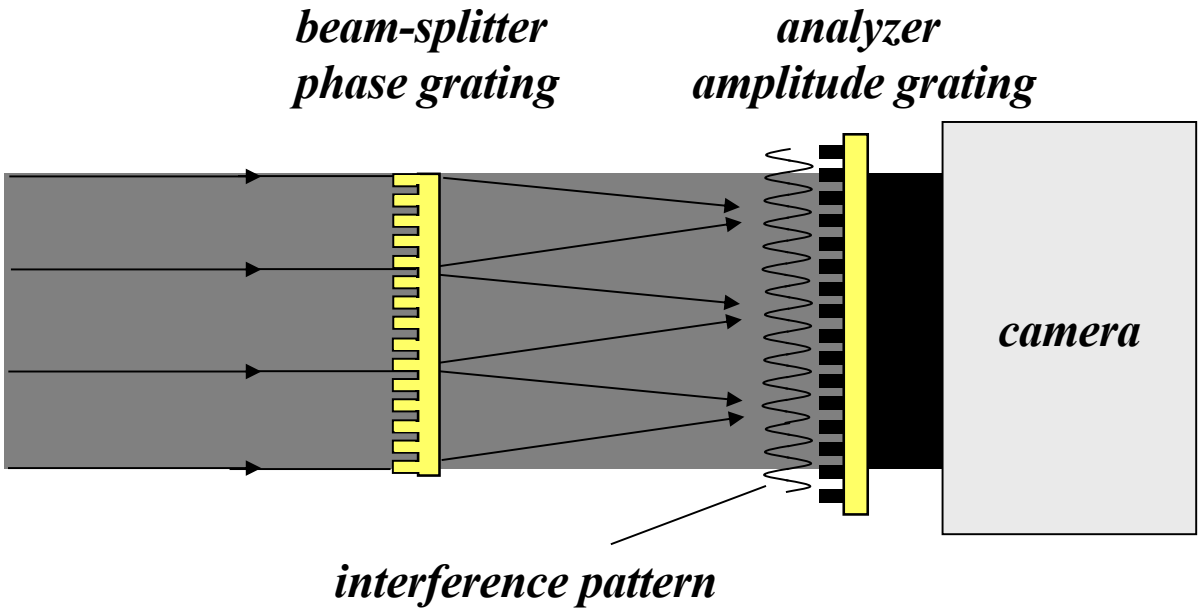
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

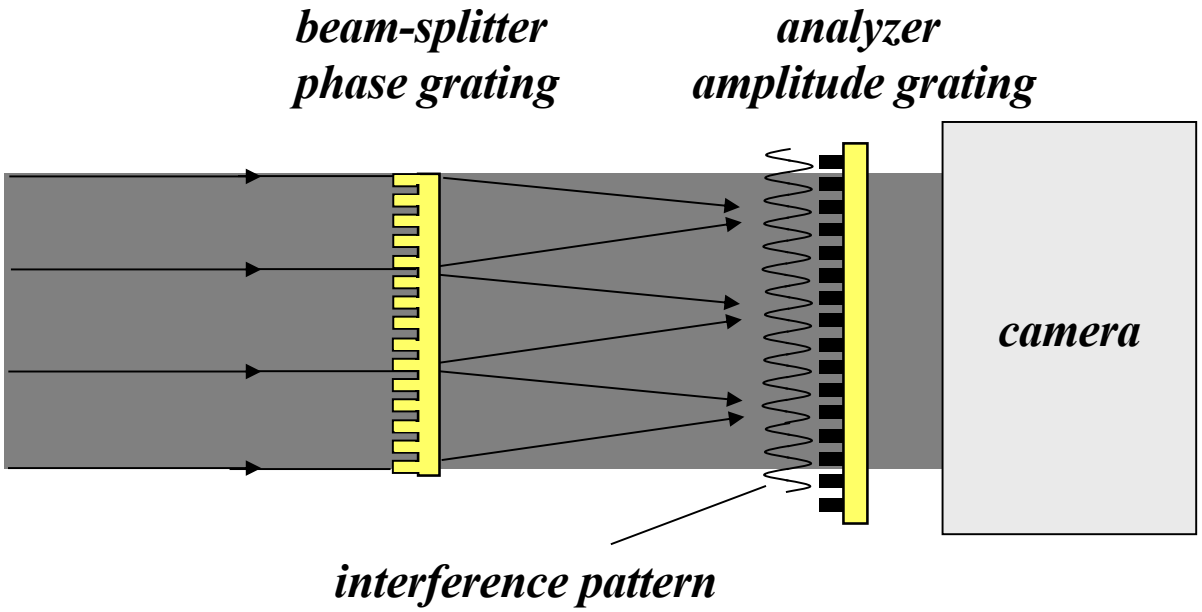
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

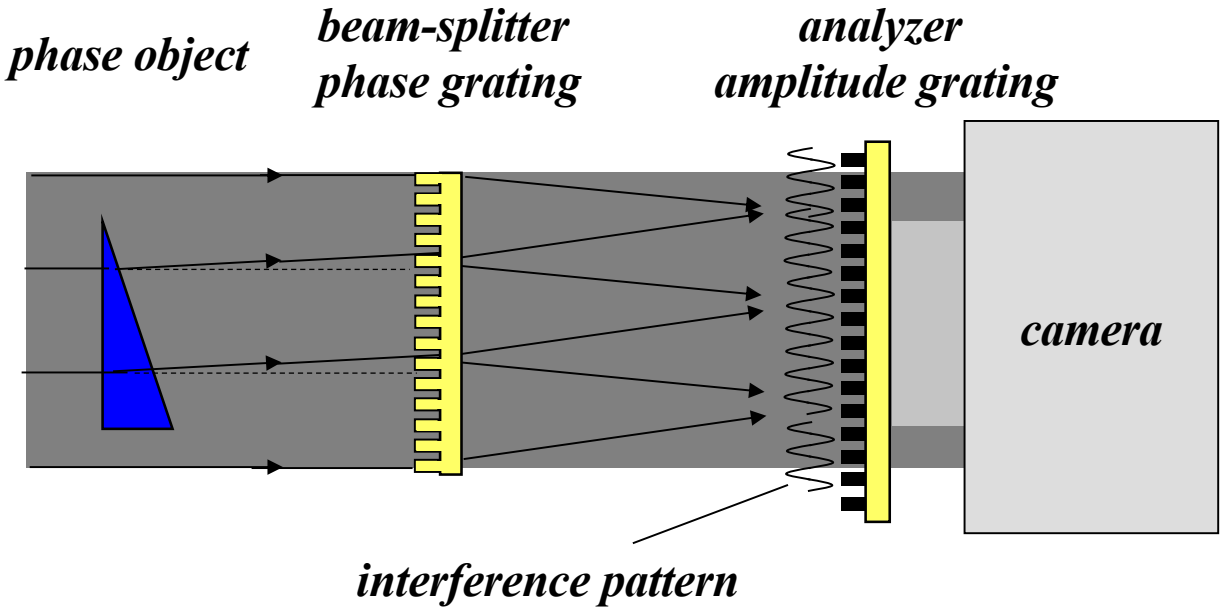
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*

Patent pending, # 05 012 121.9 (2005)

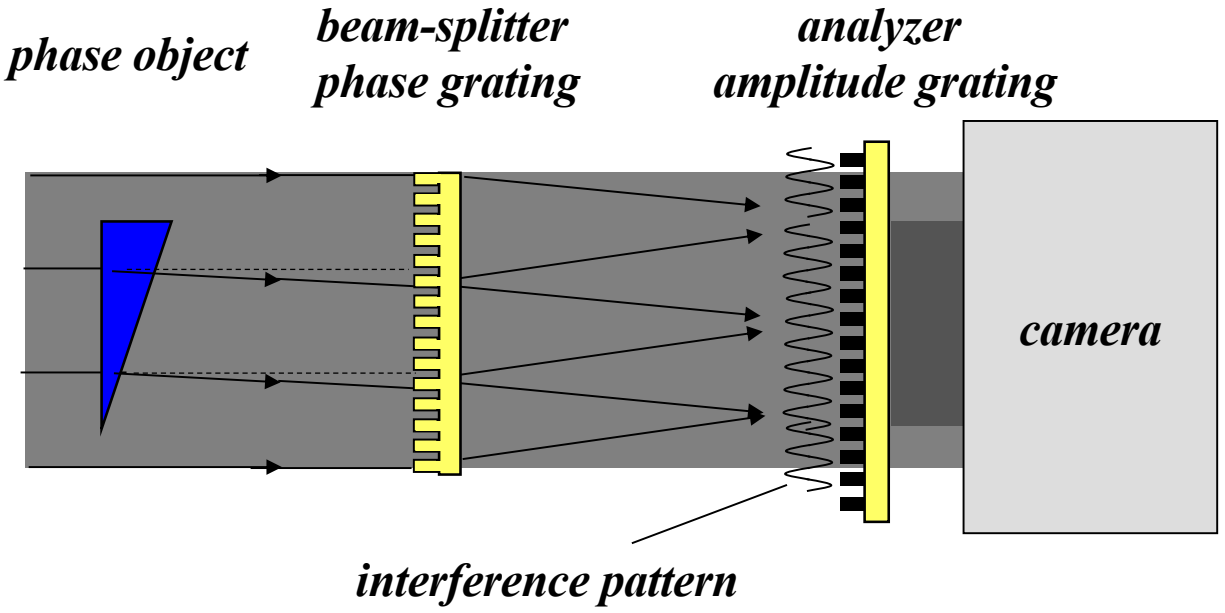
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*
- *phase object cases intensity to change*

Patent pending, # 05 012 121.9 (2005)

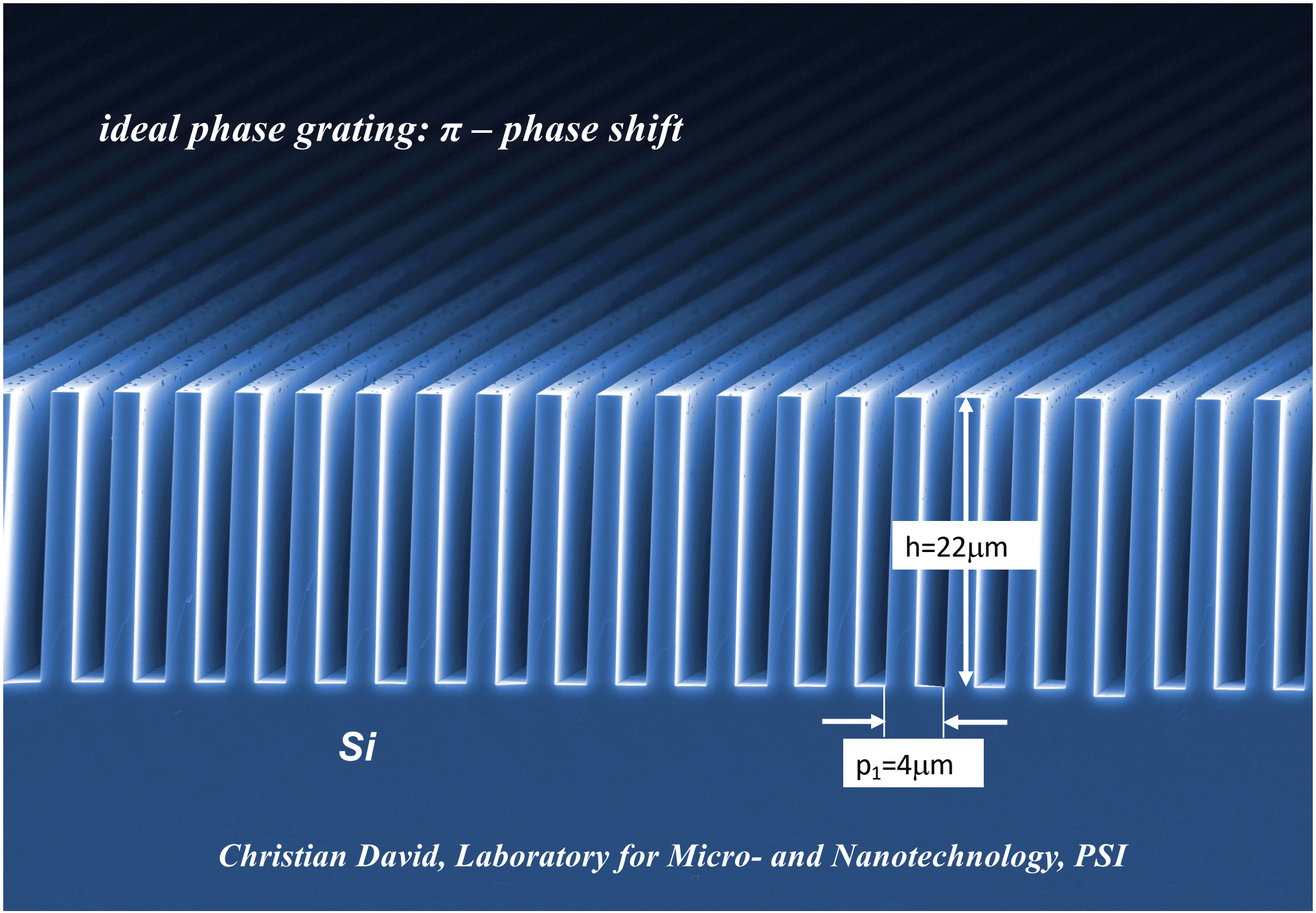
Grating Interferometer



- *phase grating as beam splitter*
- *absorption grating as transmission mask*
- *x-ray wavelength $\lambda \sim 0.1$ nm, grating periods ~ 2-4 μm*
- *phase object cases intensity to change*

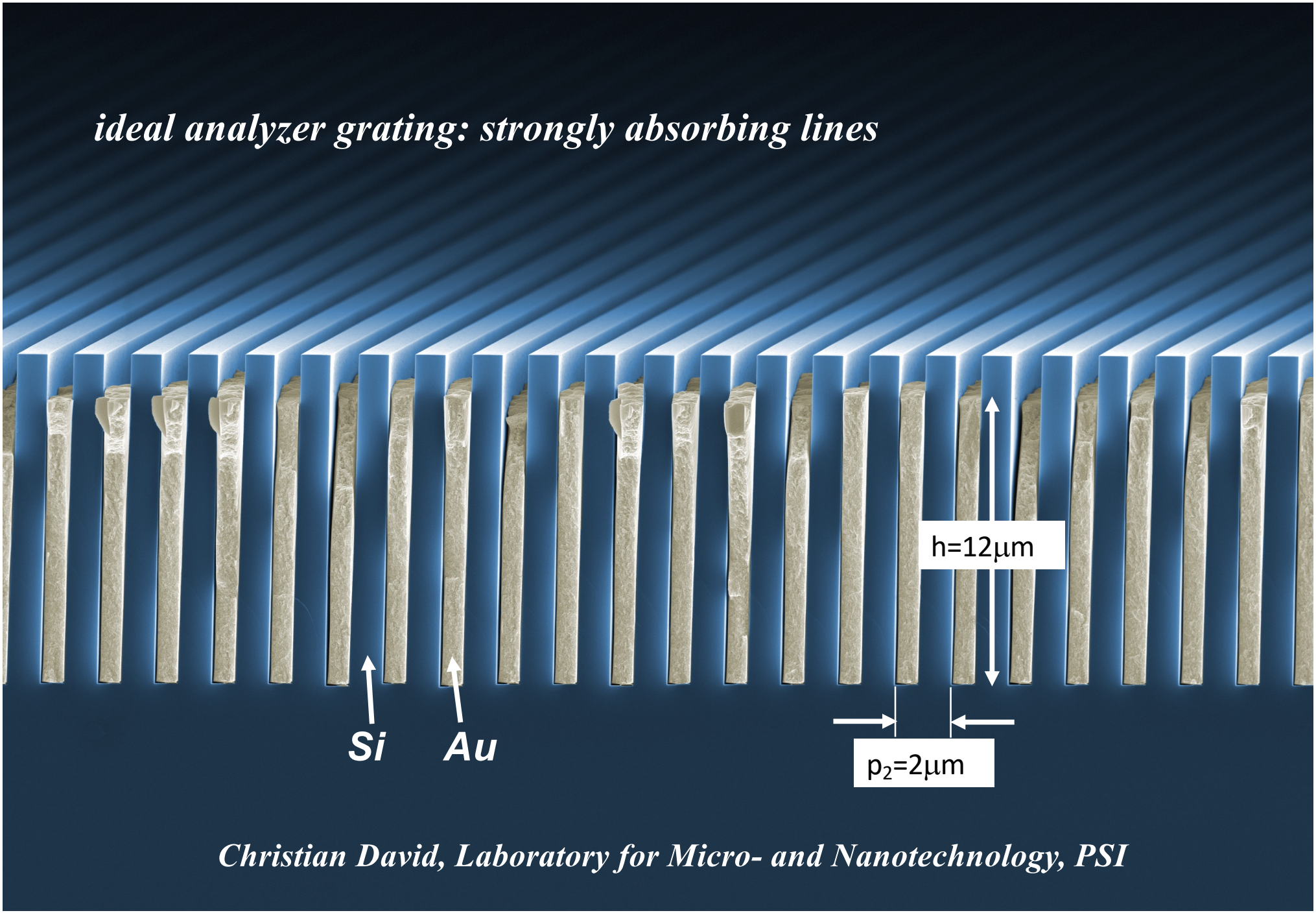
Patent pending, # 05 012 121.9 (2005)

ideal phase grating: π – phase shift



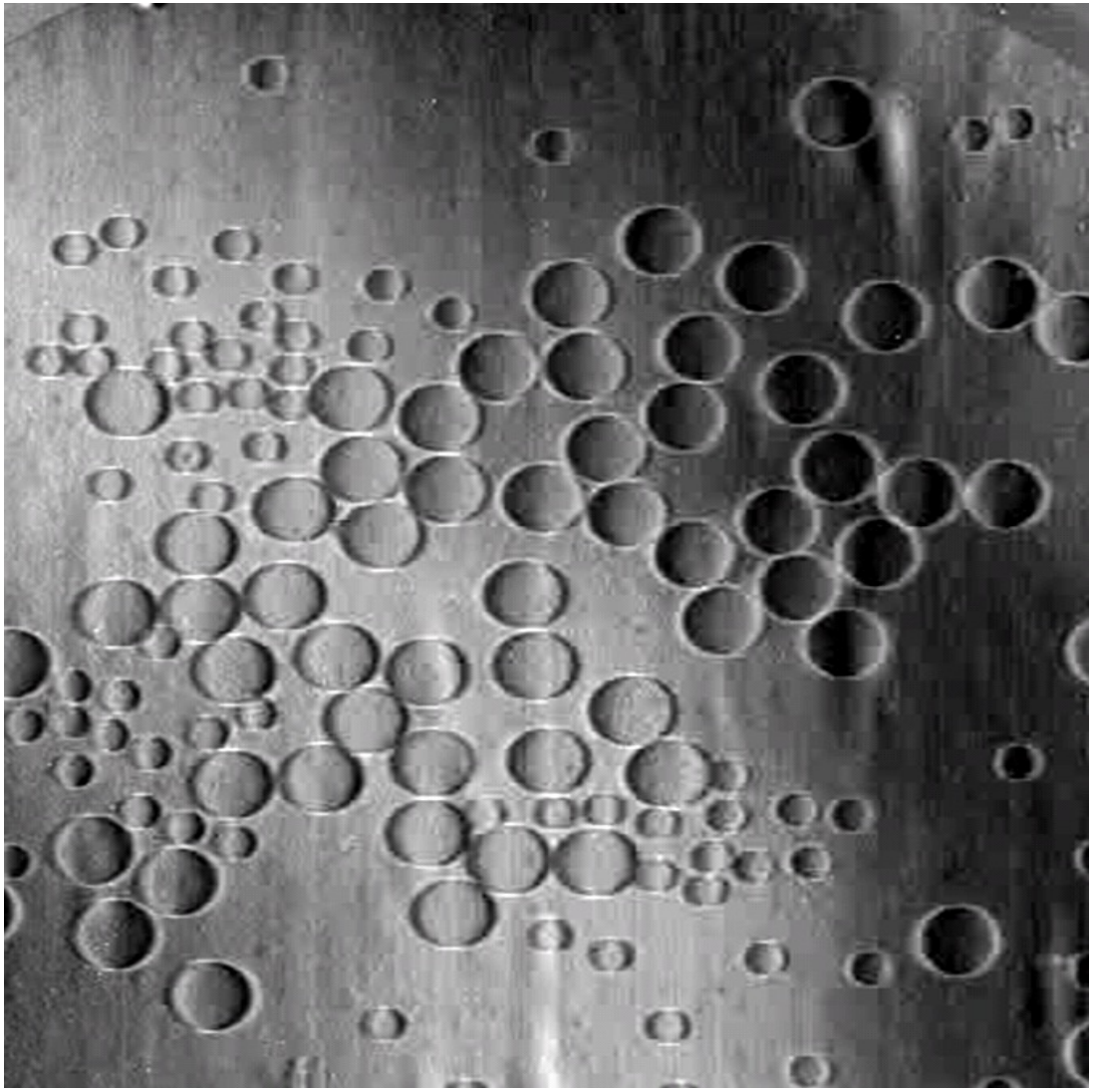
Christian David, Laboratory for Micro- and Nanotechnology, PSI

ideal analyzer grating: strongly absorbing lines



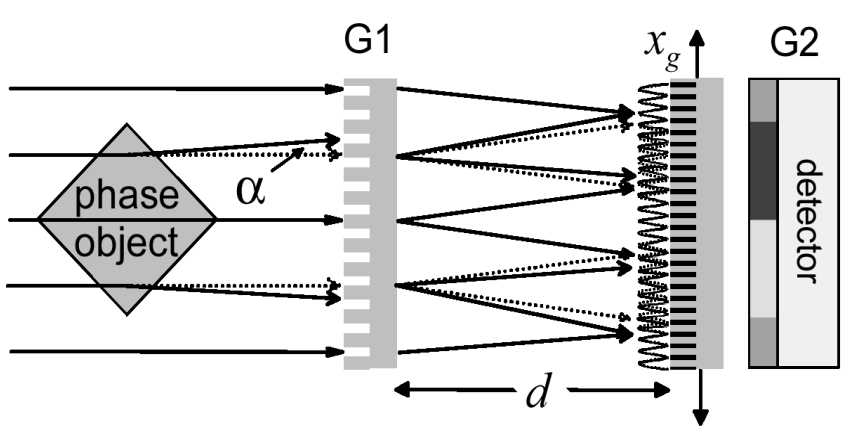
Christian David, Laboratory for Micro- and Nanotechnology, PSI

