23 October 2006, IAN 2006

Neutron Phase Imaging using a Grating Interferometer

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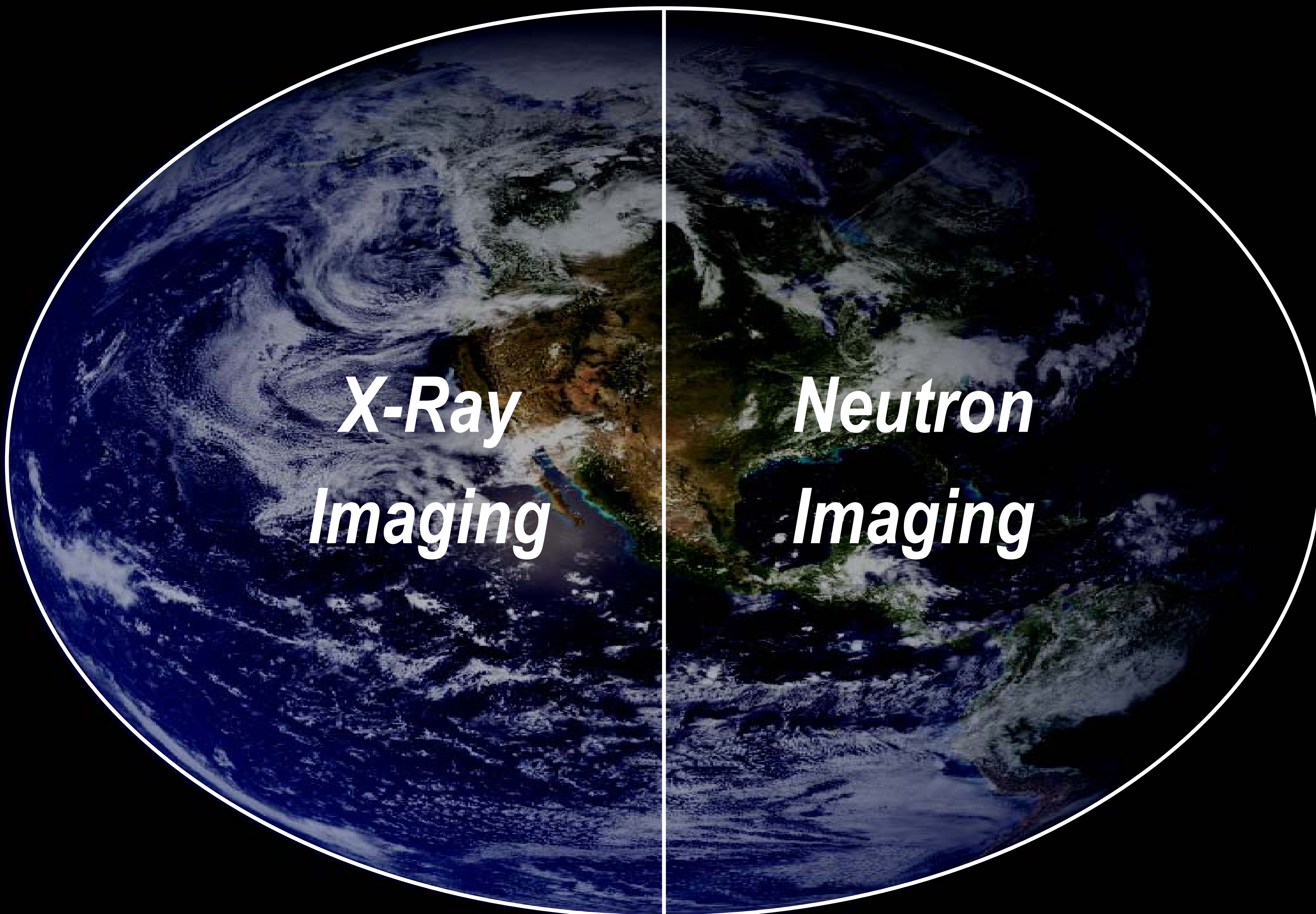
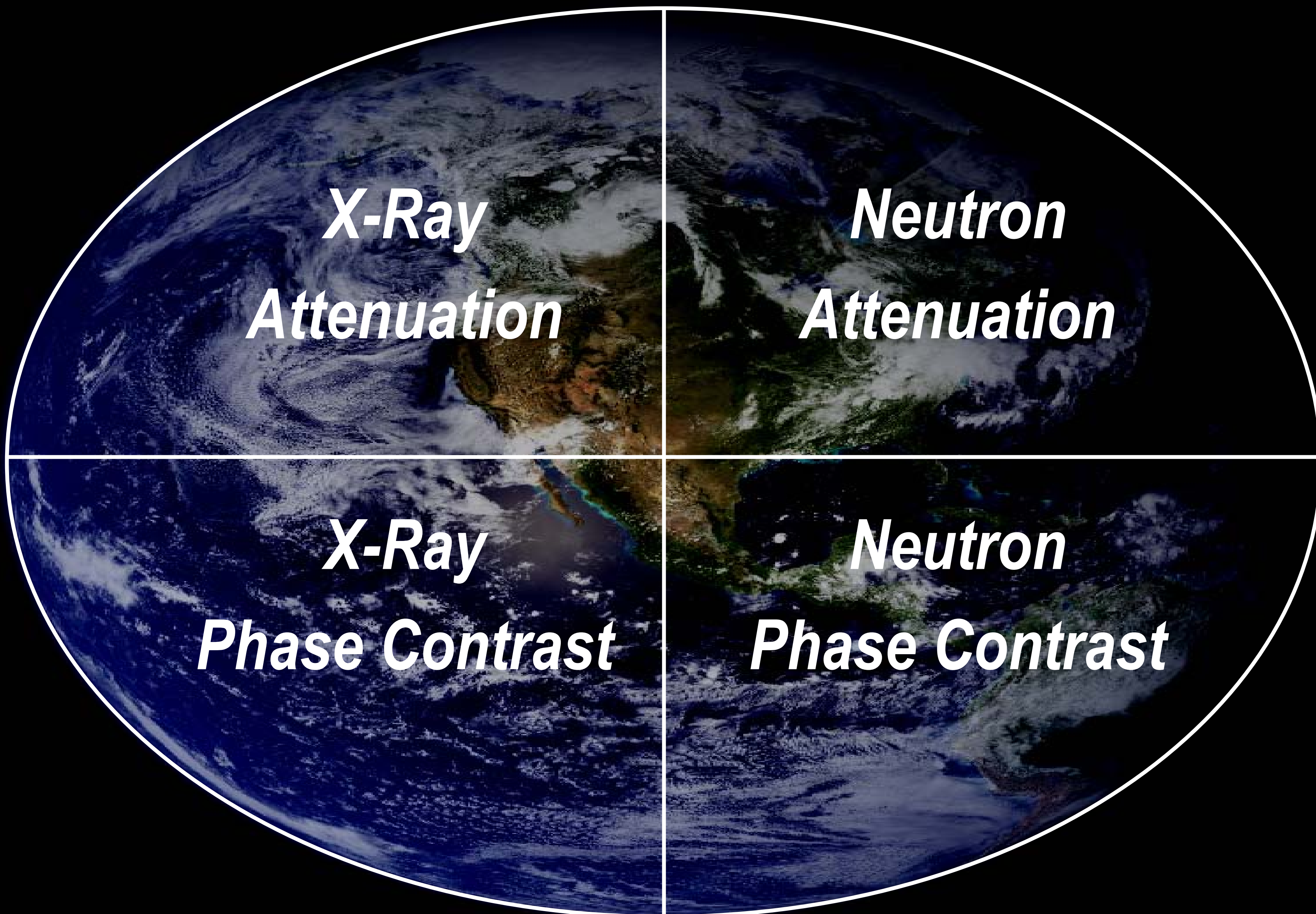