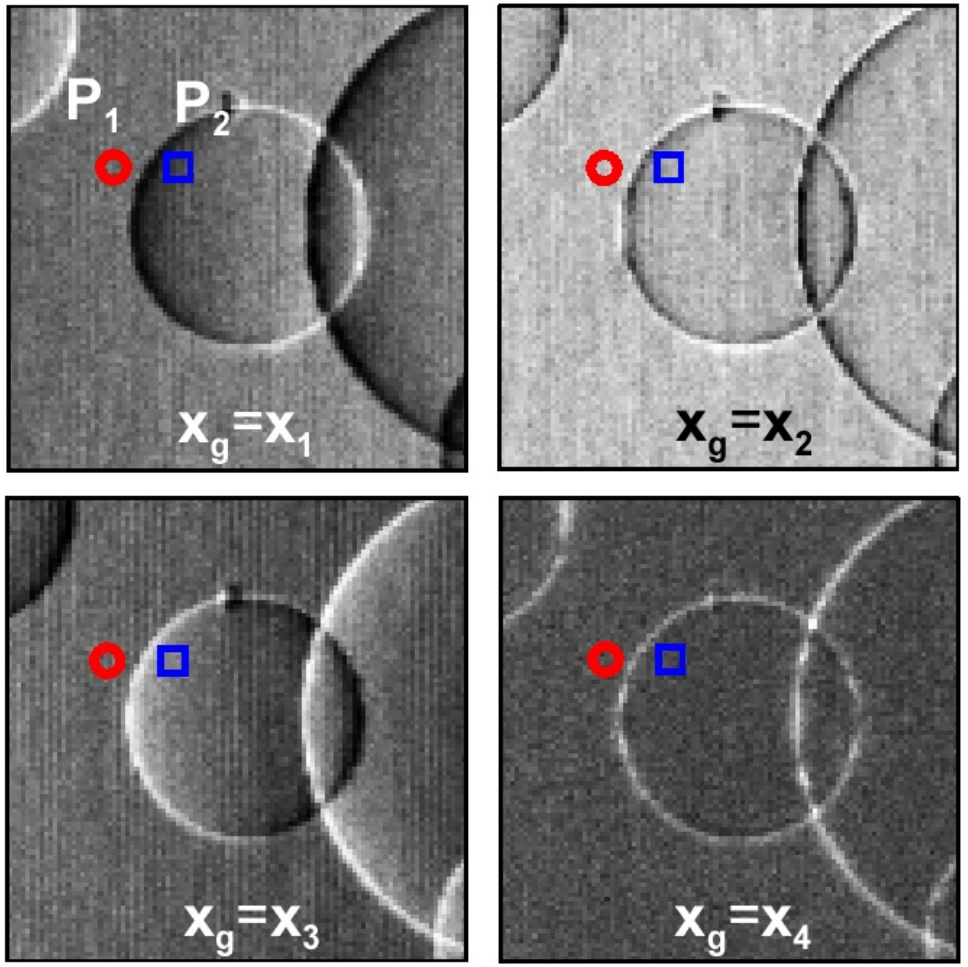
Synchrotron results

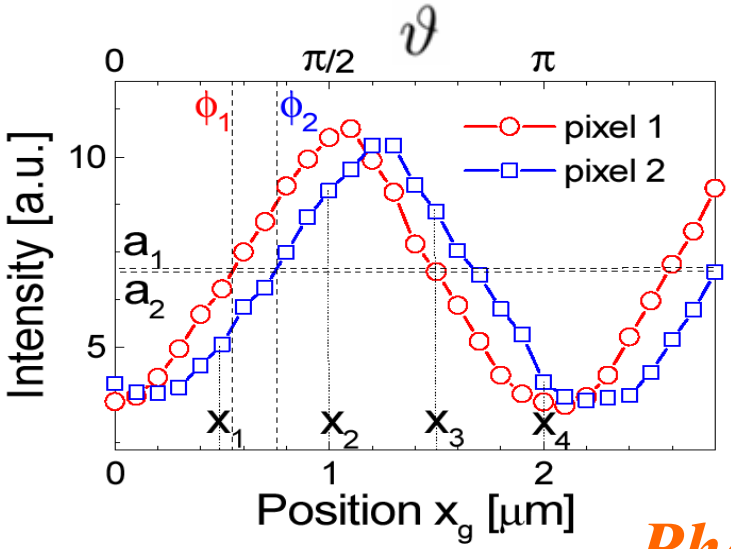


December 2002,
polystyrene spheres,
photon energy: 12.4 keV

Separation of phase shift & absorption

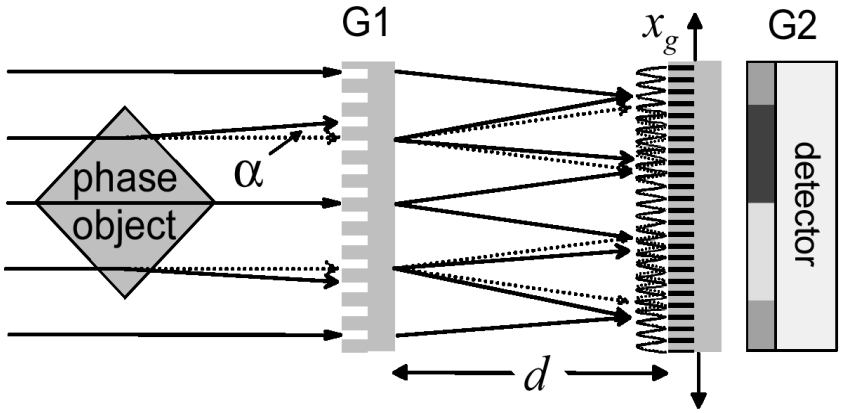




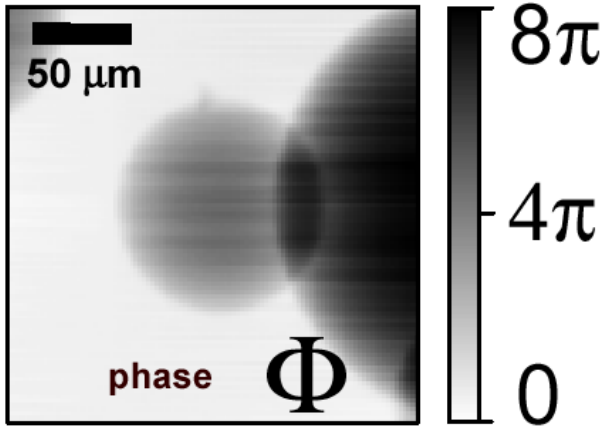


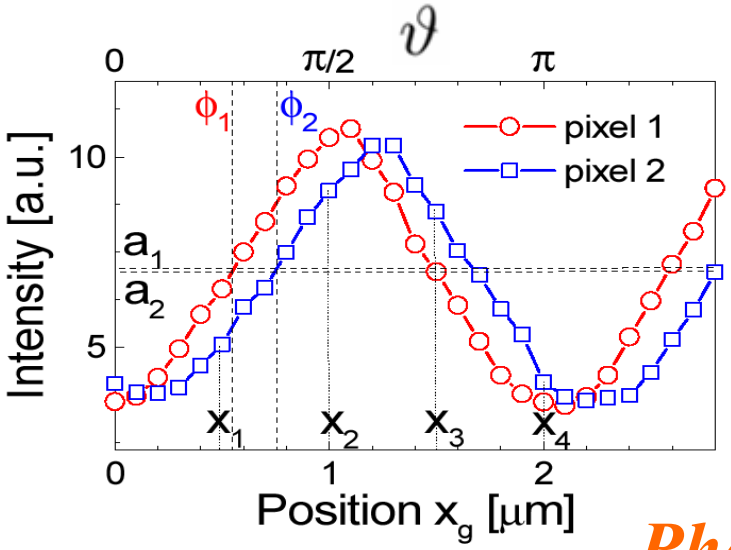
Phase stepping

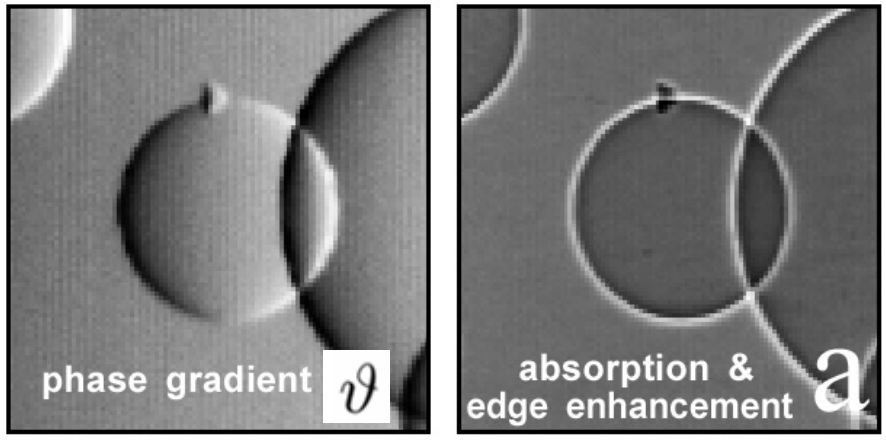
Separation of phase shift & absorption



$$\vartheta = \frac{\lambda d}{p_2}\frac{\partial \Phi}{\partial x}$$

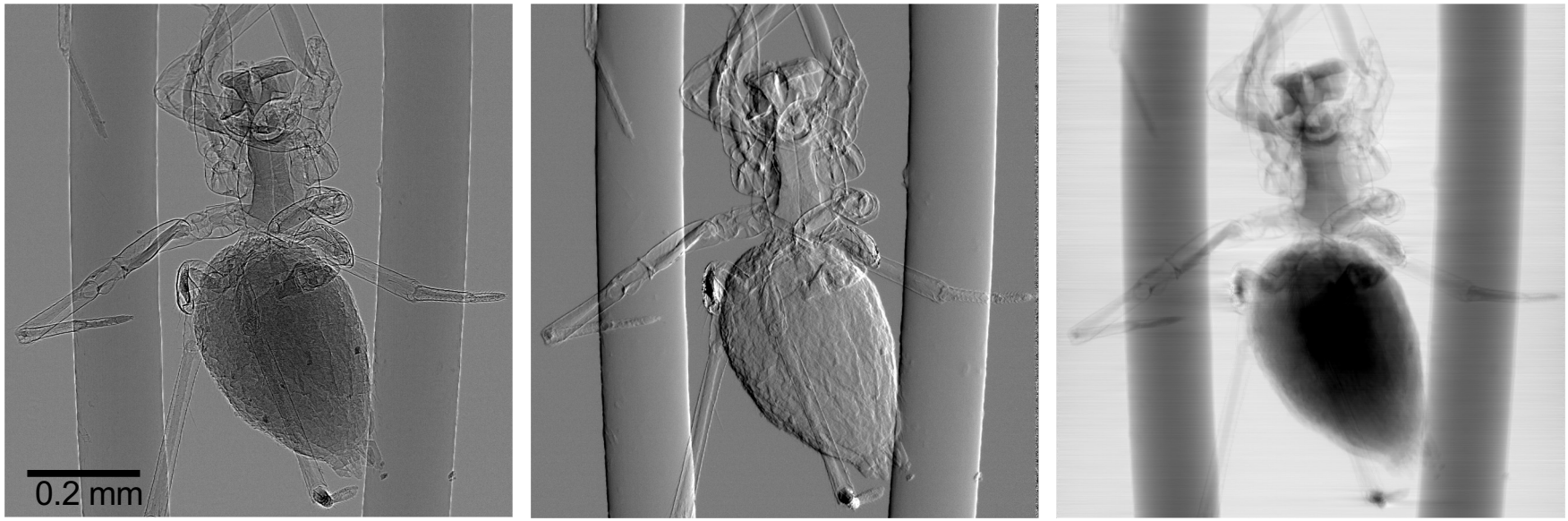






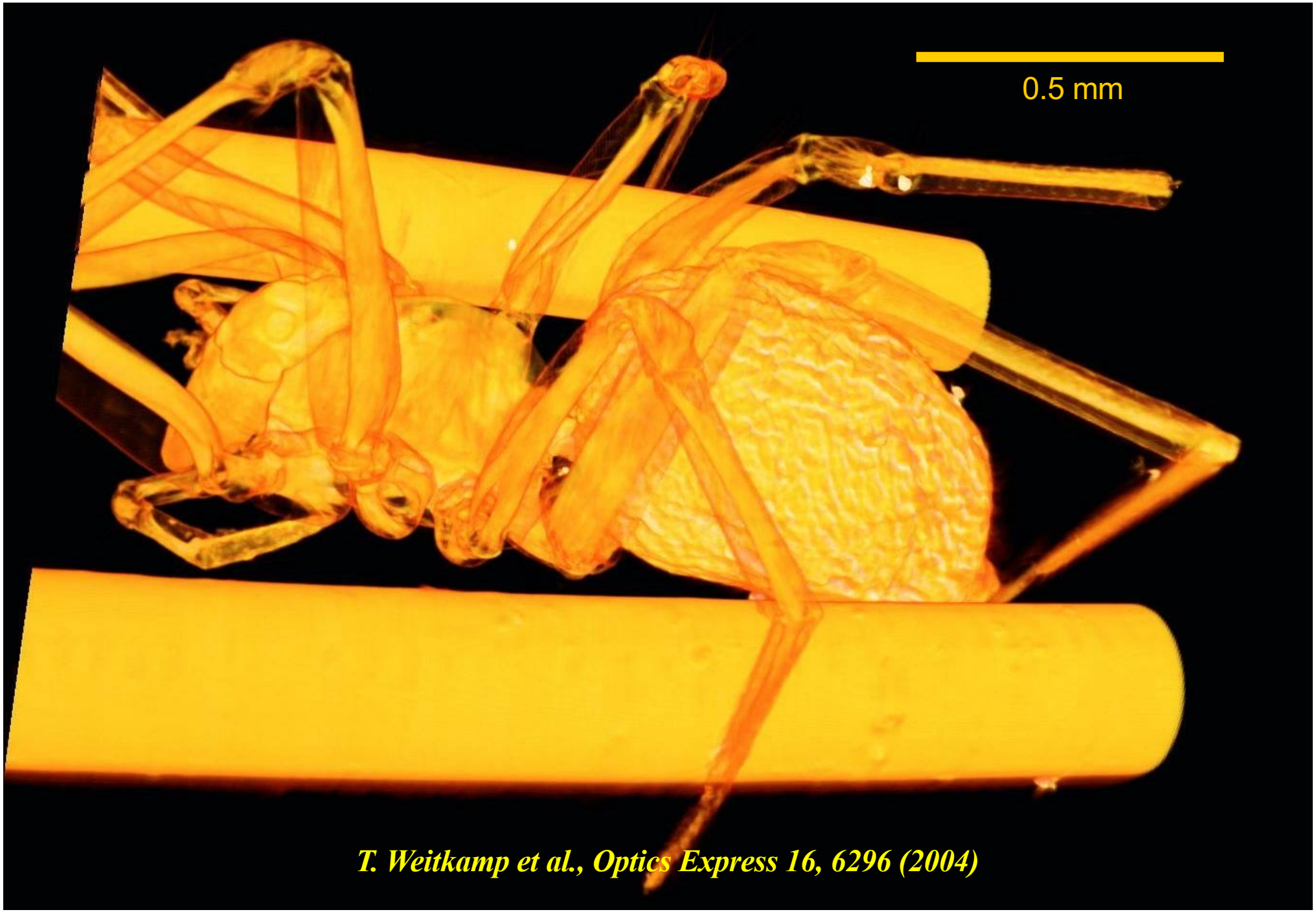
Phase stepping

Synchrotron results

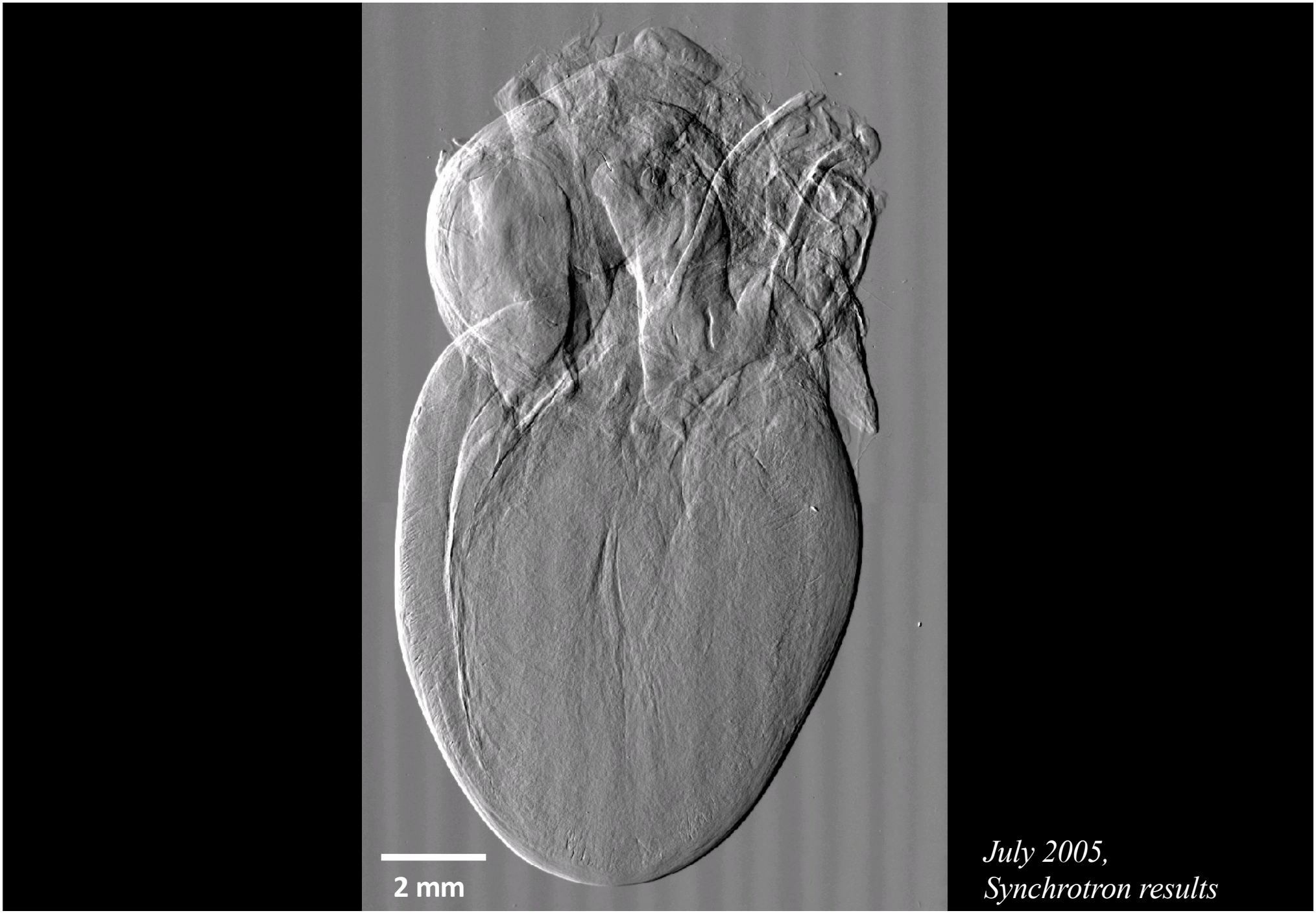


Transmission ***Phase gradient*** ***Phase***

T. Weitkamp et al., Optics Express 16, 6296 (2004)



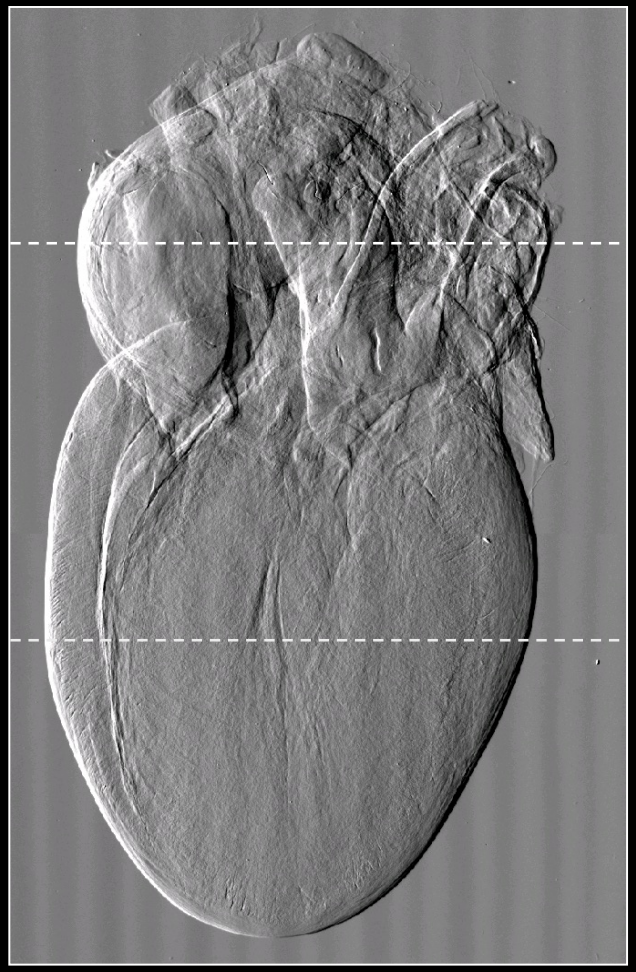
T. Weitkamp et al., Optics Express 16, 6296 (2004)



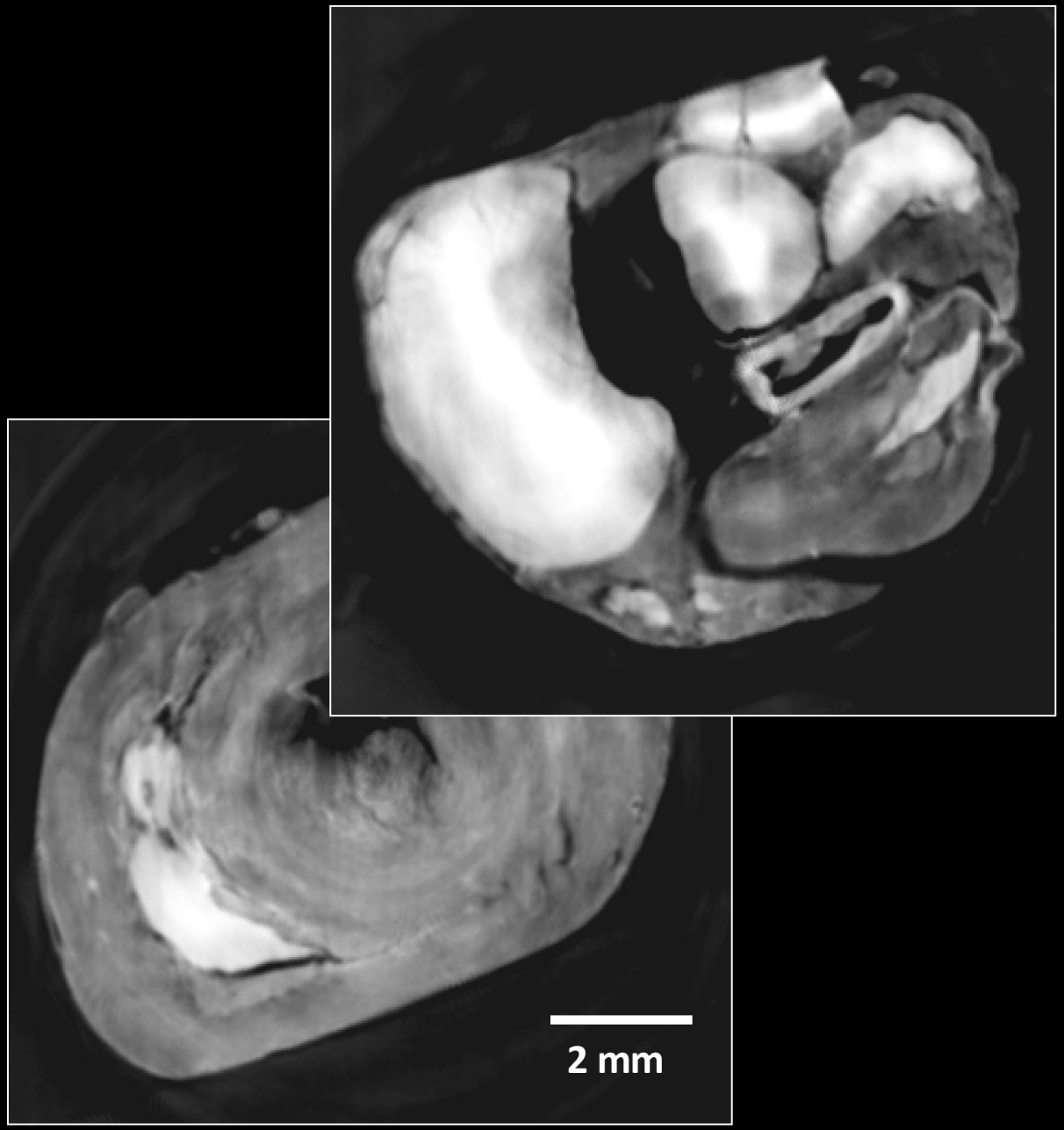
July 2005,
Synchrotron results

absorption
phase contrast

phase contrast projections

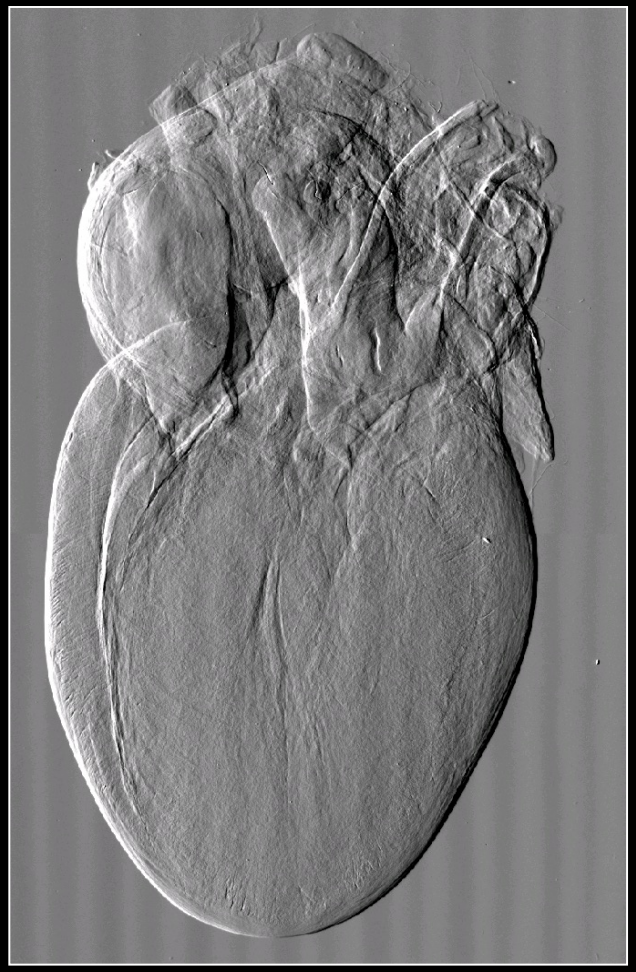


phase tomograms



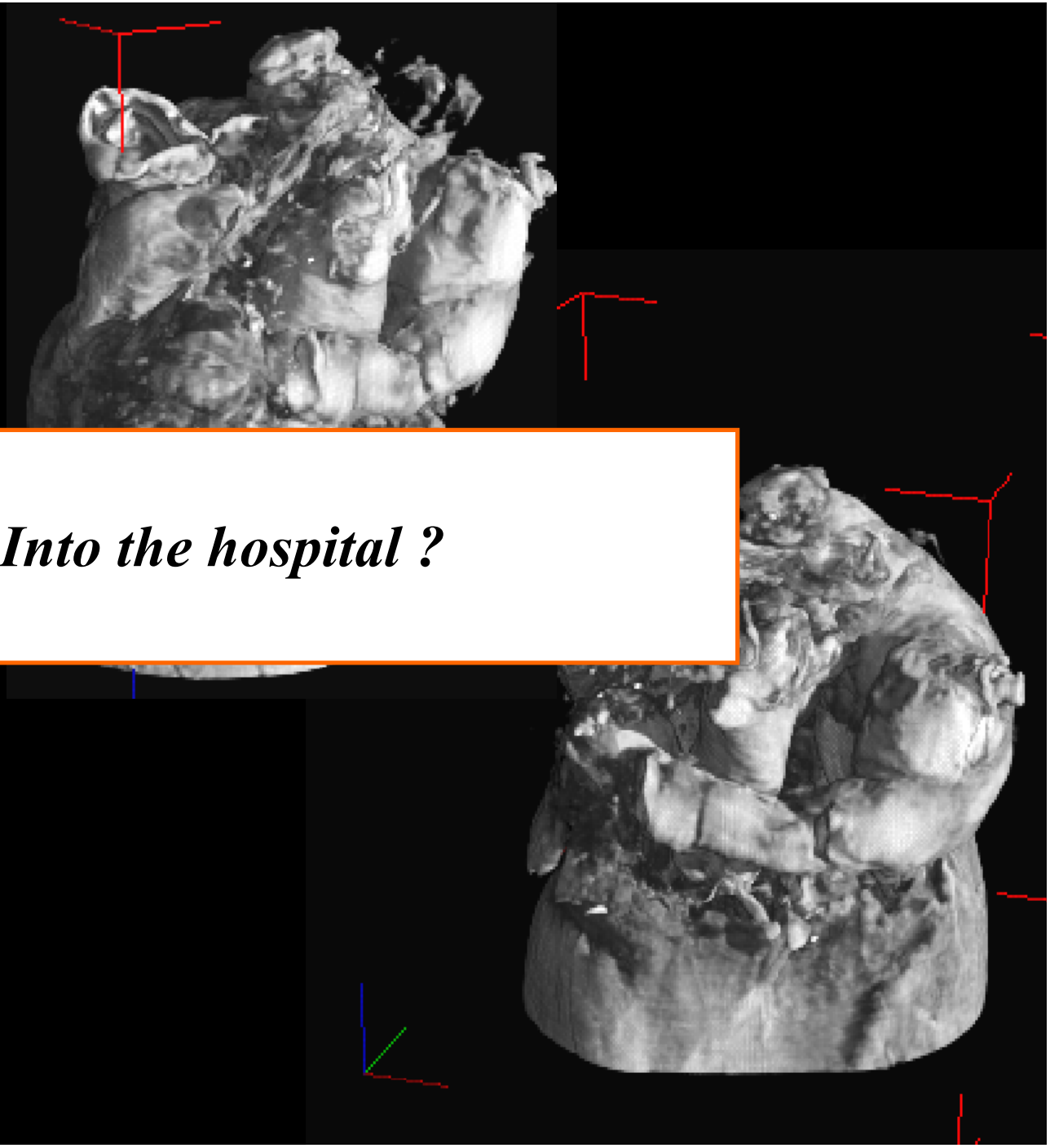
July 2005,
Synchrotron results

phase contrast projections



July 2005,
Synchrotron results

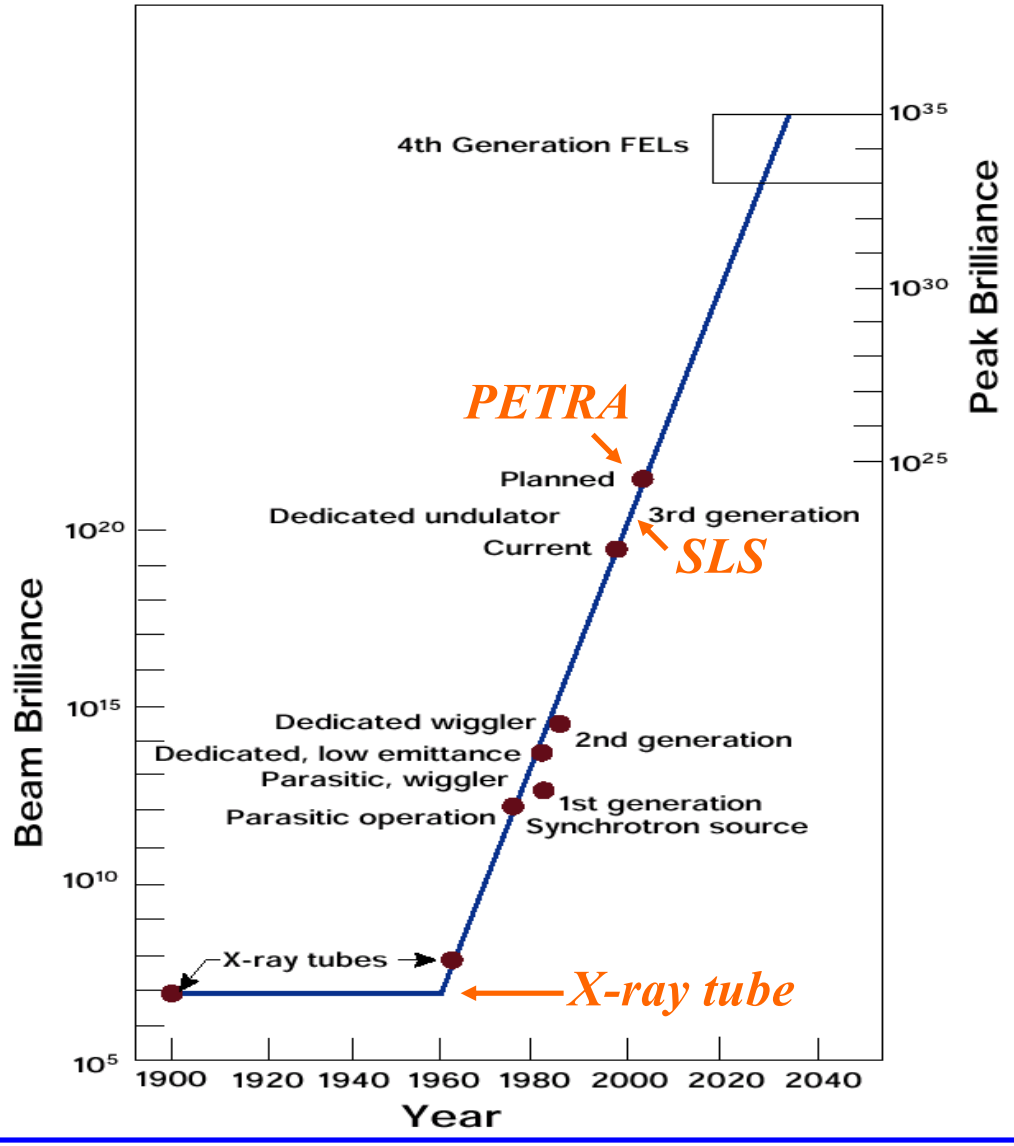
phase contrast projections



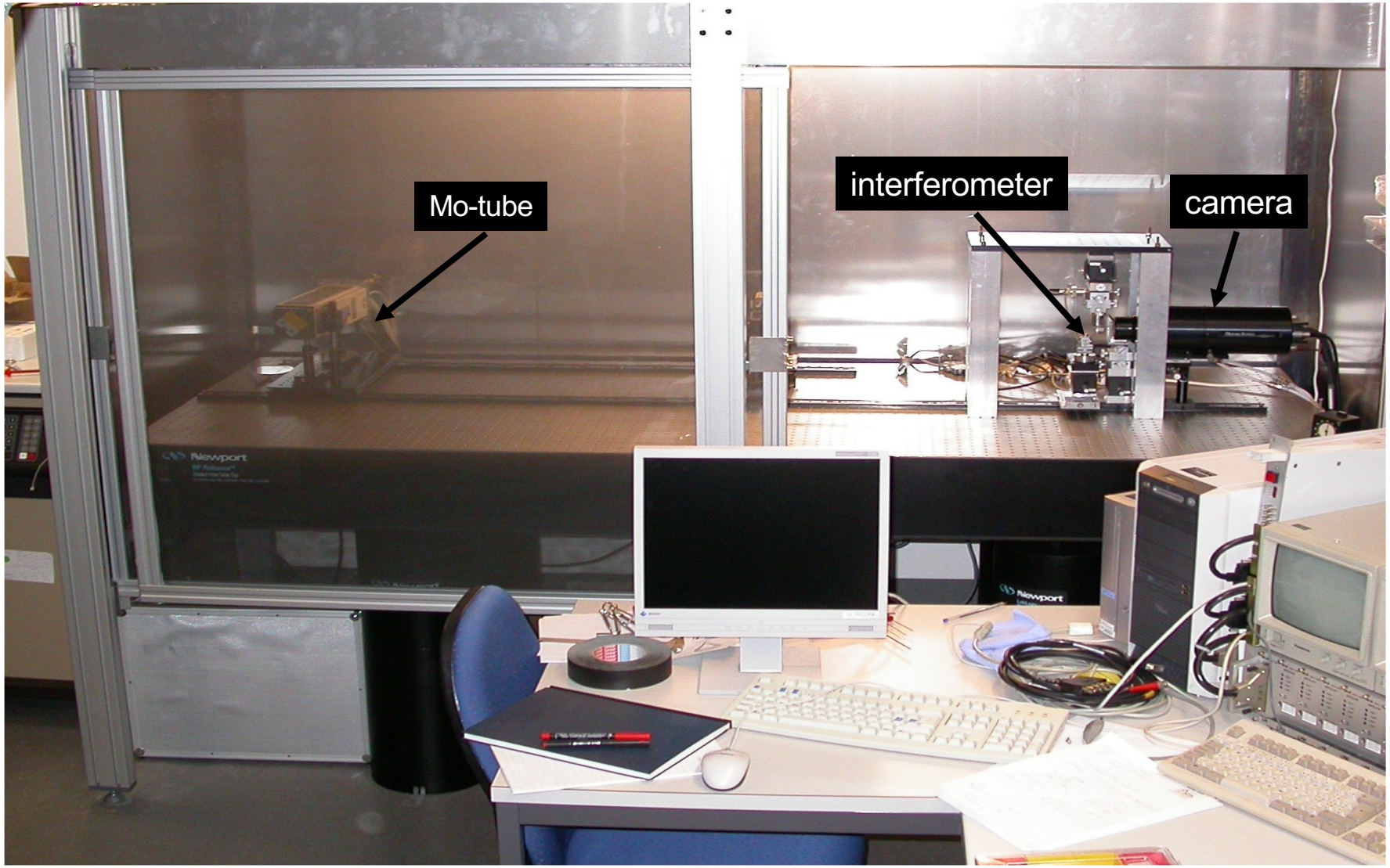
Into the hospital ?

July 2005,
Synchrotron results

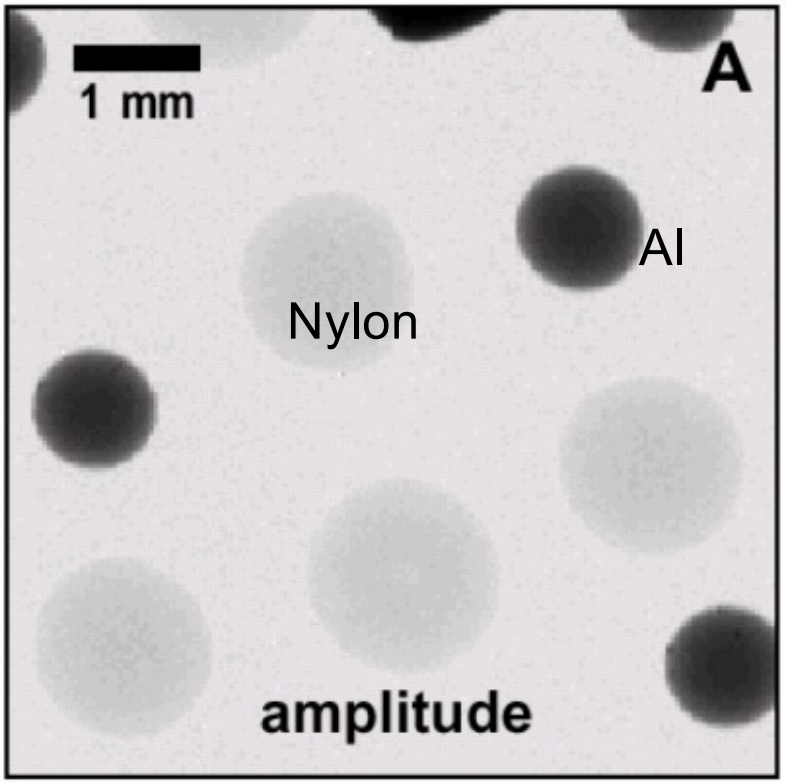
A step down in brilliance

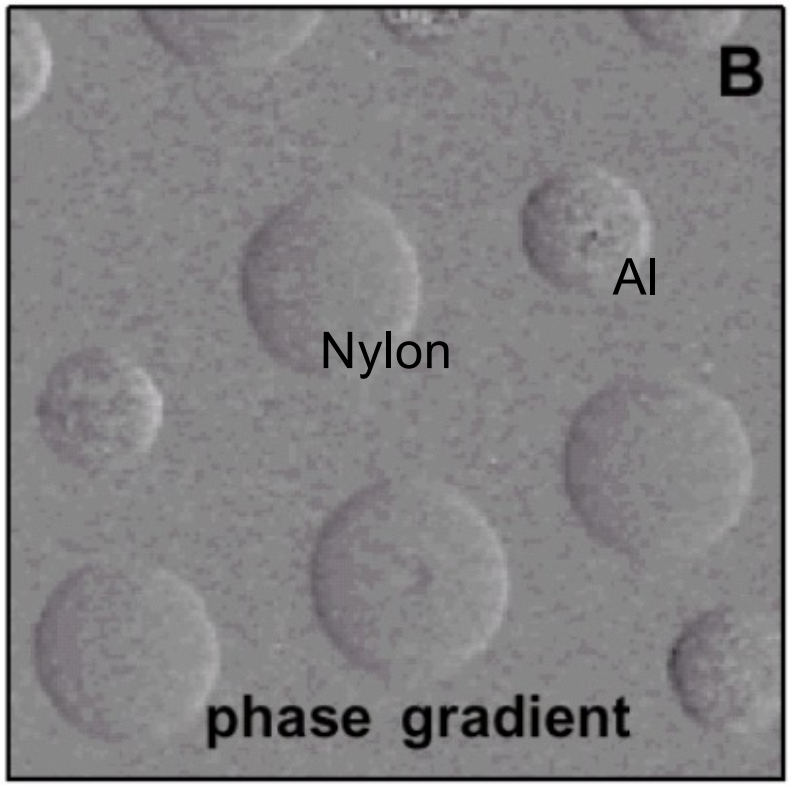


X-ray tube test setup



X-ray tube results

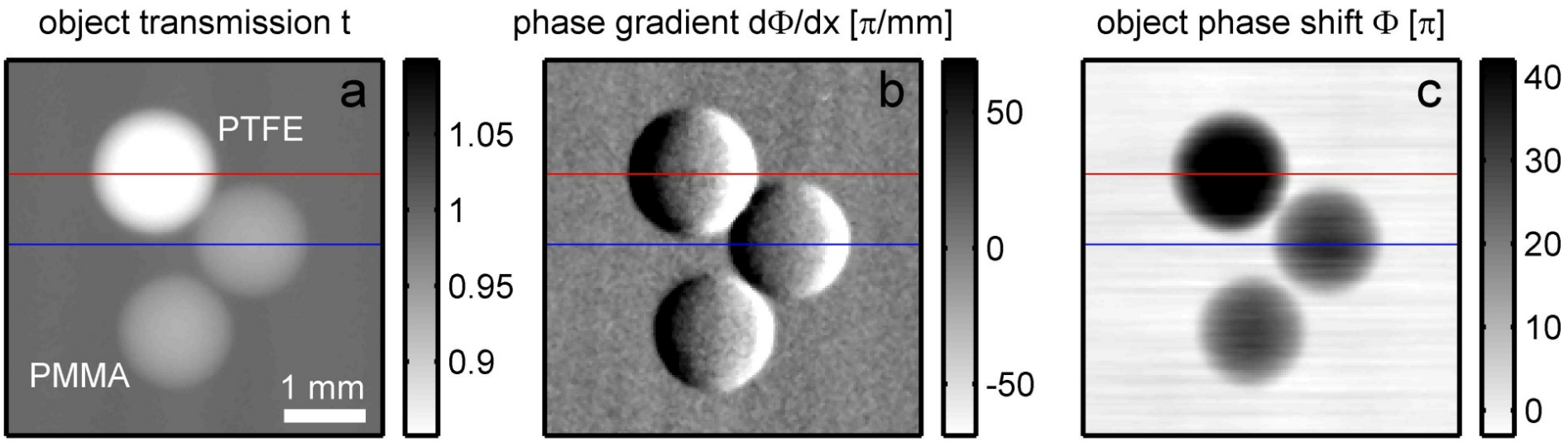




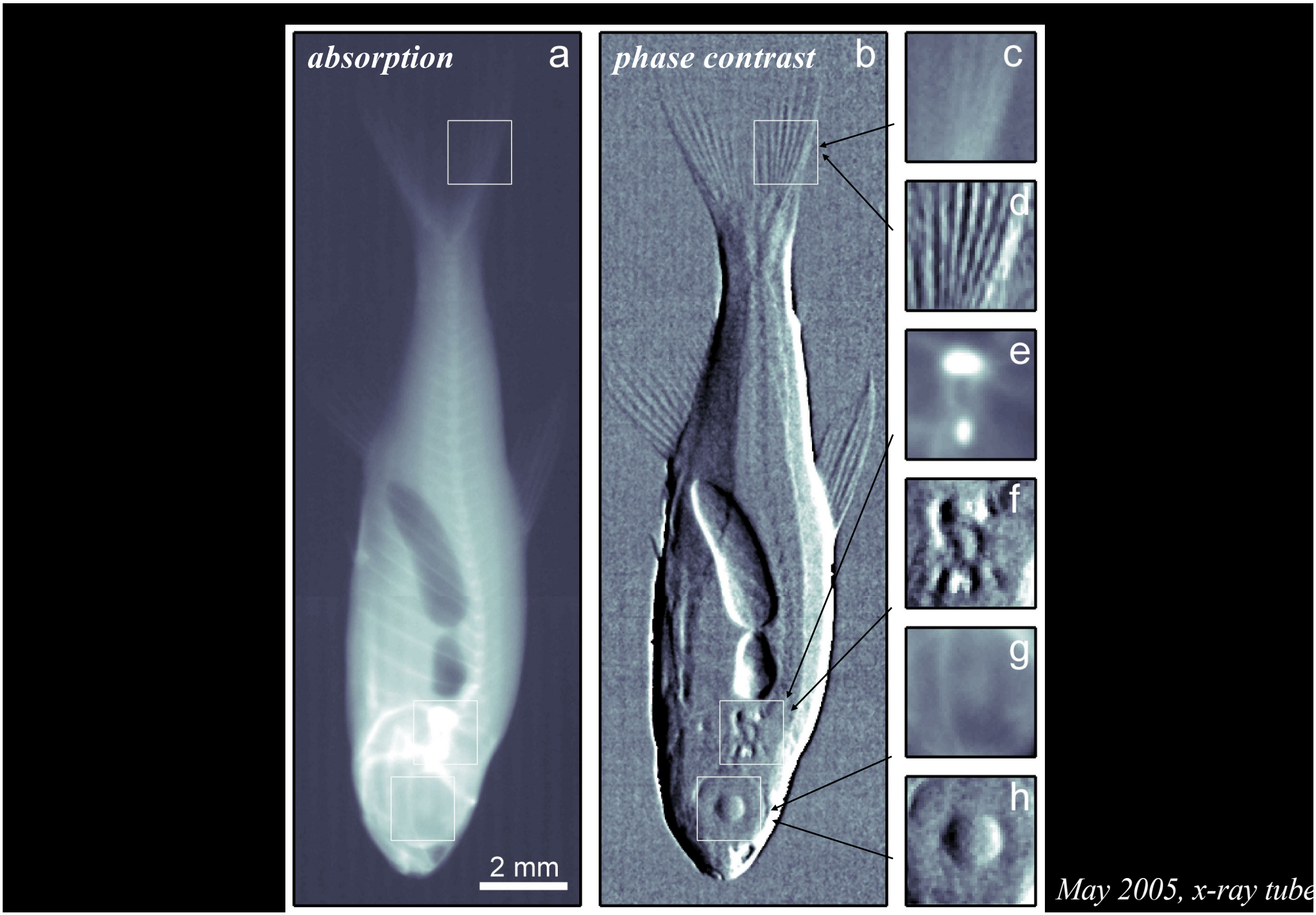
October 2004, first results !