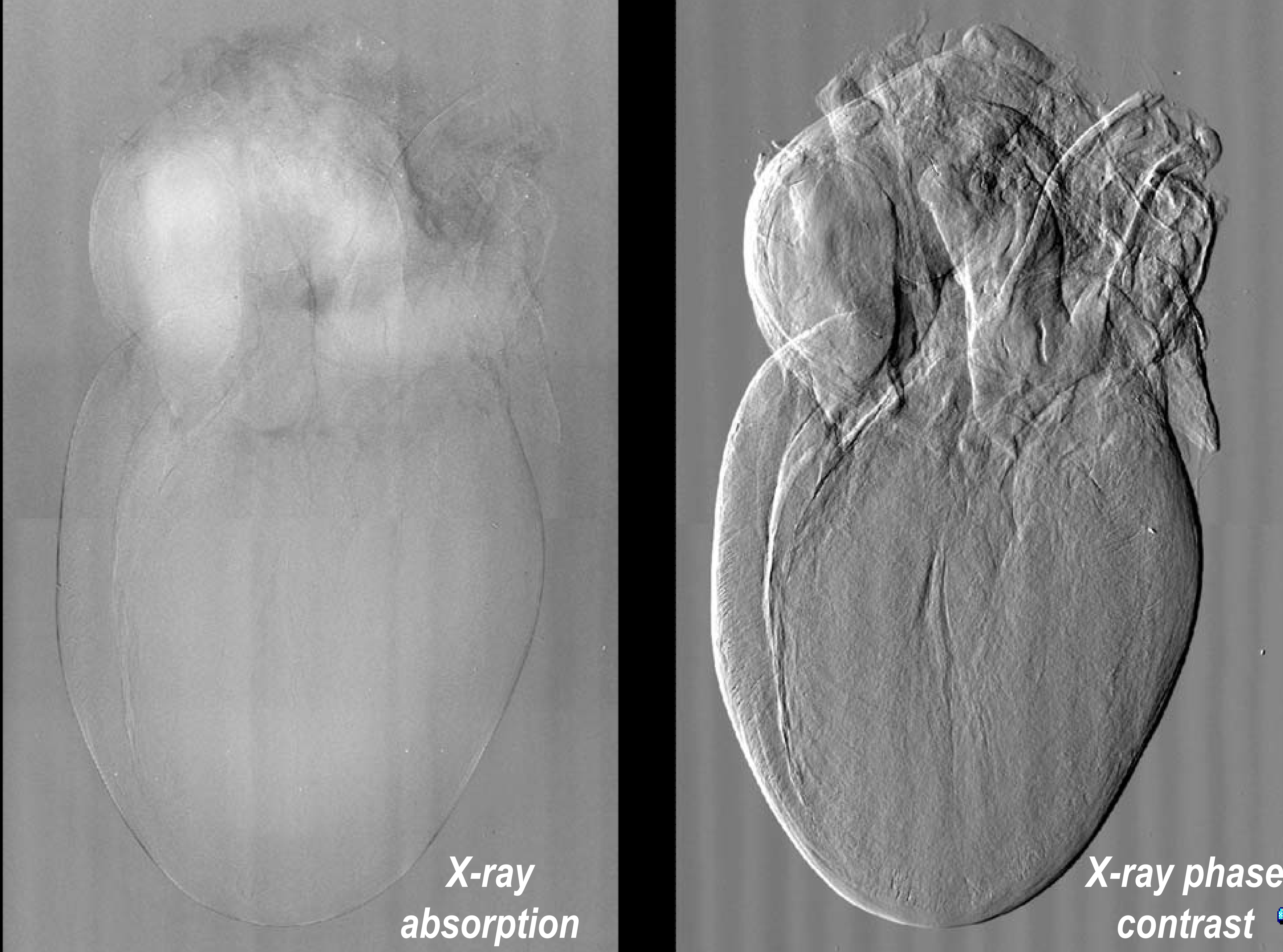
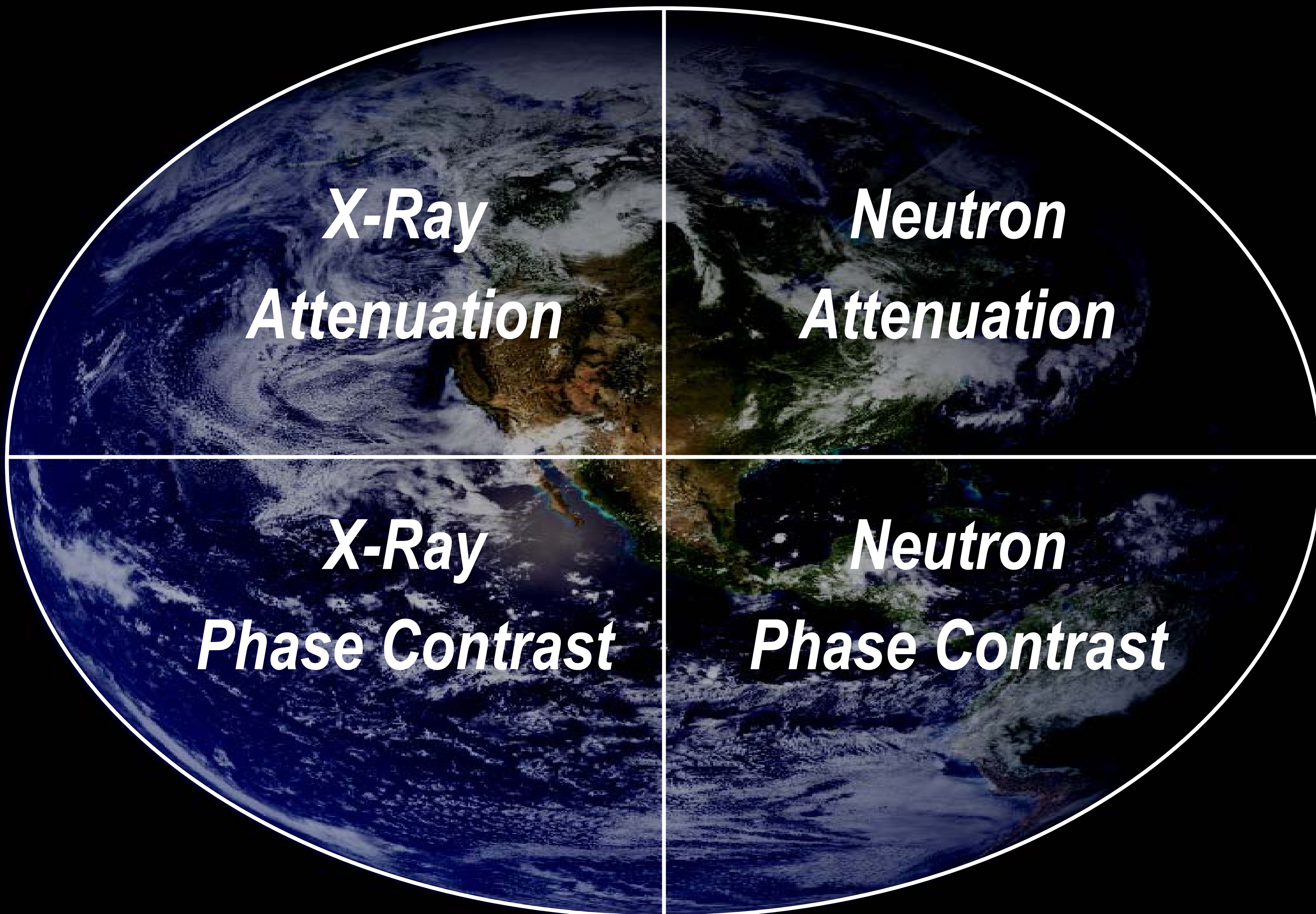
The Imaging World