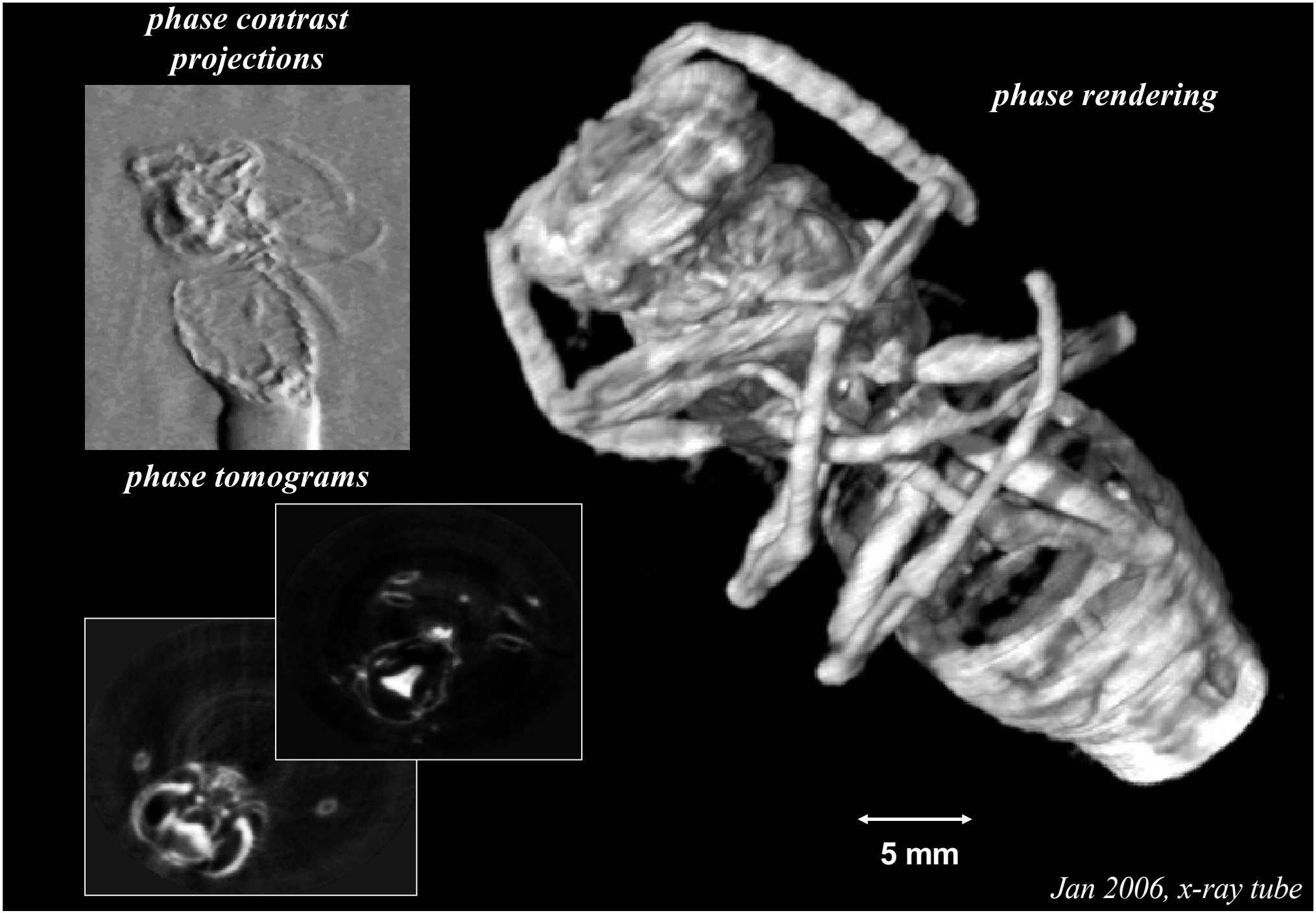
X-ray tube results

standard Seifert X-ray tube source, Mo target 1 kW, point focus: 0.8 x 0.6 mm^2, distance 1.7 m



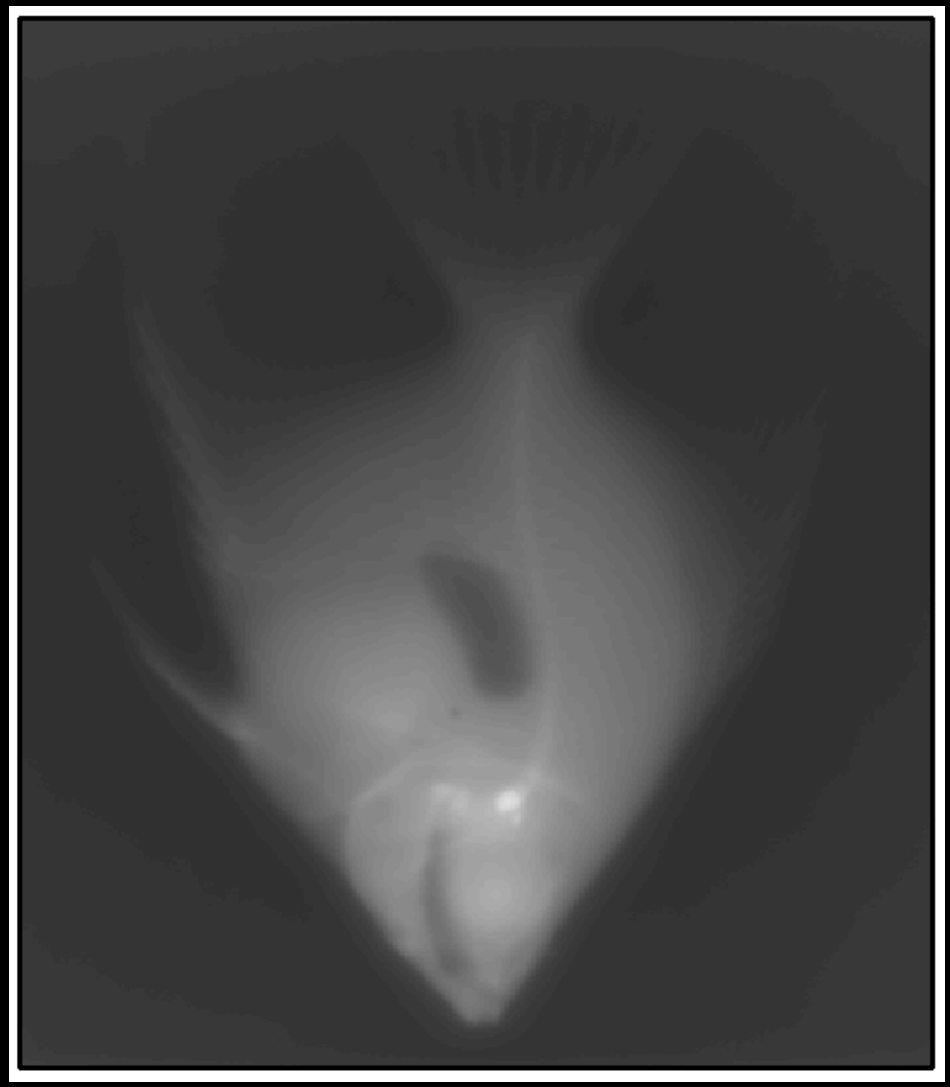
Pfeiffer et al., submitted (2005)

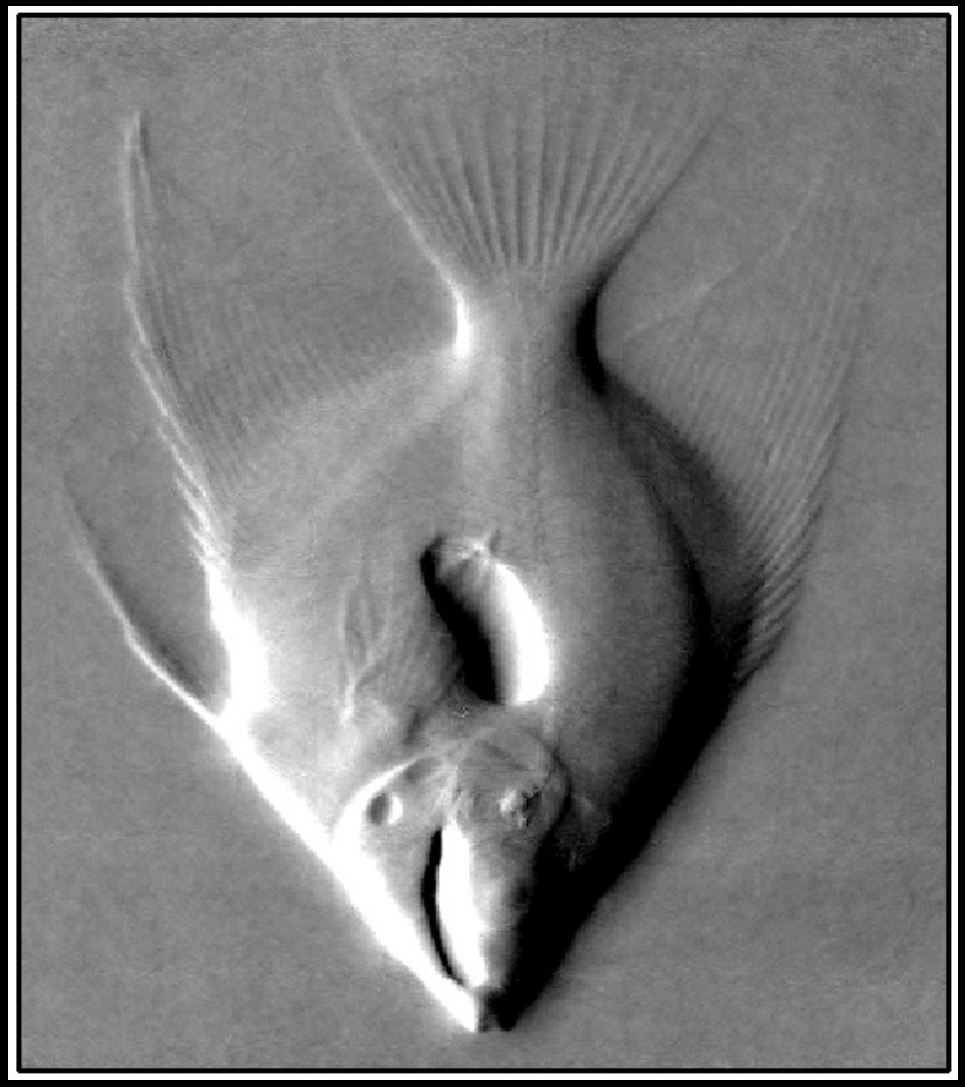

absorption
a
phase contrast
b
c
d
e
f
g
h
2 mm
May 2005, x-ray tube


phase contrast projections
phase tomograms
phase rendering
5 mm
Jan 2006, x-ray tube

absorption

phase contrast



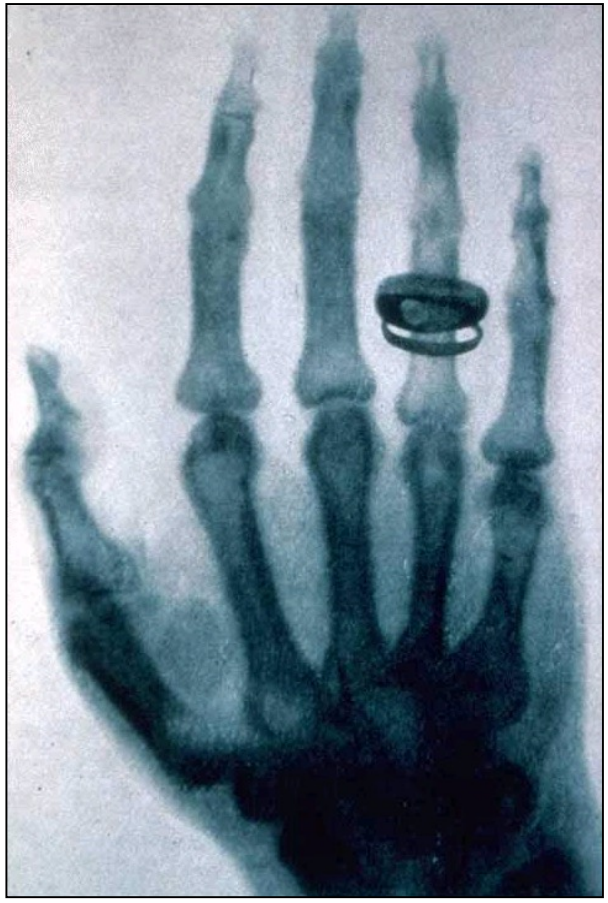


5 cm !

total exposure time: 200 sec

Jan 2006, x-ray tube

The future ?

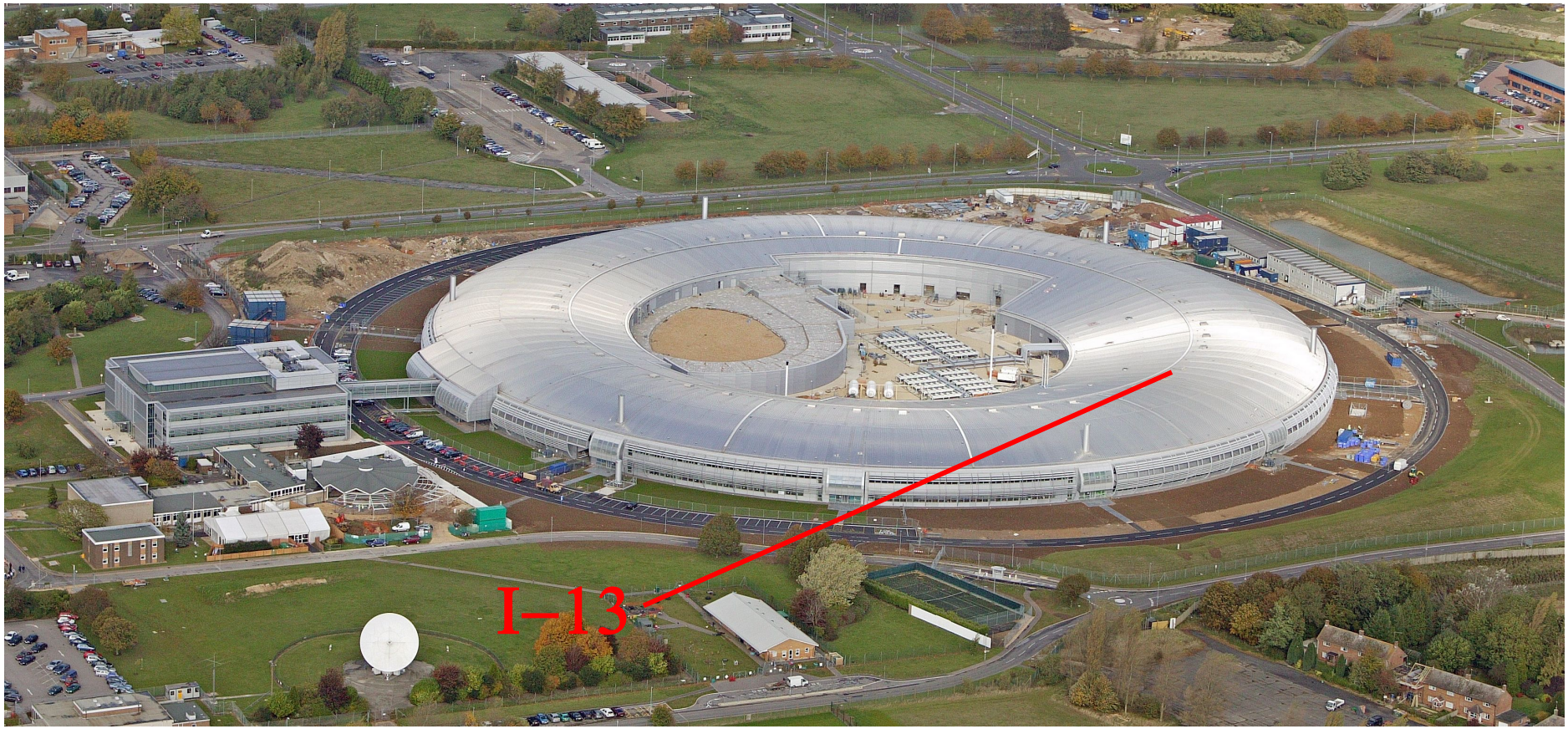


Absorption Image, 1895

?