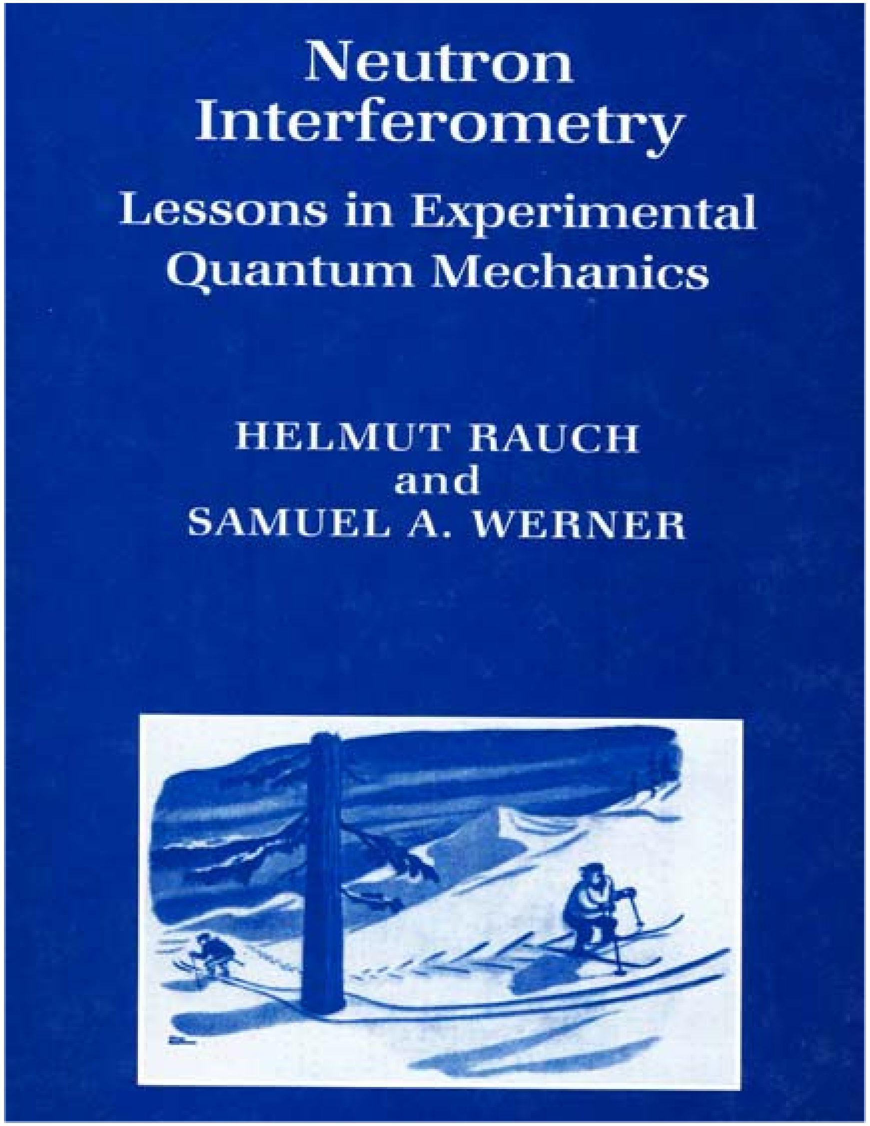

X-Ray
Imaging
Neutron
Imaging


X-Ray
Attenuation
Neutron
Attenuation
X-Ray
Phase Contrast
Neutron
Phase Contrast


X-ray absorption
X-ray phase contrast

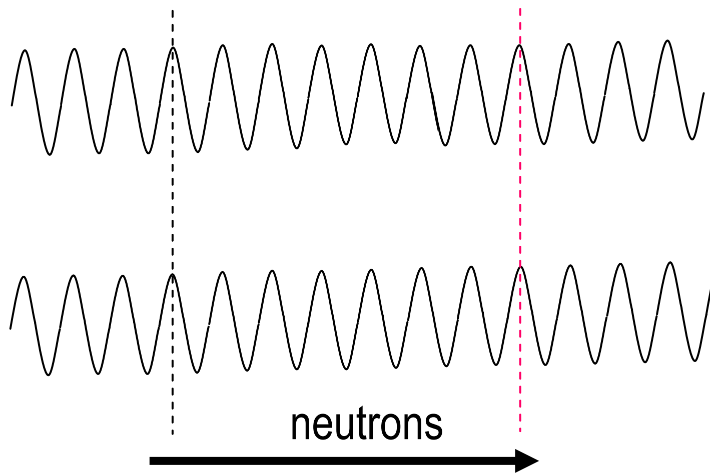

X-Ray
Attenuation
Neutron
Attenuation
X-Ray
Phase Contrast
Neutron
Phase Contrast

Neutron Interferometry = Quantum Mechanics

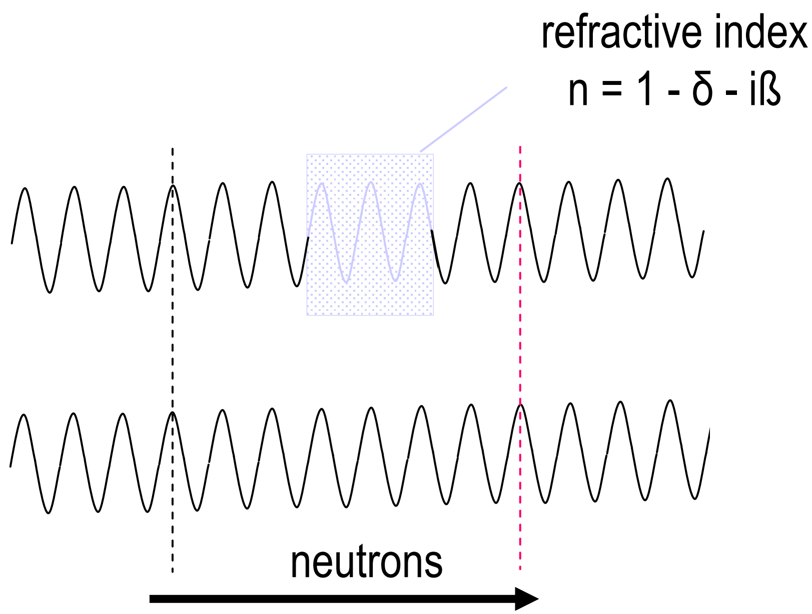


Interaction	Potential	Phase shift
Nuclear	$\frac{2\pi\hbar^2}{m} b_c \delta(\boldsymbol{r})$	$-N b_c \lambda D$
Magnetic	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(\boldsymbol{r})$	$\pm \frac{\mu B m \lambda D}{2\pi\hbar^2}$
Gravitation	$m\boldsymbol{g} \cdot \boldsymbol{r}$	$\frac{m^2 g \lambda A \sin\alpha}{2\pi h^2}$
Coriolis	$-\hbar\boldsymbol{\omega}(\boldsymbol{r} \times \boldsymbol{k})$	$\frac{2m}{\hbar} \boldsymbol{\omega}_e \cdot \boldsymbol{A}$
Aharonov–Casher (Schwinger)	$-\boldsymbol{\mu} \cdot (\boldsymbol{v} \times \boldsymbol{E})/c$	$\pm \frac{2\mu}{\hbar c} \boldsymbol{E} \cdot \boldsymbol{D}$
Scalar Aharonov–Bohm	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(t)$	$\pm \frac{\mu B T}{\hbar}$
Magnetic Josephson	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(t)$	$\pm\omega \cdot t$
Fizeau	—	$-N b_c \lambda D \left(\frac{w_x}{v_x - w_x} \right)$
Geometry (Berry)	—	$\Omega/2$