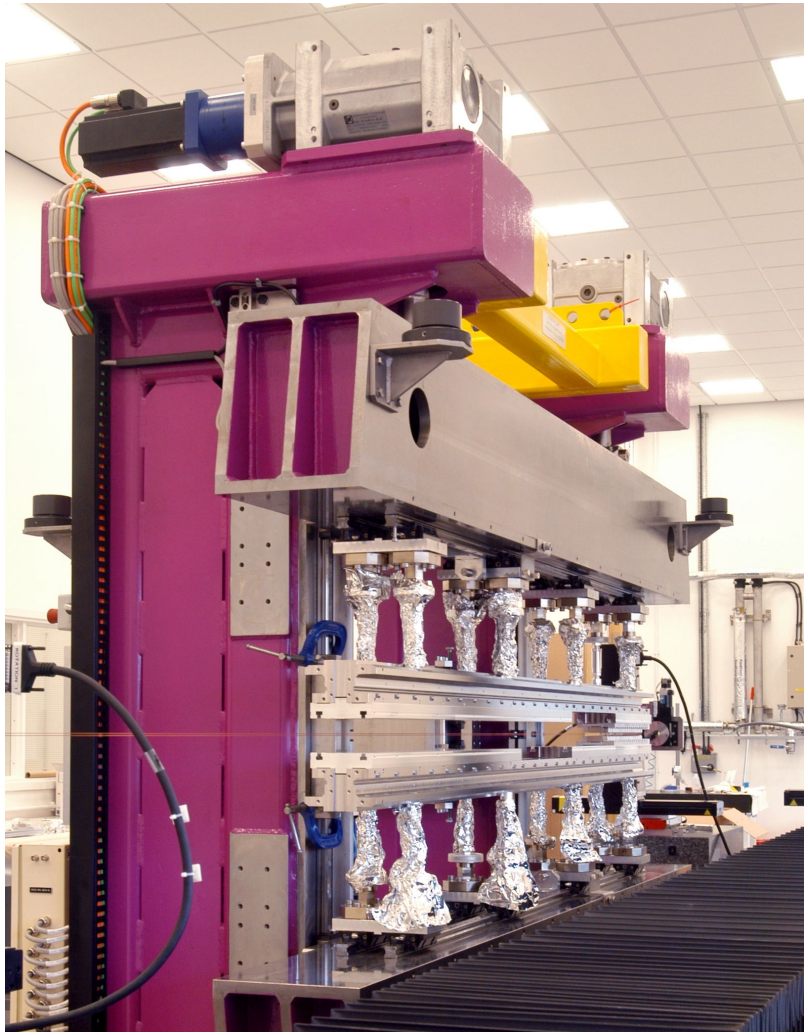
Phase Image

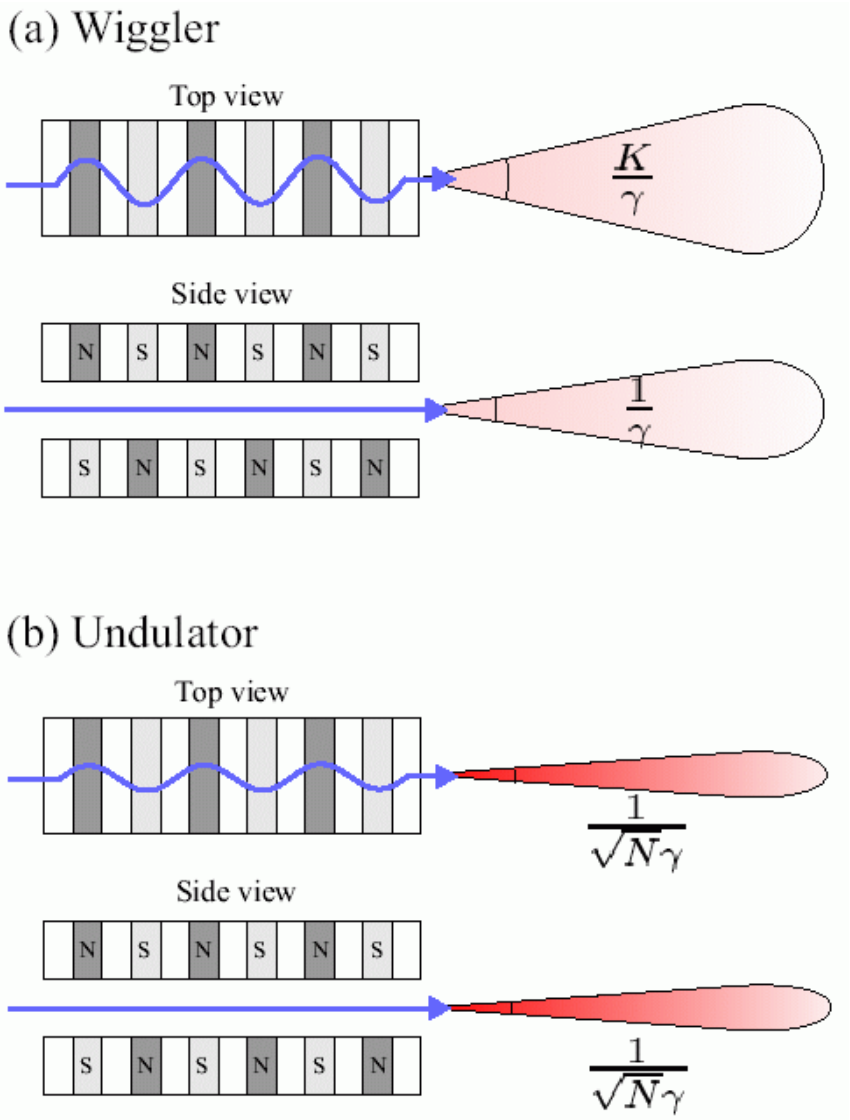
Diamond Light Source, Oct 2005



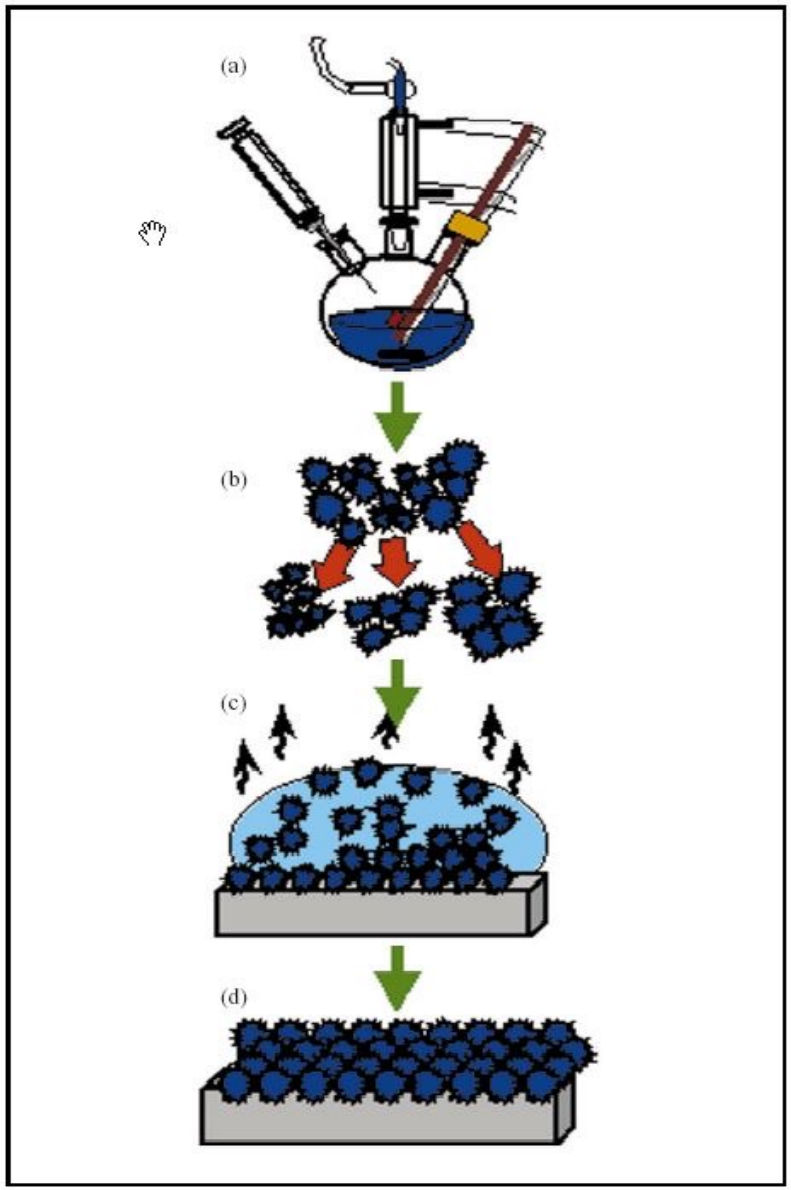
I16 Materials and Magnetism Beamline

Undulator Radiation Source



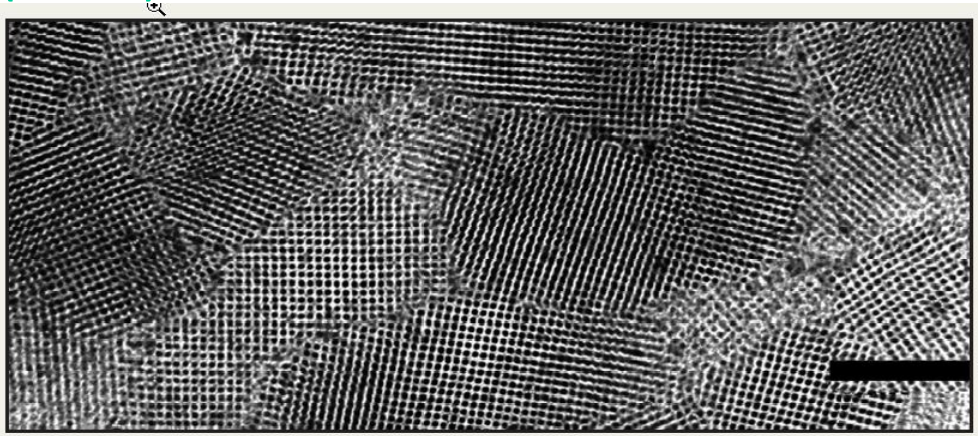


Chemical Synthesis of Nanocrystals



- Reactants introduced rapidly
- High temperature solvent
- Surfactant/organic capping agent
- Square superlattice (200nm scale)

C. B. Murray, IBM J. Res. & Dev. **45** 47 (2001)



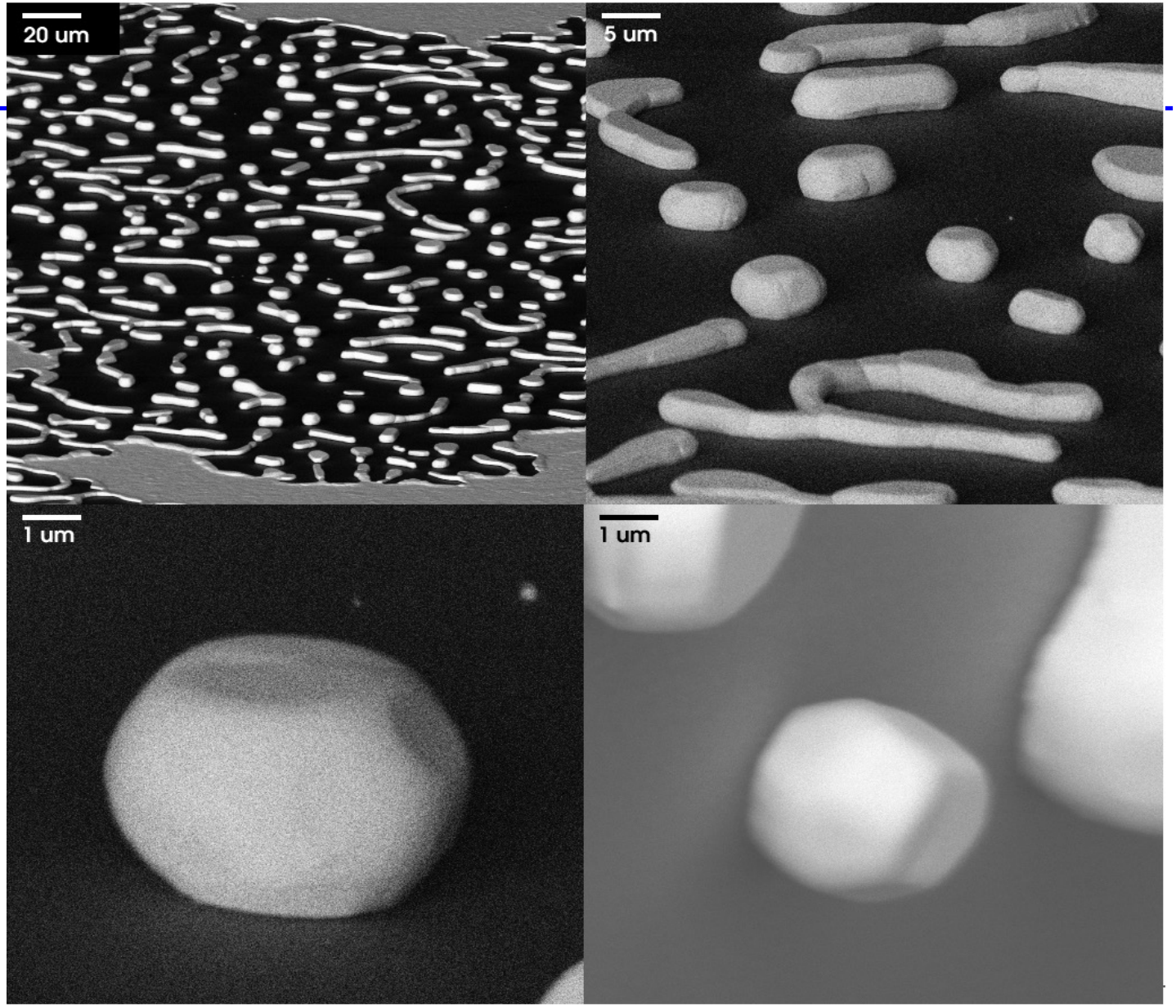
SEMS

Sample preparation:

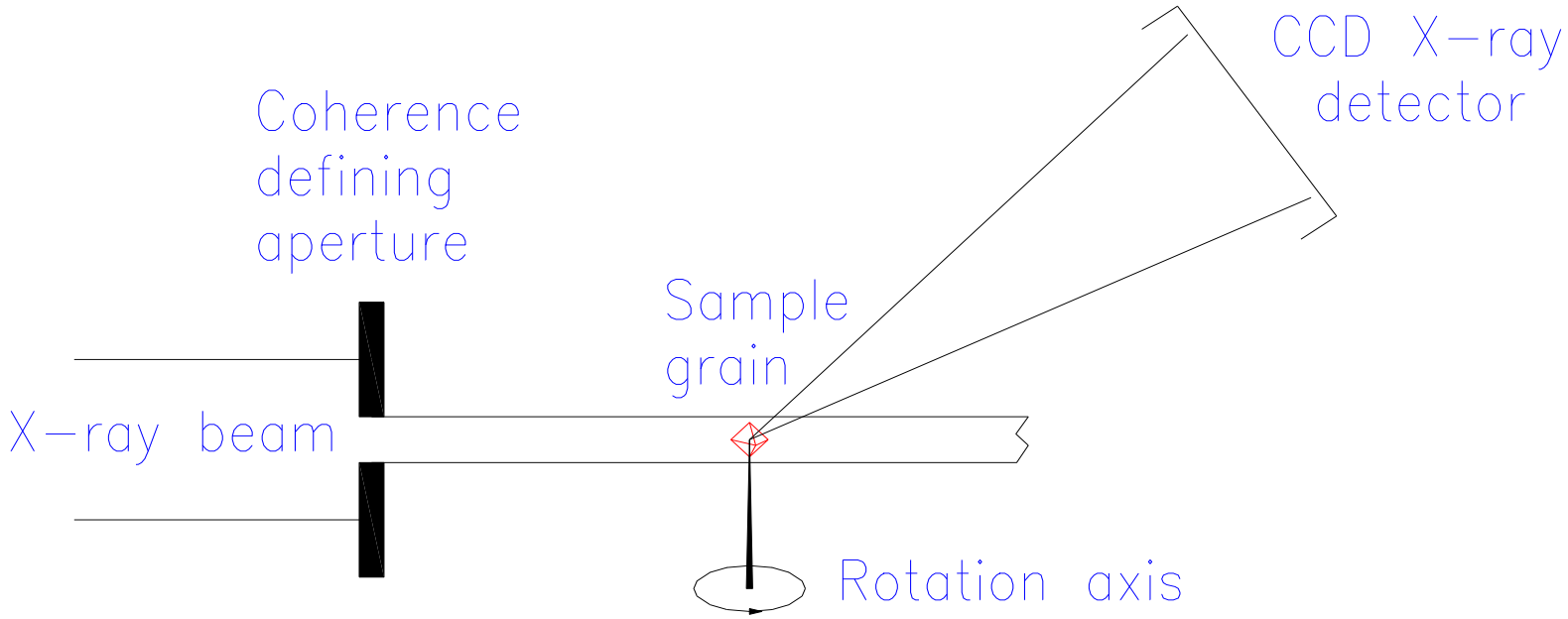
Au blanket film

Quartz substrate

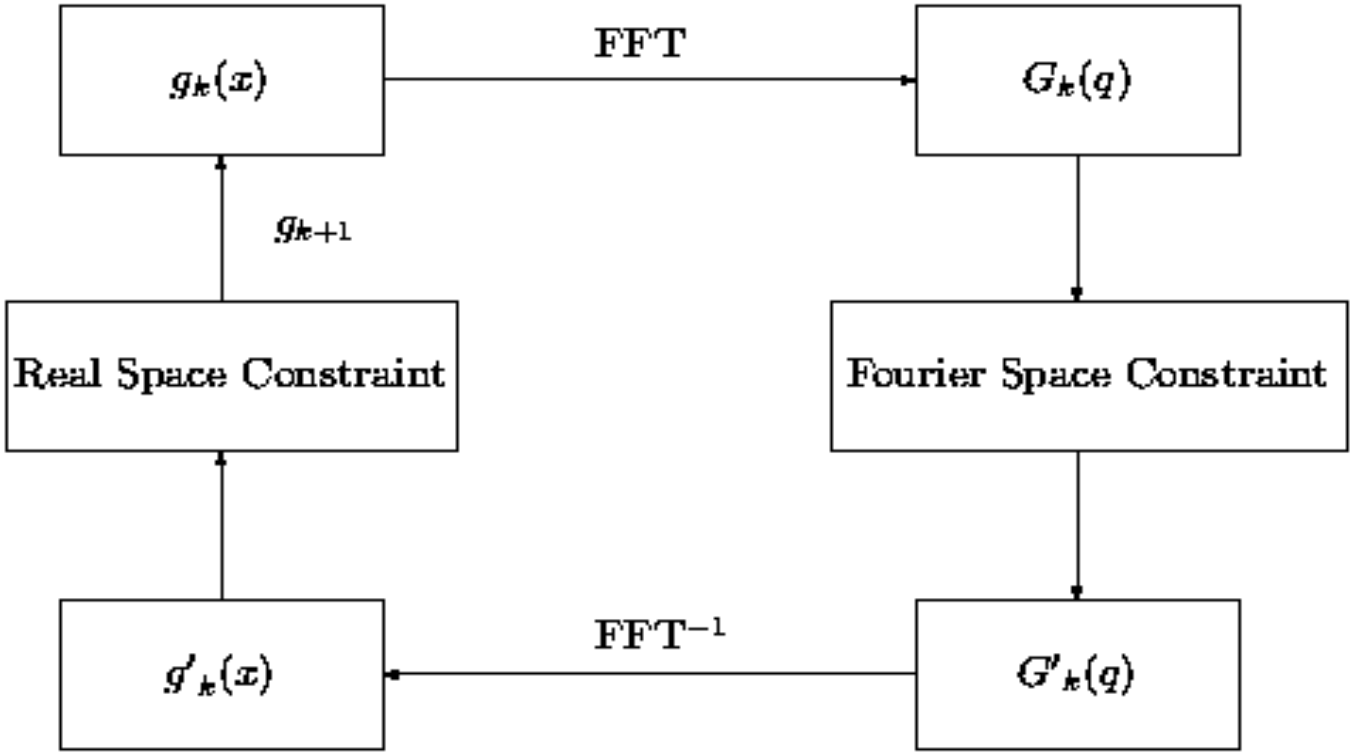
Annealed at 950°C for 70 hrs.



Lensless X-ray Microscope

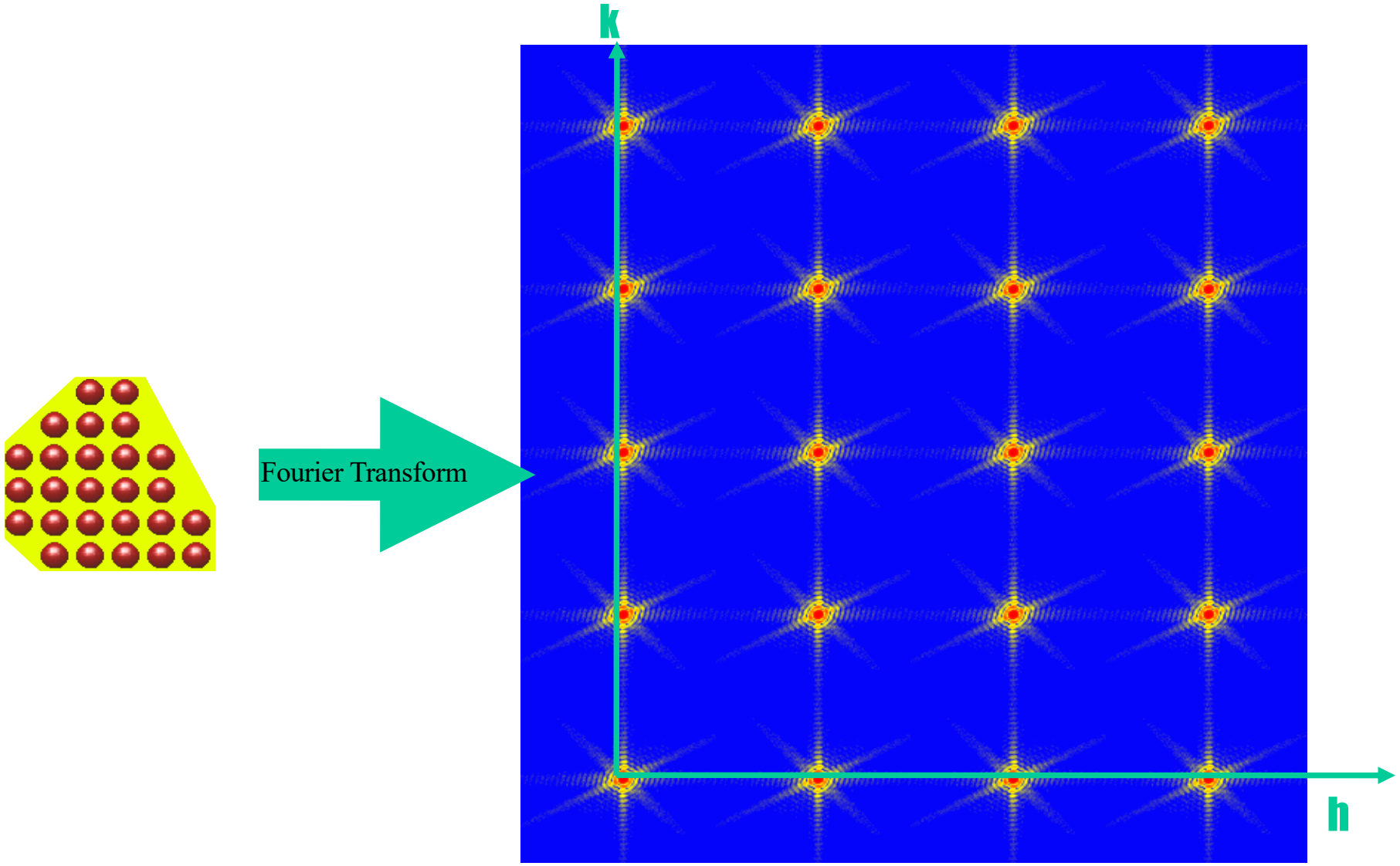


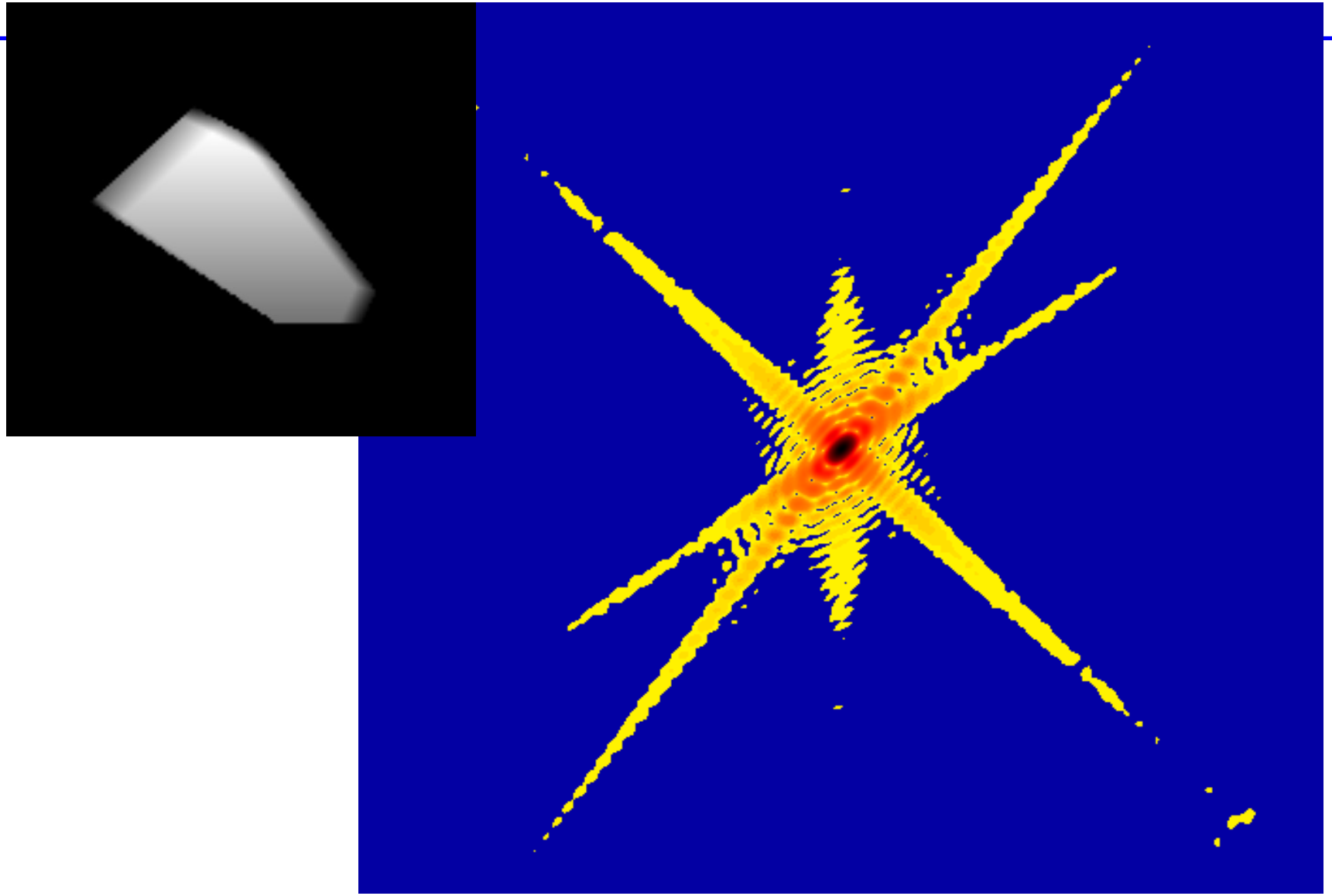
Generic "Error Reduction" method



J. R. Fienup Appl. Opt. 21 2758 (1982)
R. W. Gerchberg and W. O. Saxton Optik 35 237 (1972)

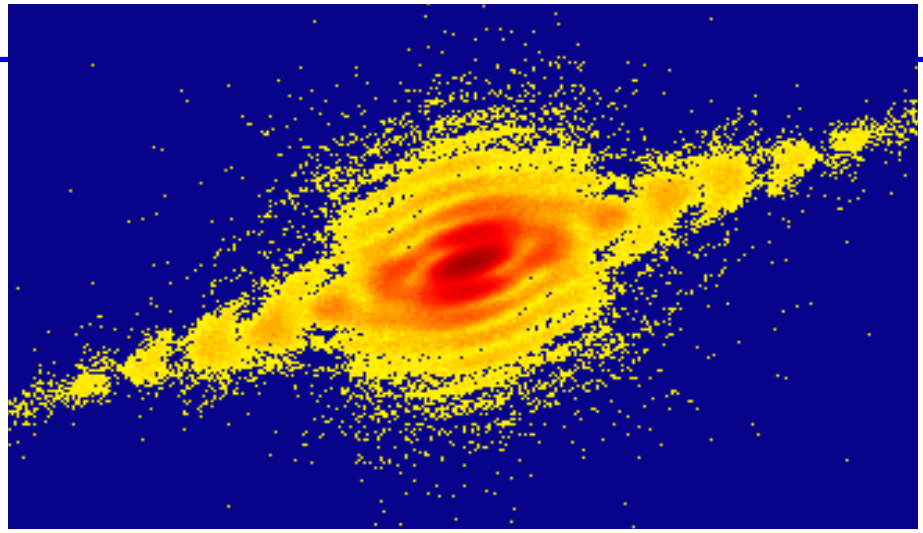
Coherent Diffraction from Crystals

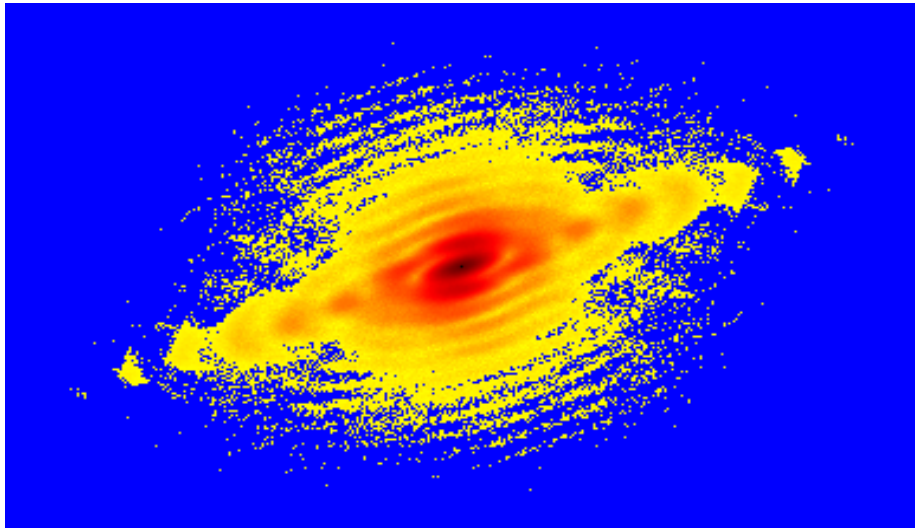


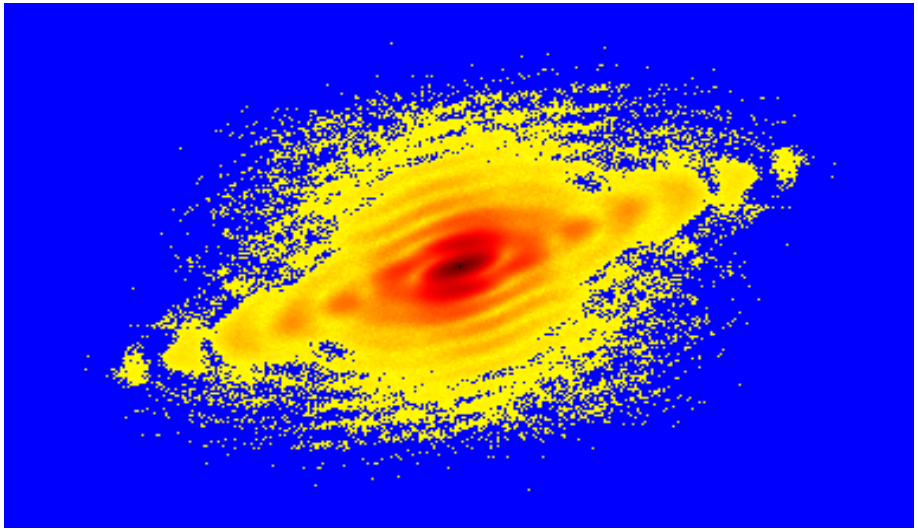


Symmetrized Data and two best fits

Chisq=0.0005

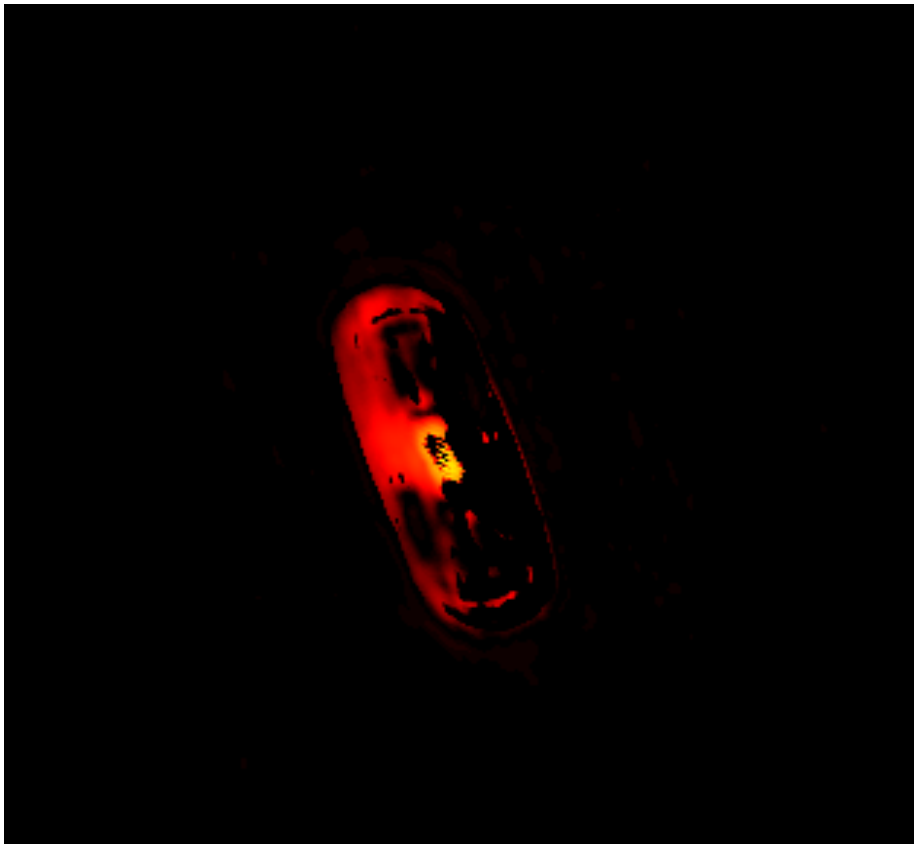


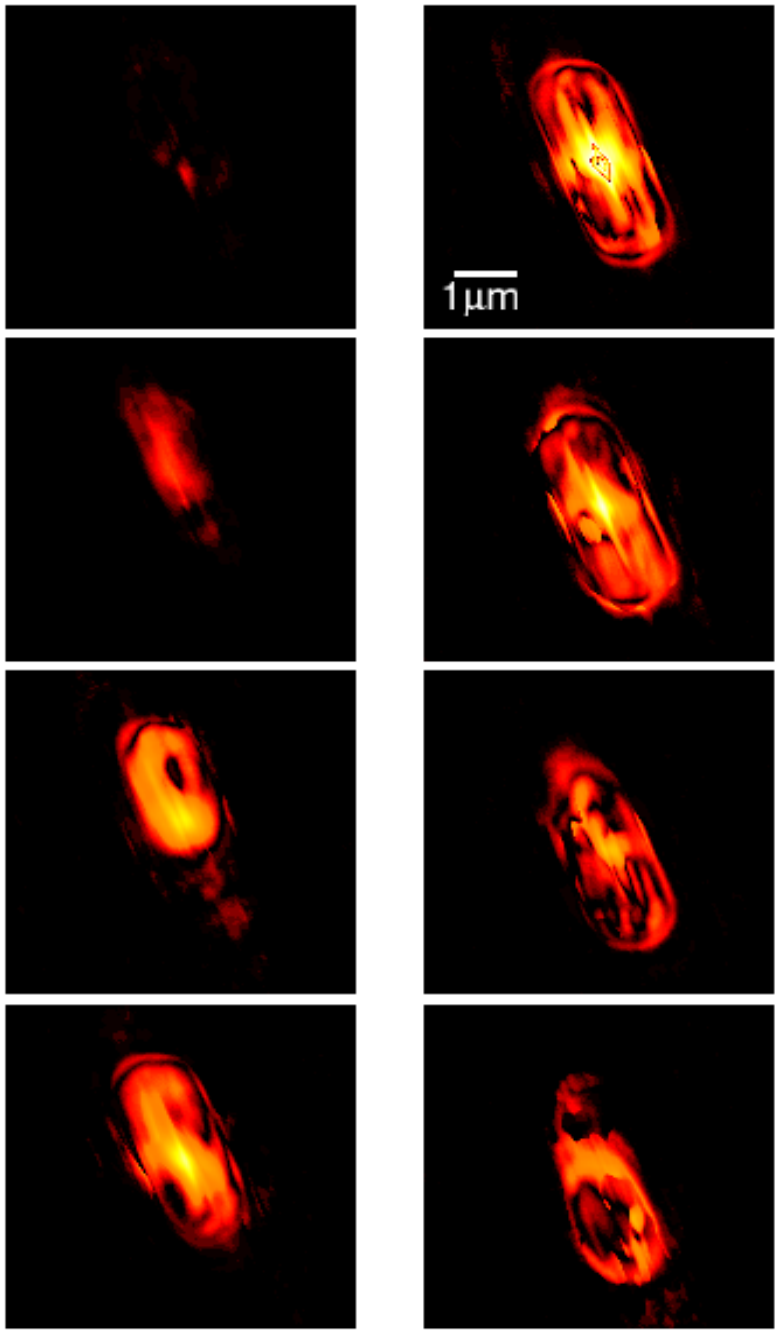


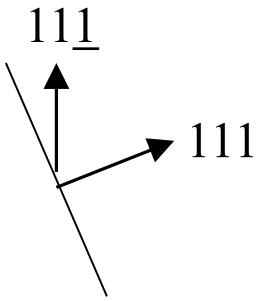


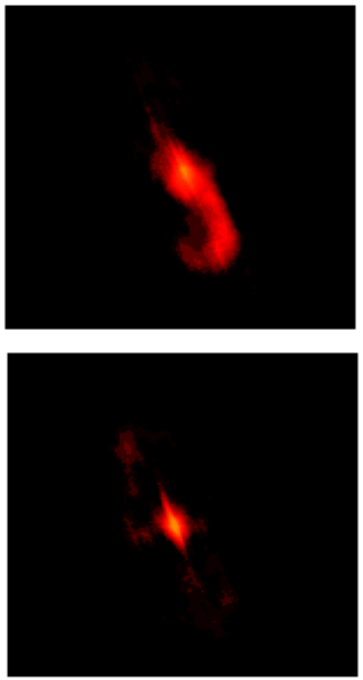
2D Reconstructions

chisquare = 0.0005

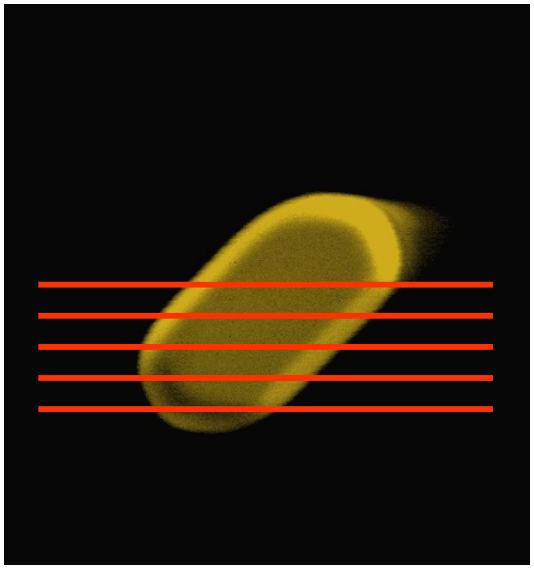


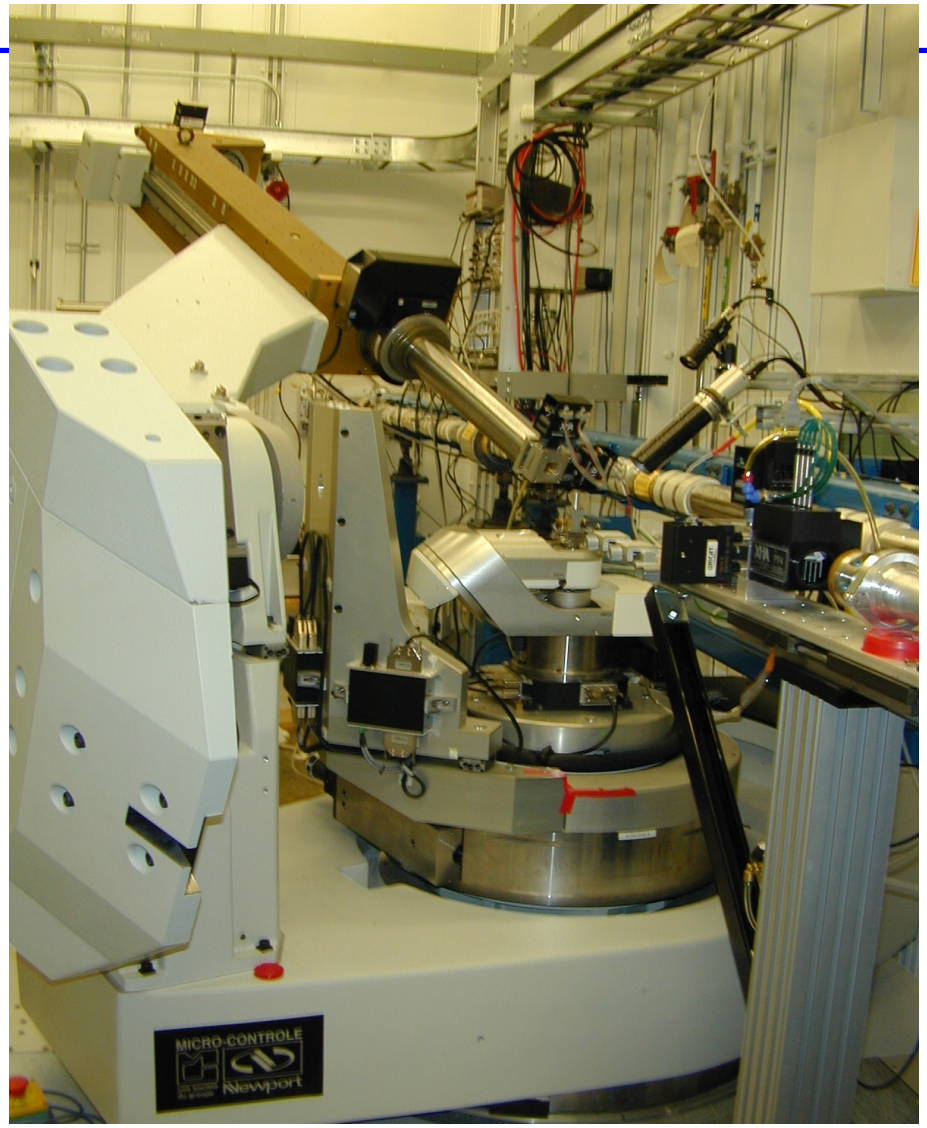


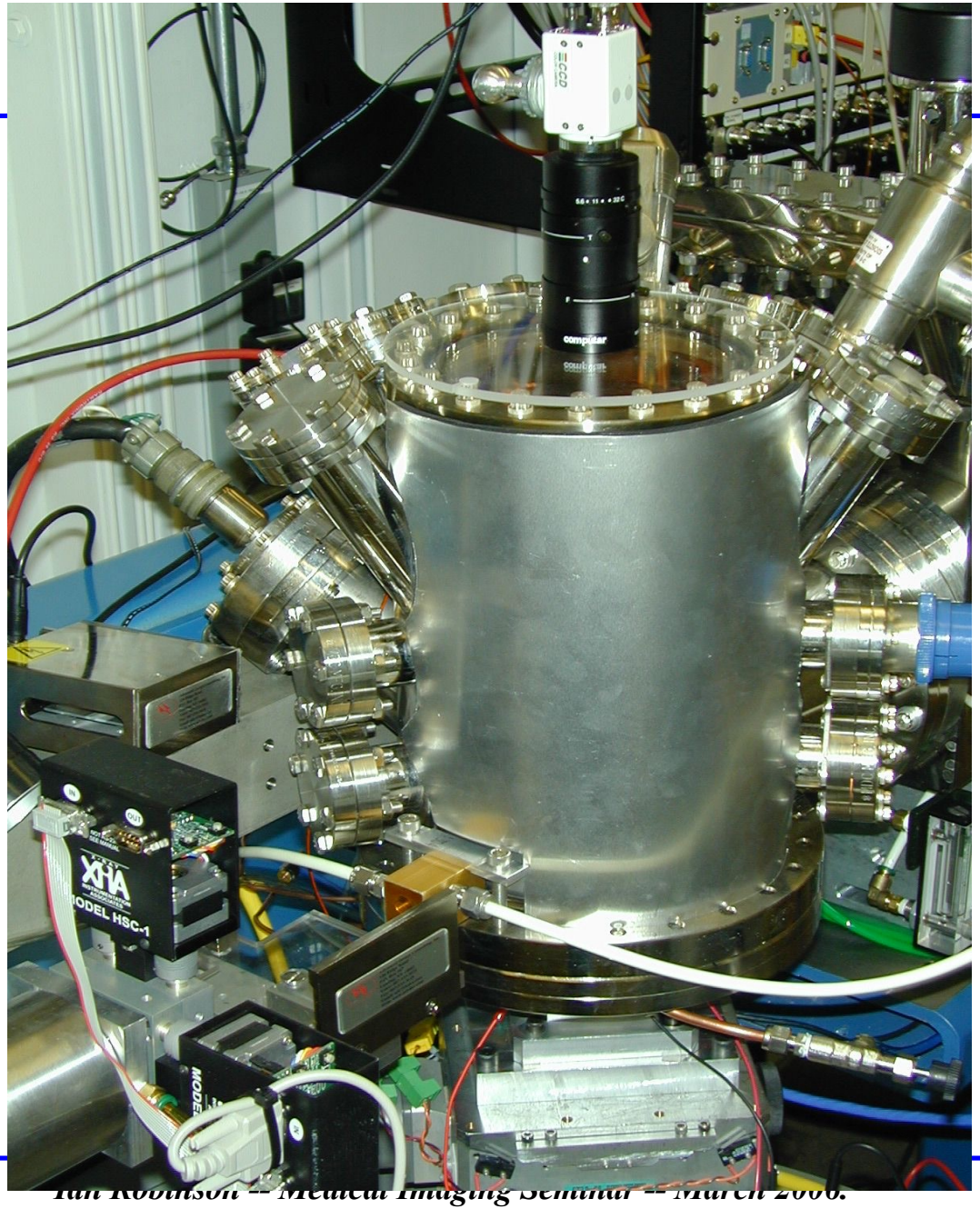




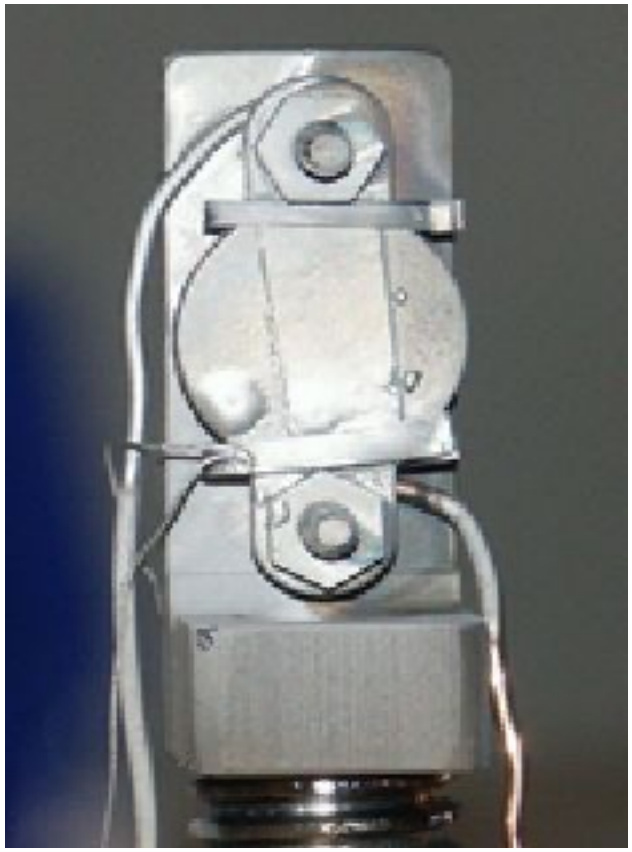
Slices through plan view SEM:

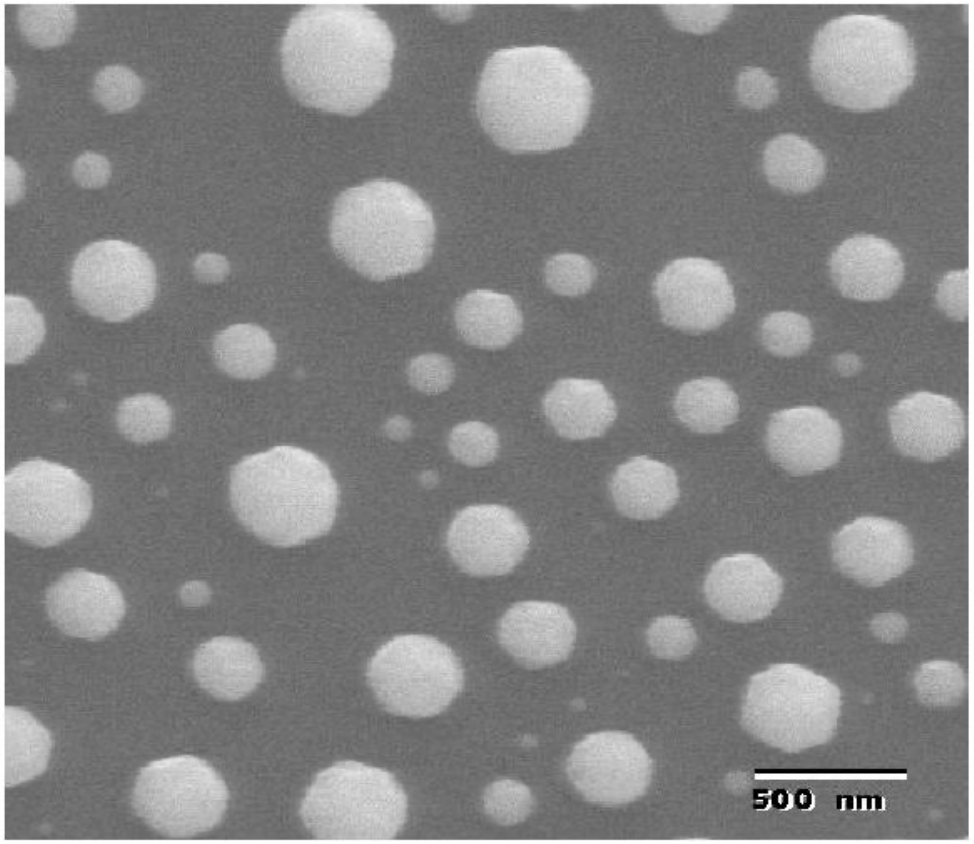



MICRO-CONTROLE
Newport


compular
XIA
MODEL HSC-1

In situ growth of Pb crystals

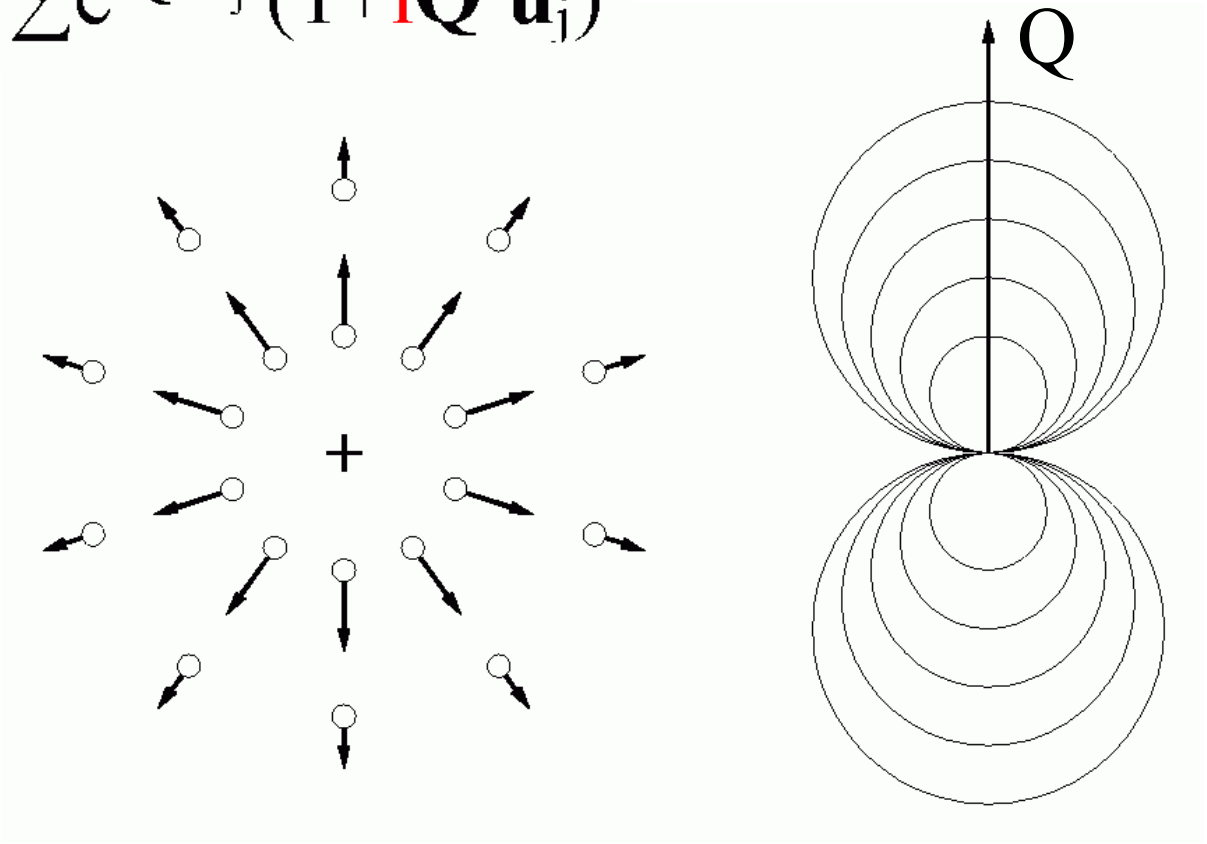




Diffraction by Strain of Point Defect

$$A \sim \sum e^{i\mathbf{Q}\cdot(\mathbf{R}_j+\mathbf{u}_j)}$$
$$\approx \sum e^{i\mathbf{Q}\cdot\mathbf{R}_j}\,(1+i\mathbf{Q}\cdot\mathbf{u}_j)$$

Imaginary density



Good statistics, 3D diffraction data

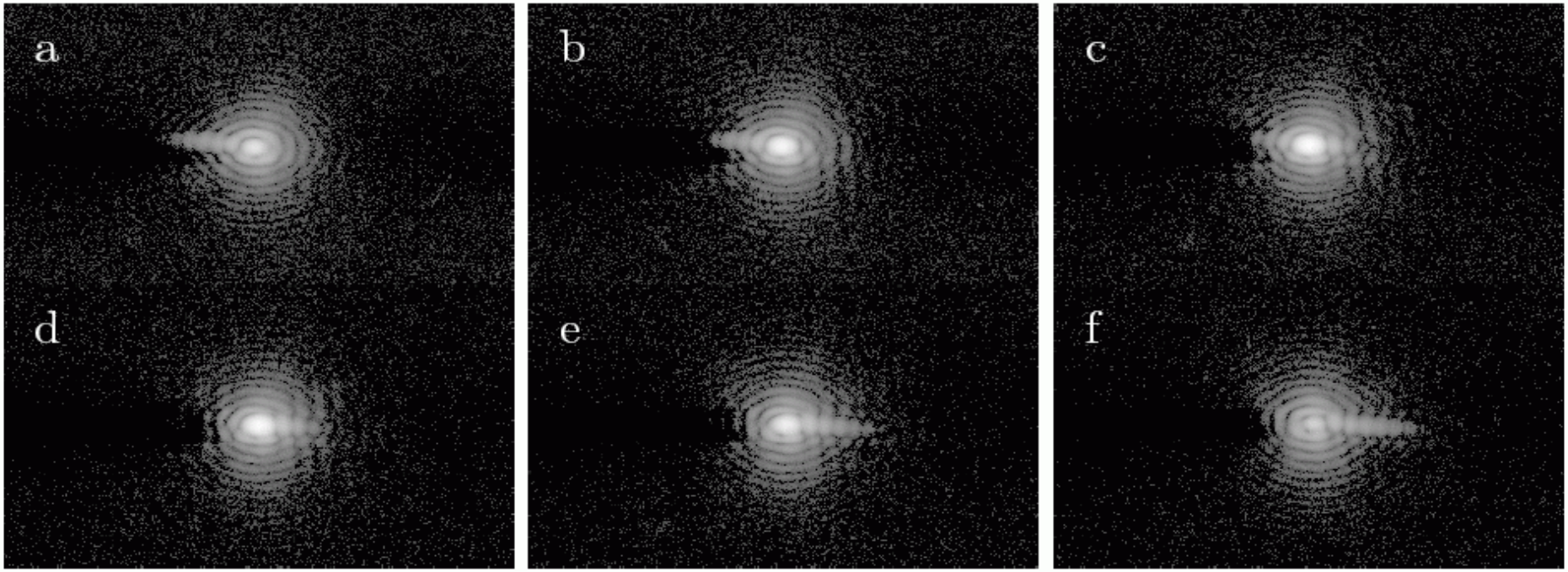
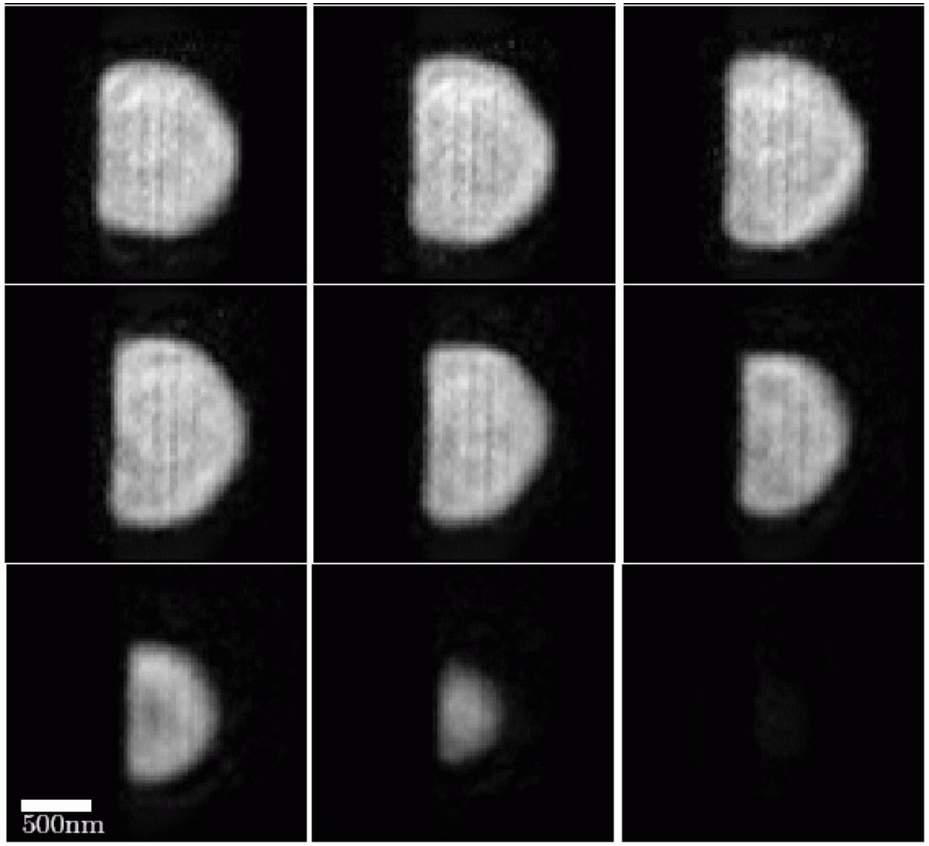
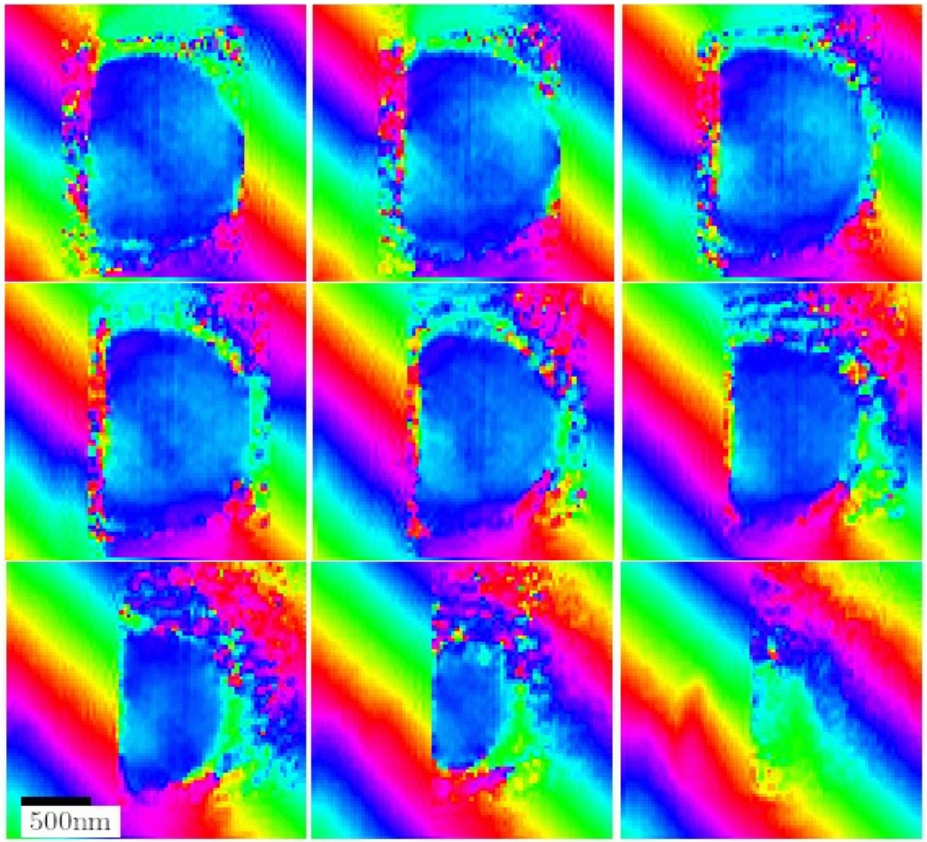
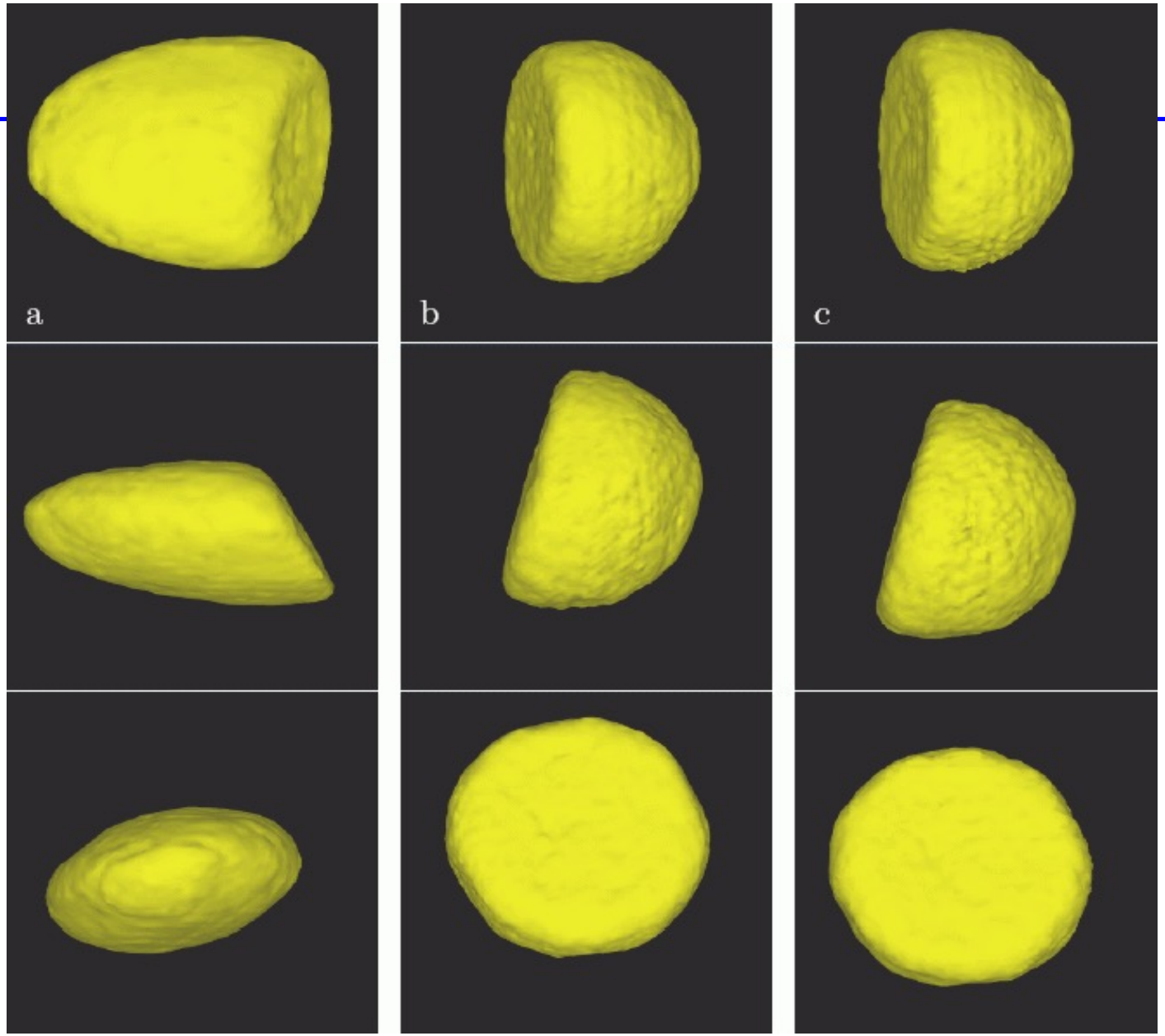


Figure 4.12: Center slices from 3D CXD pattern from Pb sample, on a log scale. Data file 296 from 10/03.