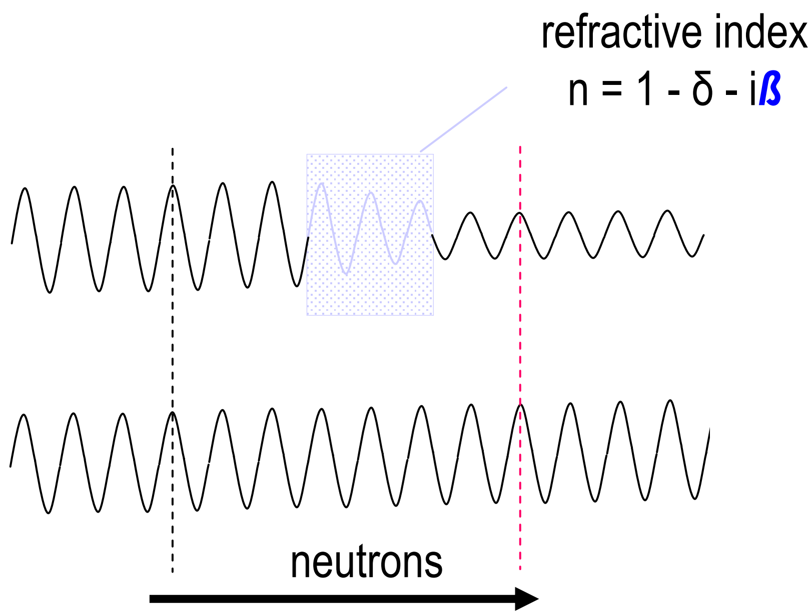
Phase sensitive imaging



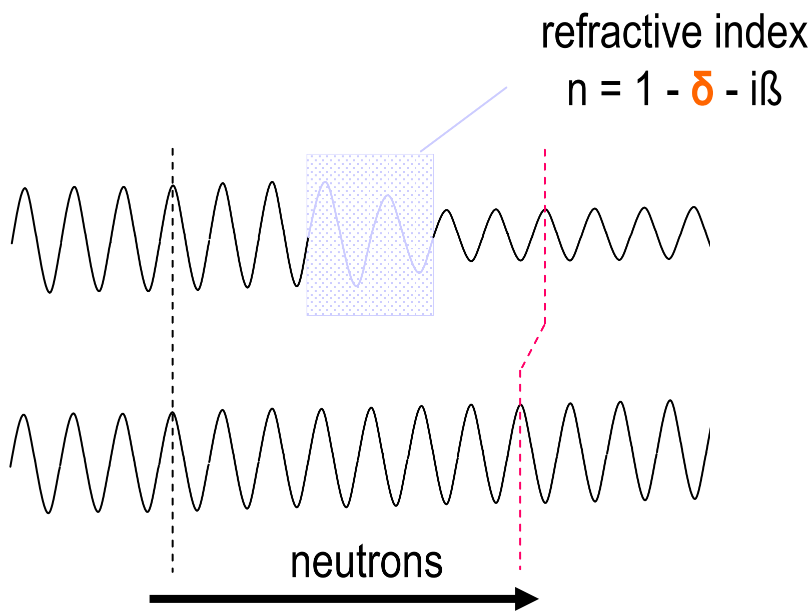
Phase sensitive imaging



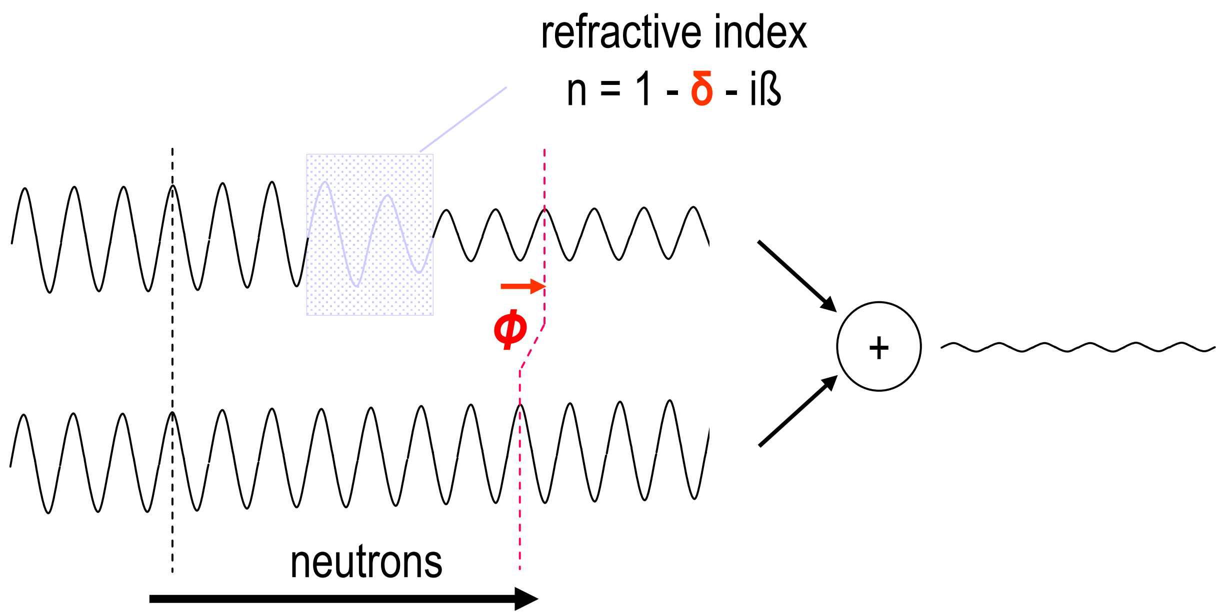
Phase sensitive imaging



Phase sensitive imaging



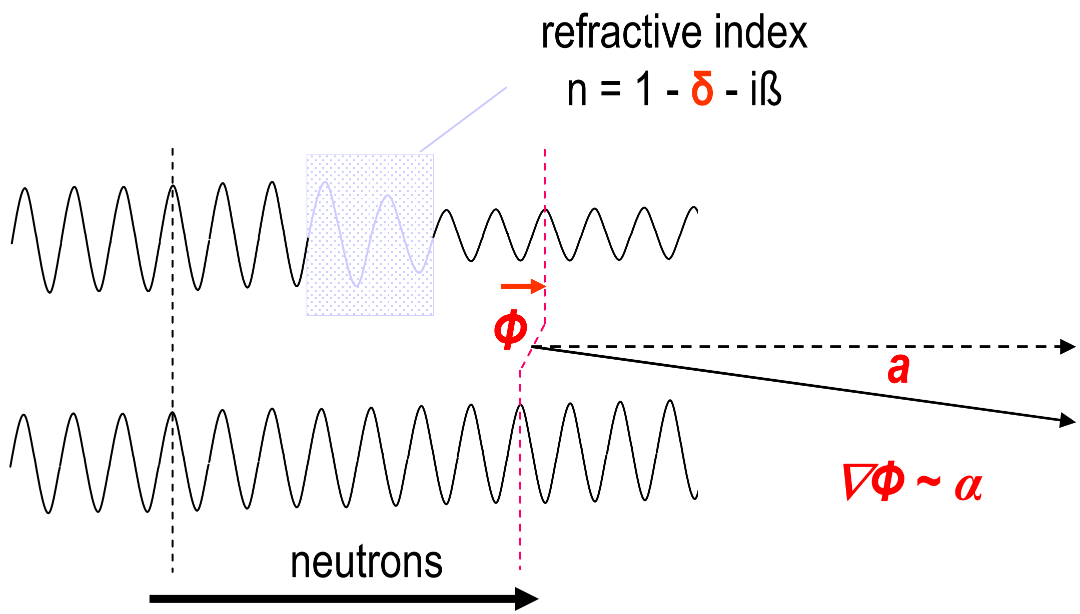
Phase sensitive imaging



To obtain phase sensitive images, measure:

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

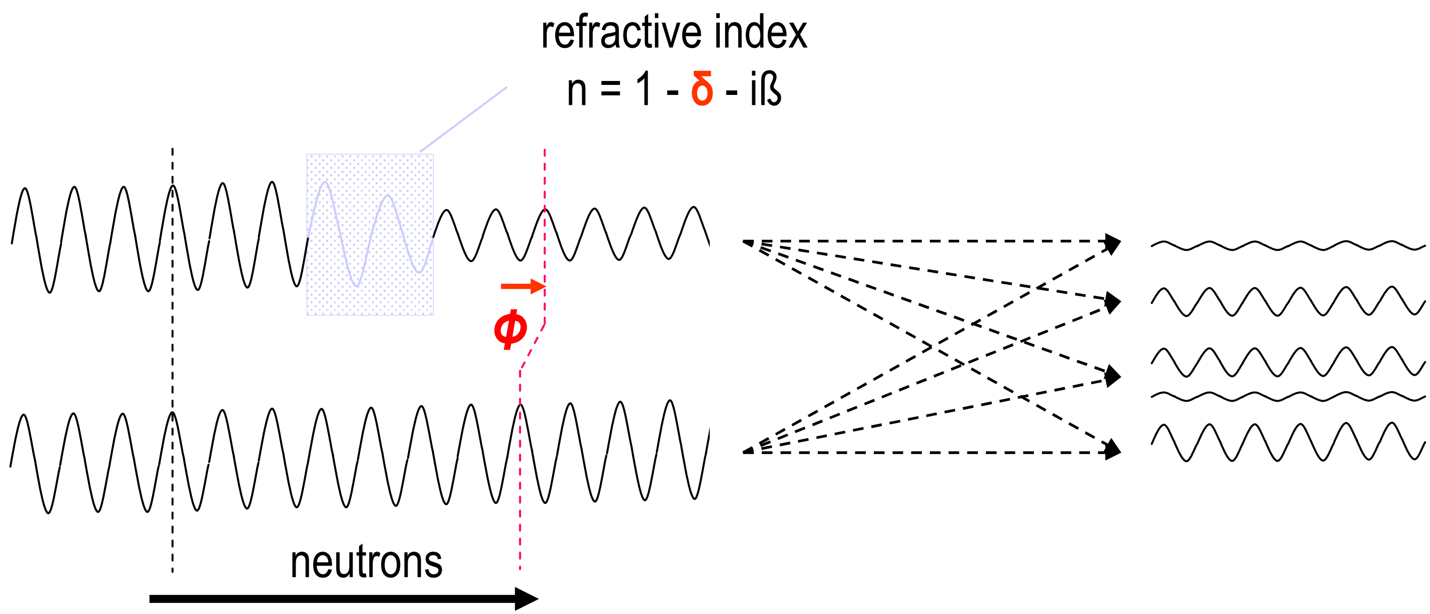
Phase sensitive imaging



To obtain phase sensitive images, measure:

Φ	***with a crystal interferometer (Bonse & Hart 1965)***
$\nabla\Phi$	***with differential phase contrast (Ingal 1995, Treimer 2003)***