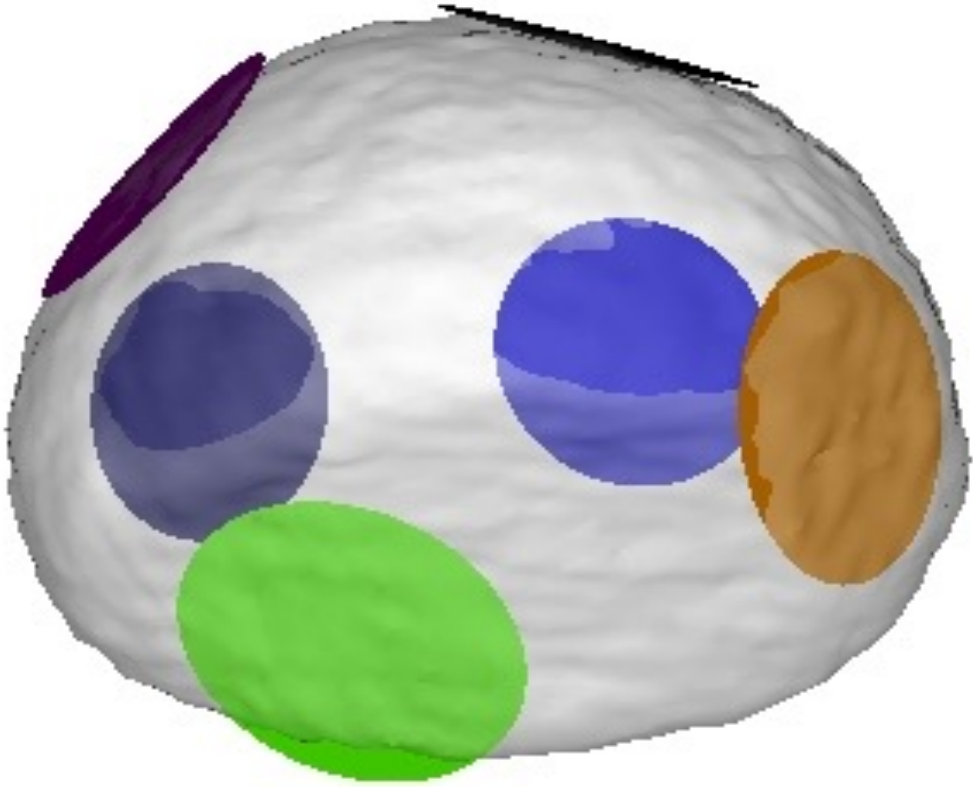
Then refine amplitude and *phase*

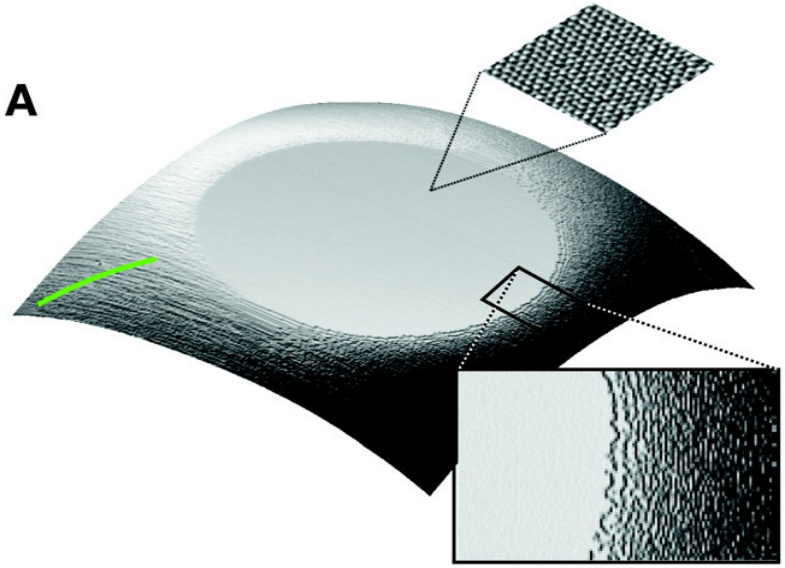





a
b
c

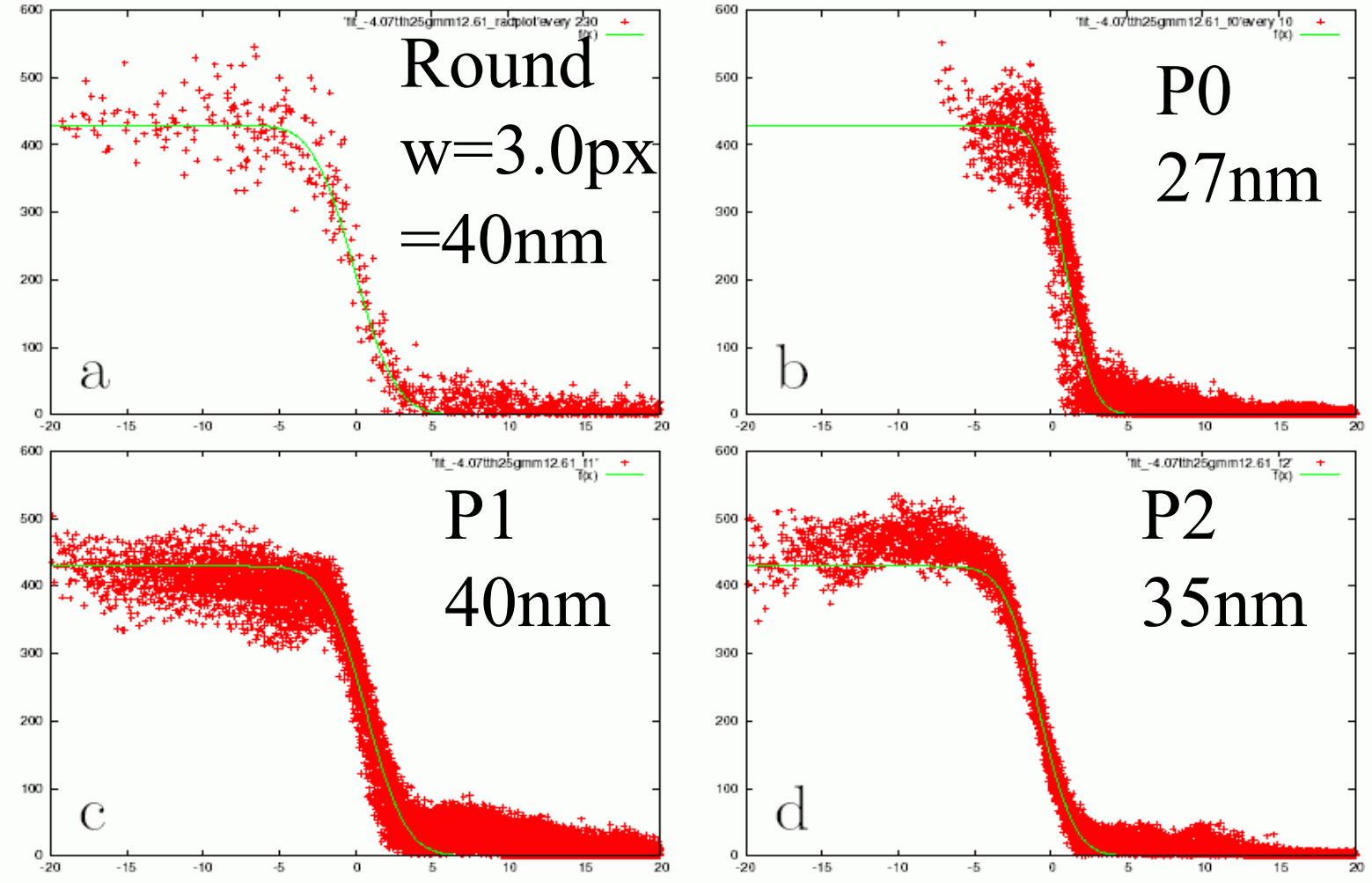
Facets of Equilibrium Crystal Shape



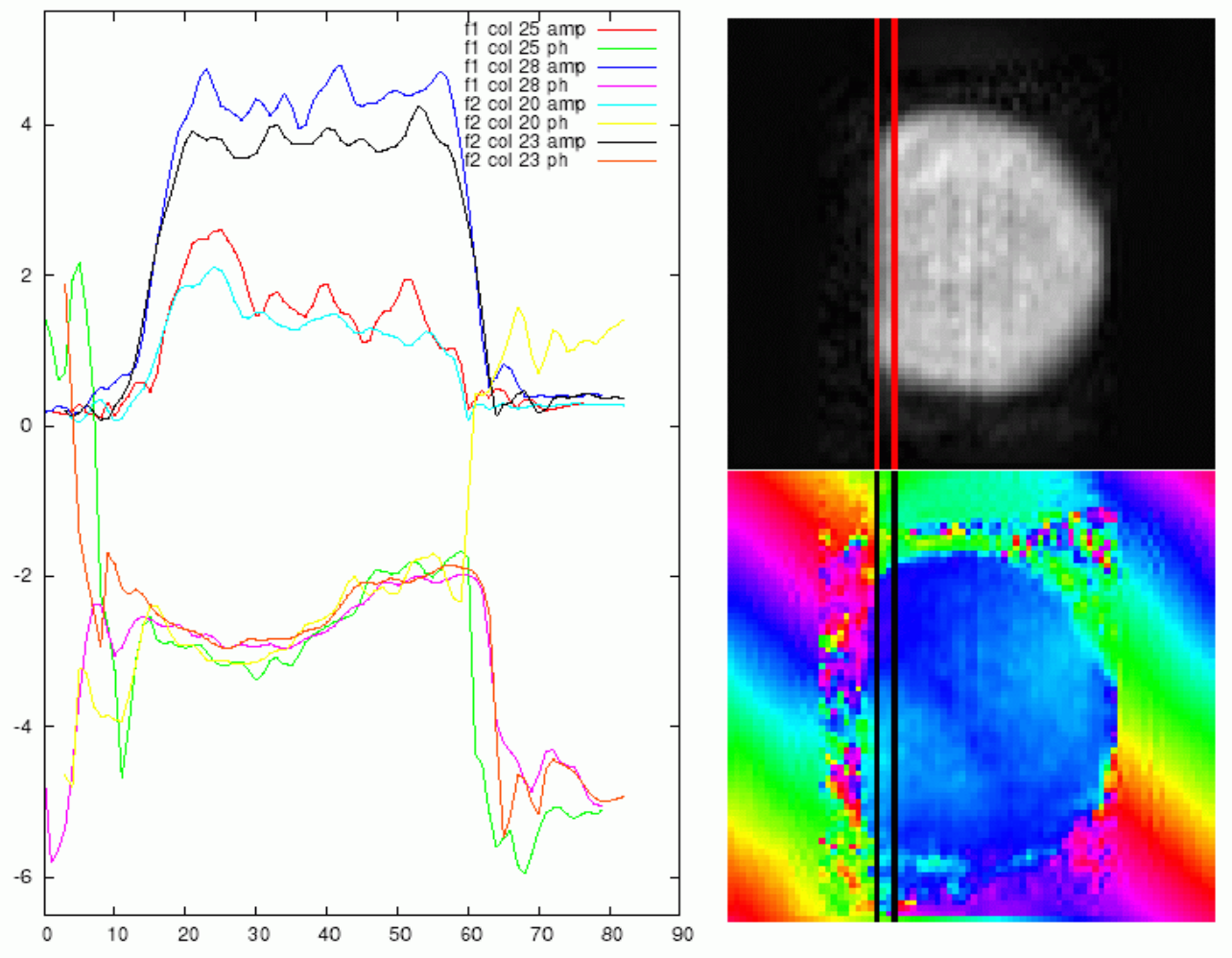


Thurmer K, Williams E, Reutt-Robey J
Science **297** 2033 (2002)

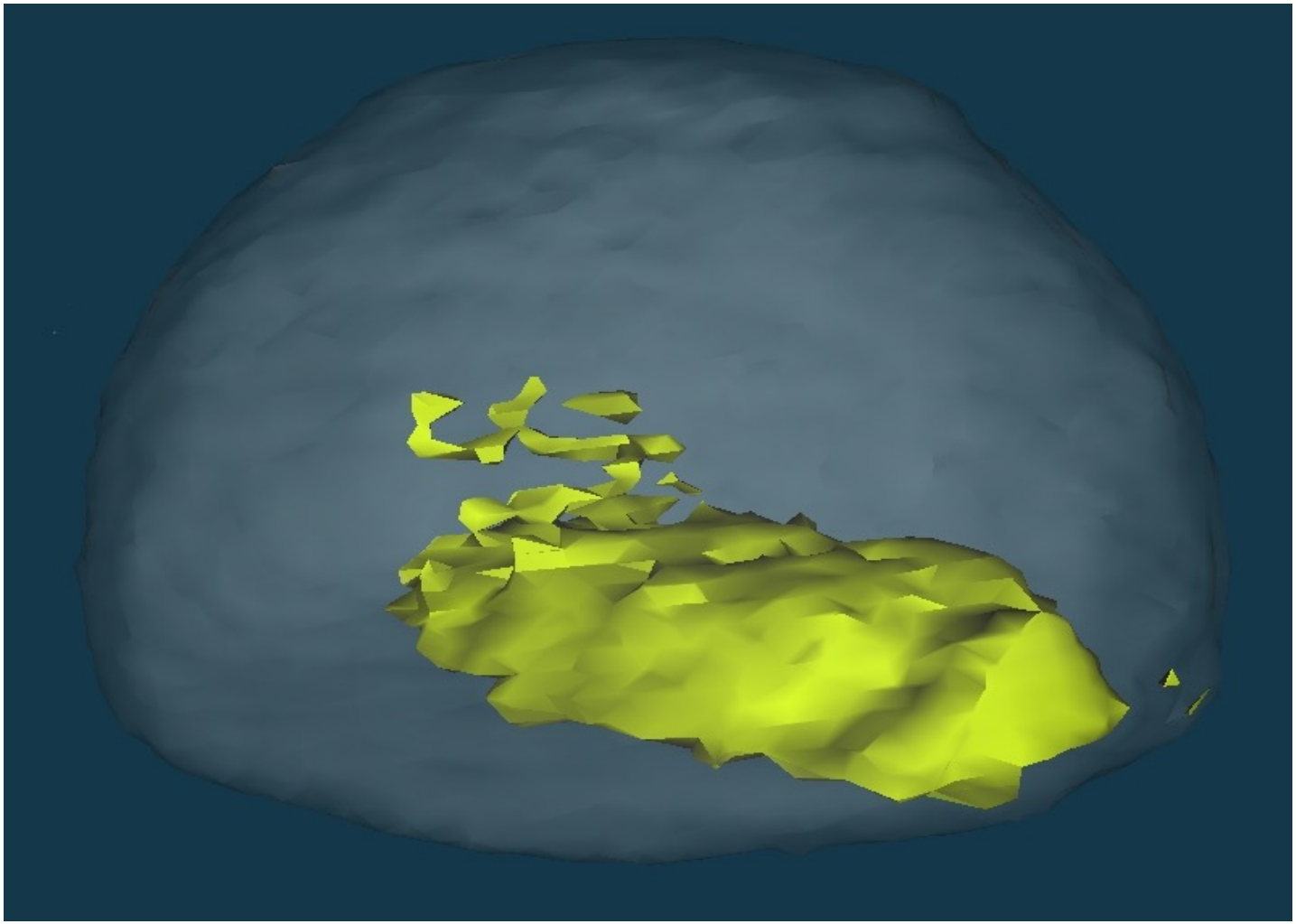
Density distribution across surface



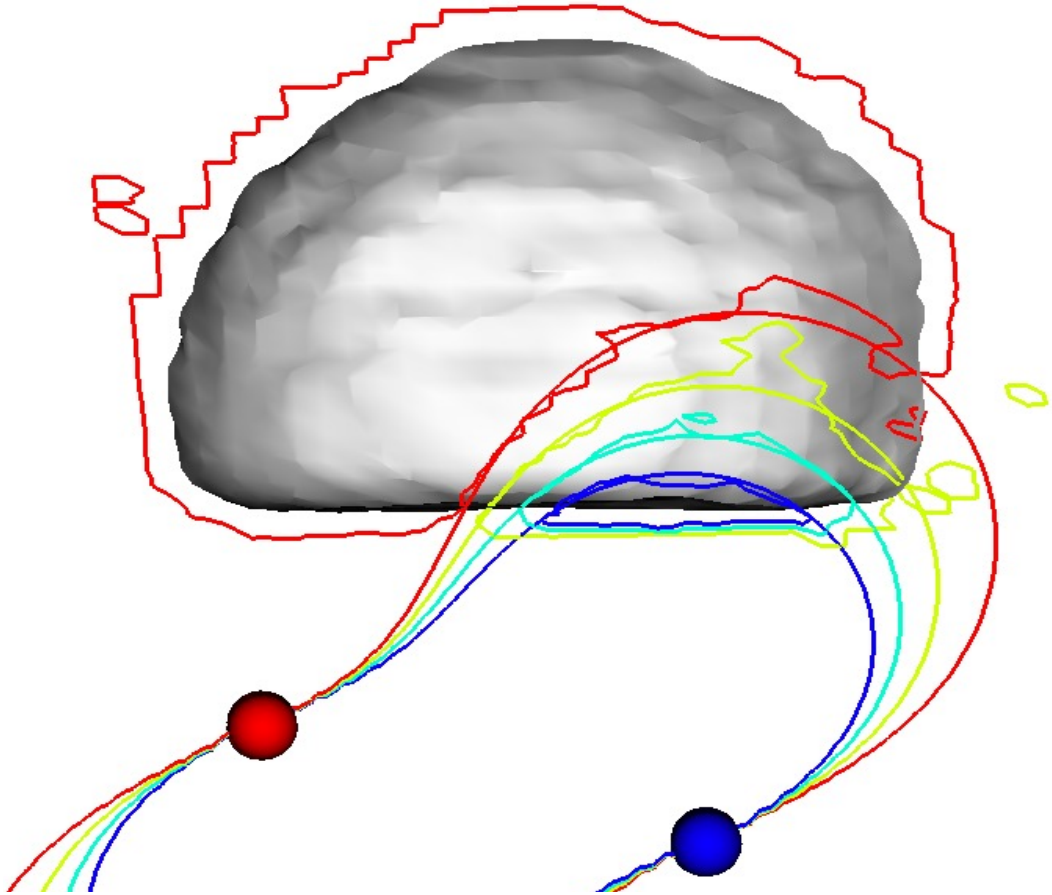
Phase structure near substrate interface

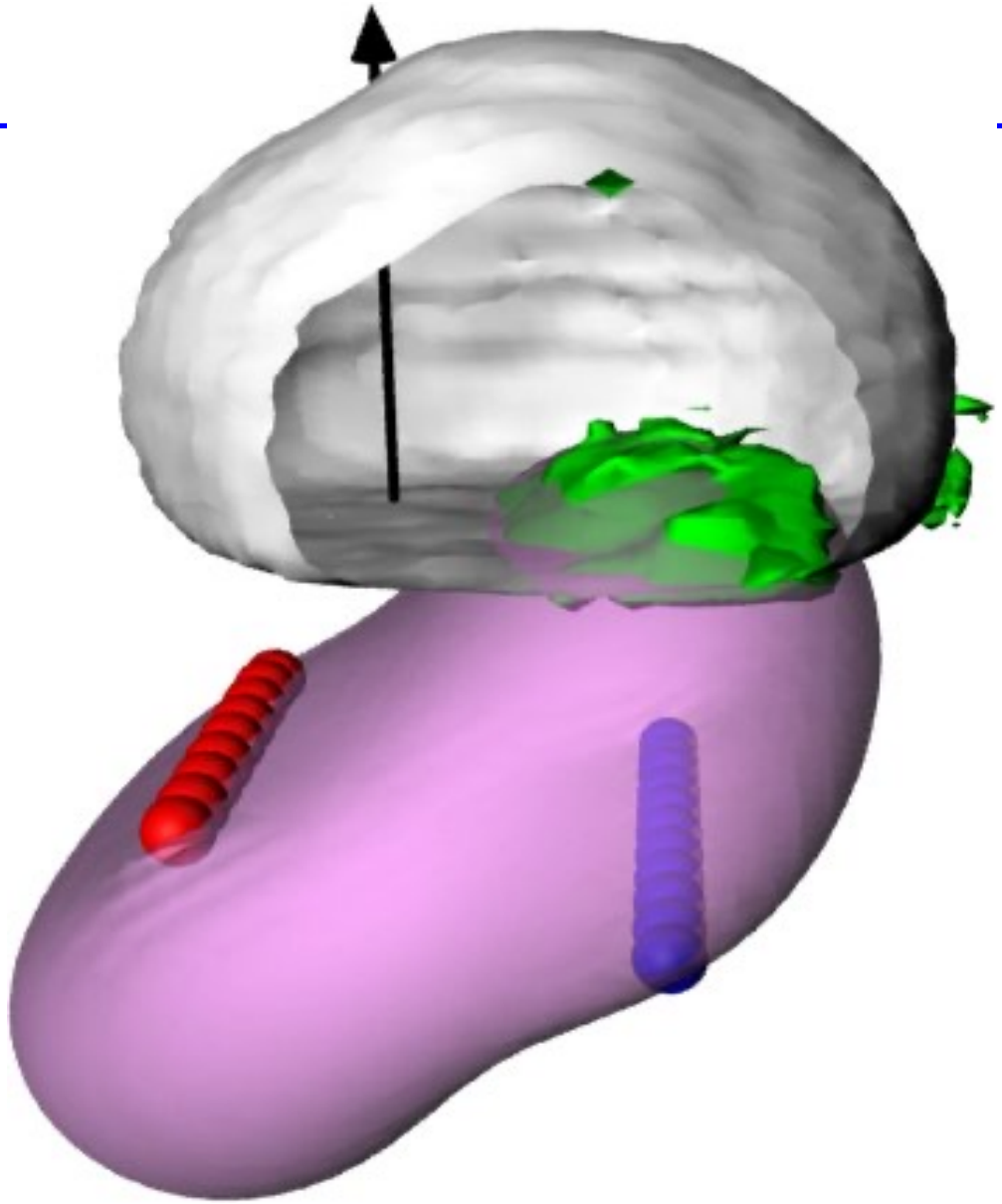


Modeling of 3D Phase Bump



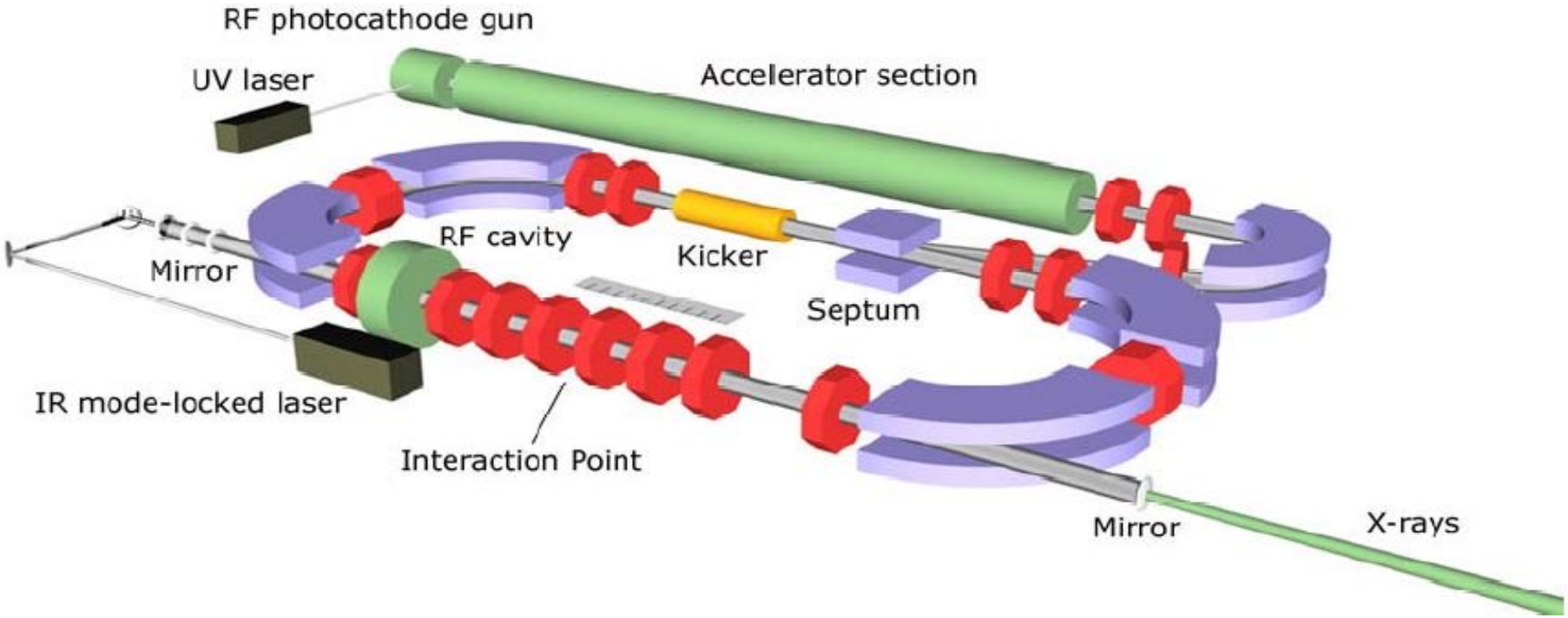
Field lines of Point Charges





Compact Light Source

Ron Ruth, Lyncean Technologies

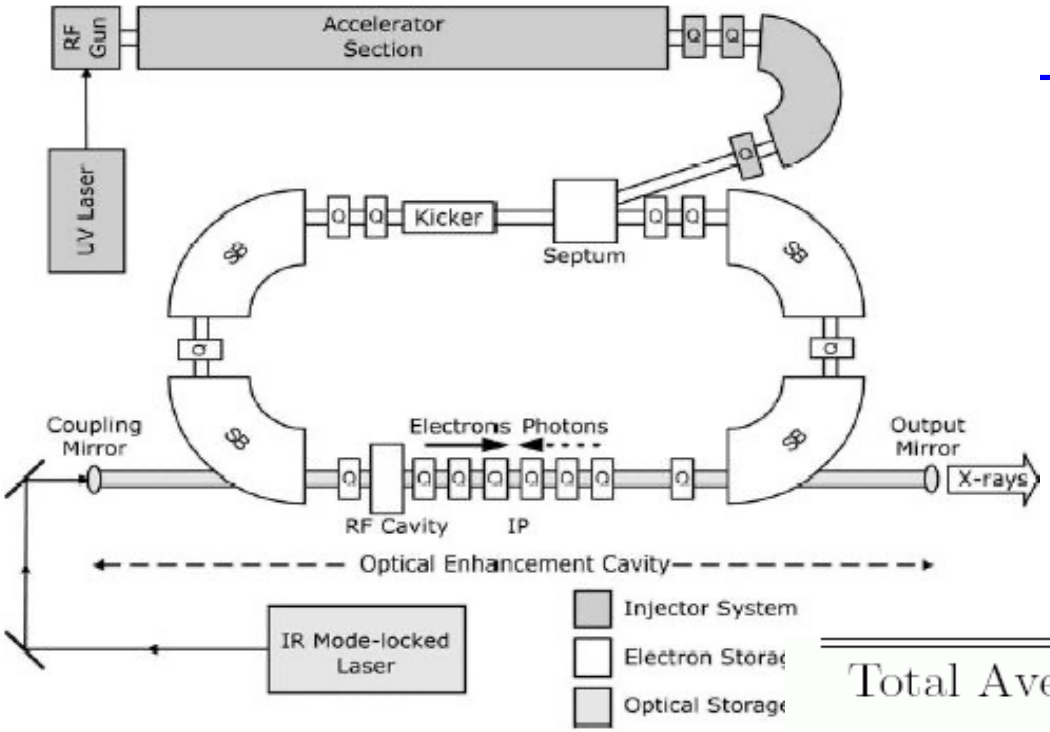


CLS Specifications

R. J. Loewen, Ph.D. Thesis

SLAC (2003)

50MeV (γ=100) + 1μm laser



$$\omega = \frac{4\gamma^2}{(1+\gamma^2\theta^2)}\,\omega_0$$

Total Average Flux	$\gtrsim 10^{13}$ ph/s
Avg. "Monochromatic" Flux*	$\approx 10^{10}$ ph/s
Source Spot Size†	30 μm radius
Source Divergence†	$\approx$ 3 mrad
Source Brightness	$\gtrsim 10^{11}$
X-ray Energy Range‡	12 keV $\pm$ 6 keV

Molecular Movies using XFEL

Conclusions and Outlook

Franz Pfeiffer pfeiffer@psi.ch

- Phase contrast imaging has medical applications
- Achievable and practical using gratings
- Diffraction phasing by computation instead of lens
- Strain fields imaged as phase objects
- Single molecules one day using XFEL
- Medical imaging opportunity now using CLS

Acknowledgements

Christian Grünzweig, Jens Bruder, Ana Diaz, Christian David, Oliver Bunk, Ian Johnson, Marco Stampanoni, Xavier Donath, Gabriel Frei, Henrik Rønnow, Eberhard Lehmann,

Paul Scherrer Institut, Switzerland

Timm Weitkamp,

ANKA, Forschungszentrum Karlsruhe, Germany

Peter Cloetens,

ESRF Grenoble, France

Ivan Vartanyants

HASYLAB, DESY, Germany

Ian Robinson

University of Illinois, USA => University College London, U.K.