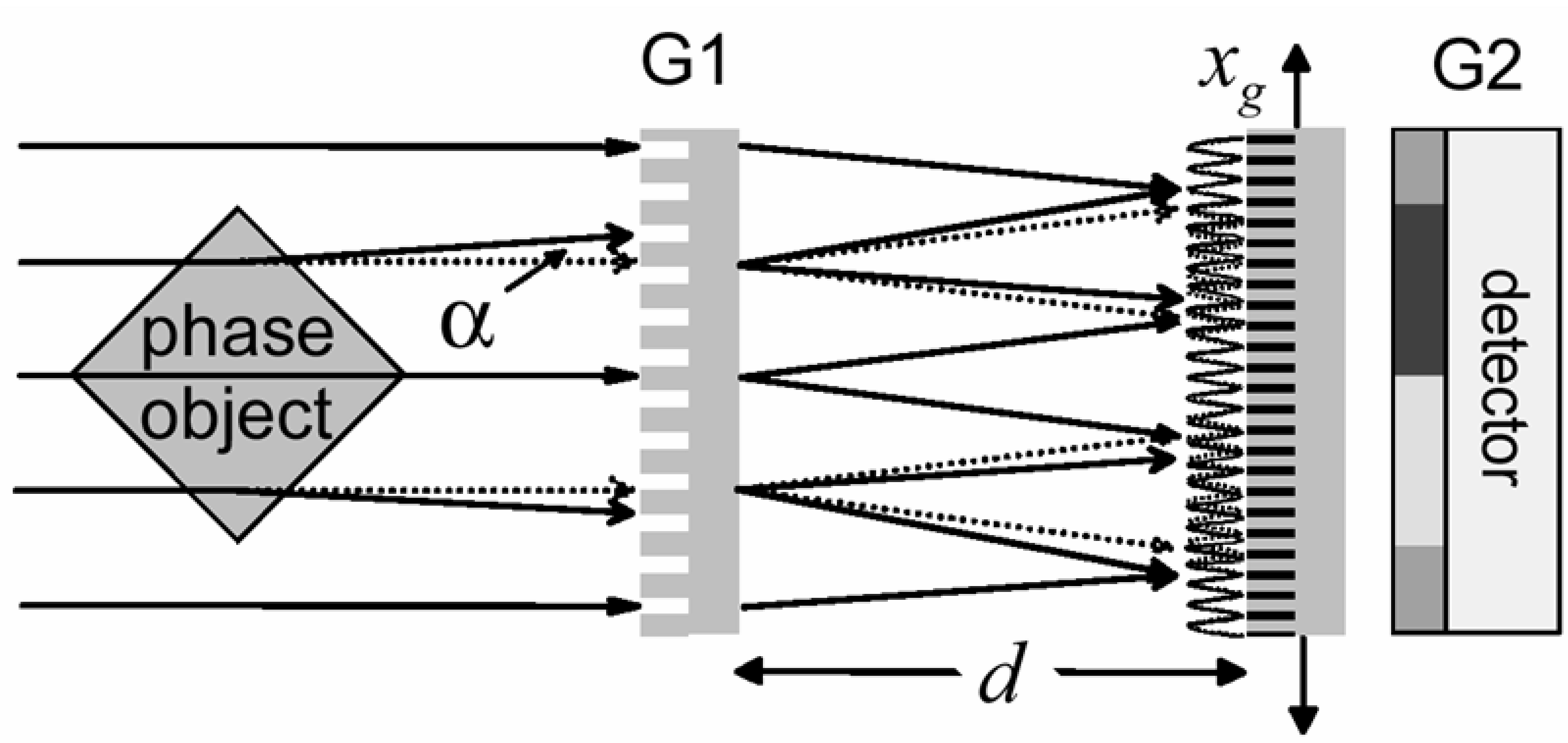
Phase sensitive imaging



To obtain phase sensitive images, measure:

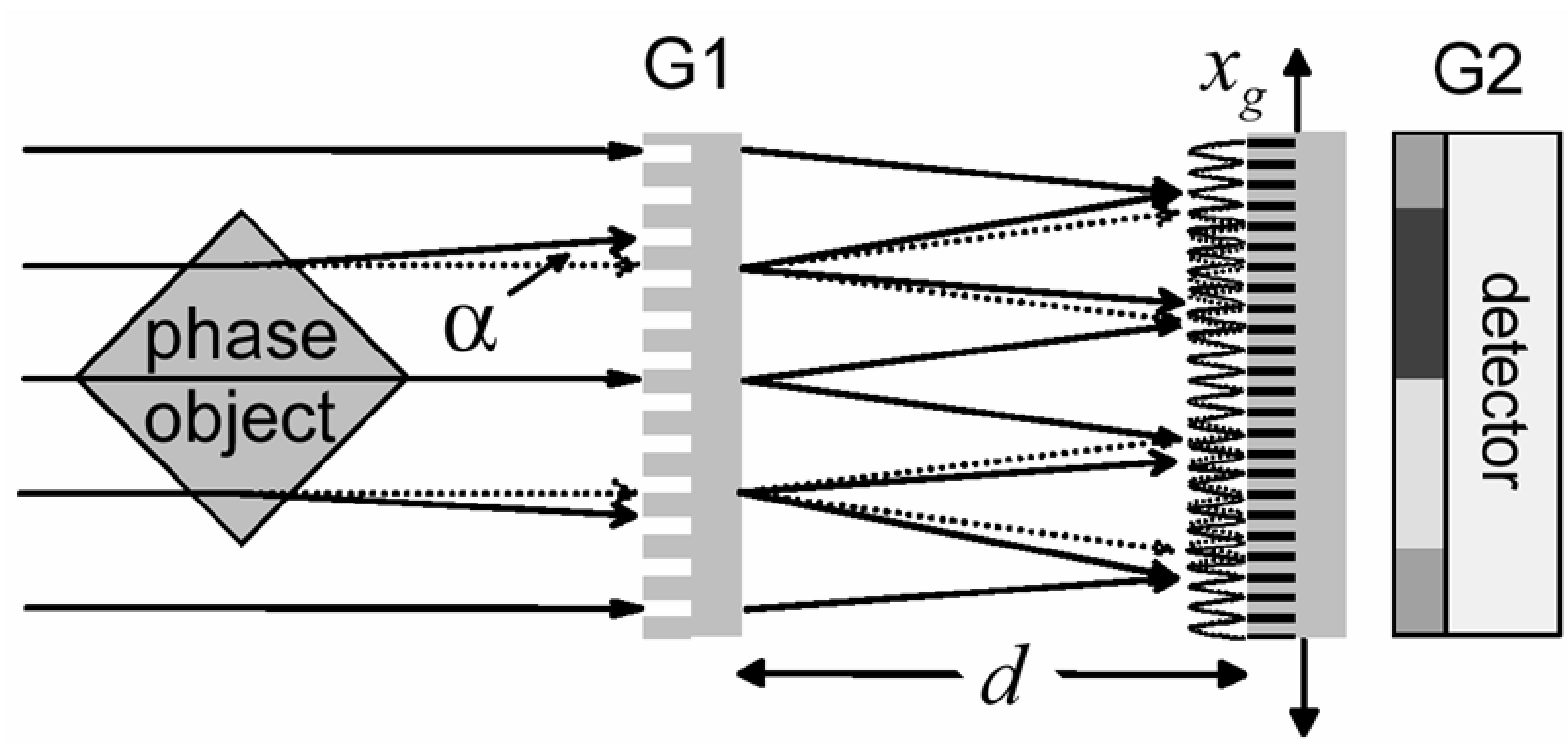
Φ	***with a crystal interferometer (Bonse & Hart 1965)***
∇Φ	***with differential phase contrast (Ingal 1995, Treimer 2003)***
ΔΦ	***with in-line holography (Cloetens 1999, Allman 2000)***

Neutron Grating Interferometer



Idea: polychromatic detection of angles !

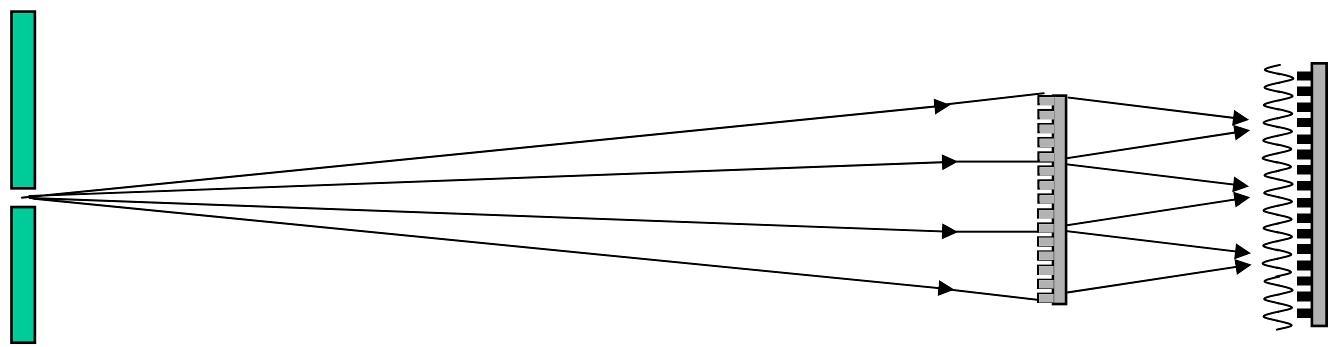
Neutron Grating Interferometer



This setup works well with highly brilliant sources, but is not very efficient with spallation or reactor neutron sources or an x-ray tube !

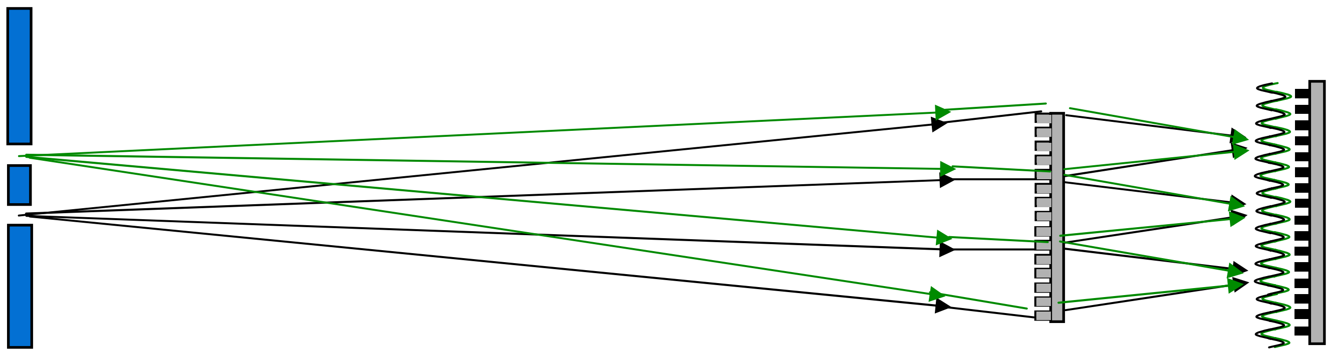
Higher efficiency with Talbot-Lau geometry

single slit



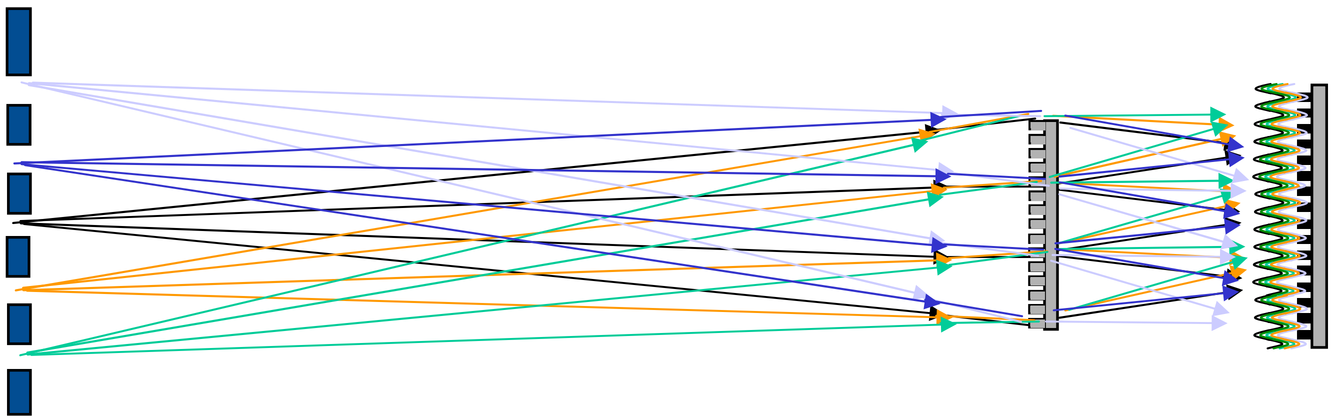
Higher efficiency with Talbot-Lau geometry

double slit



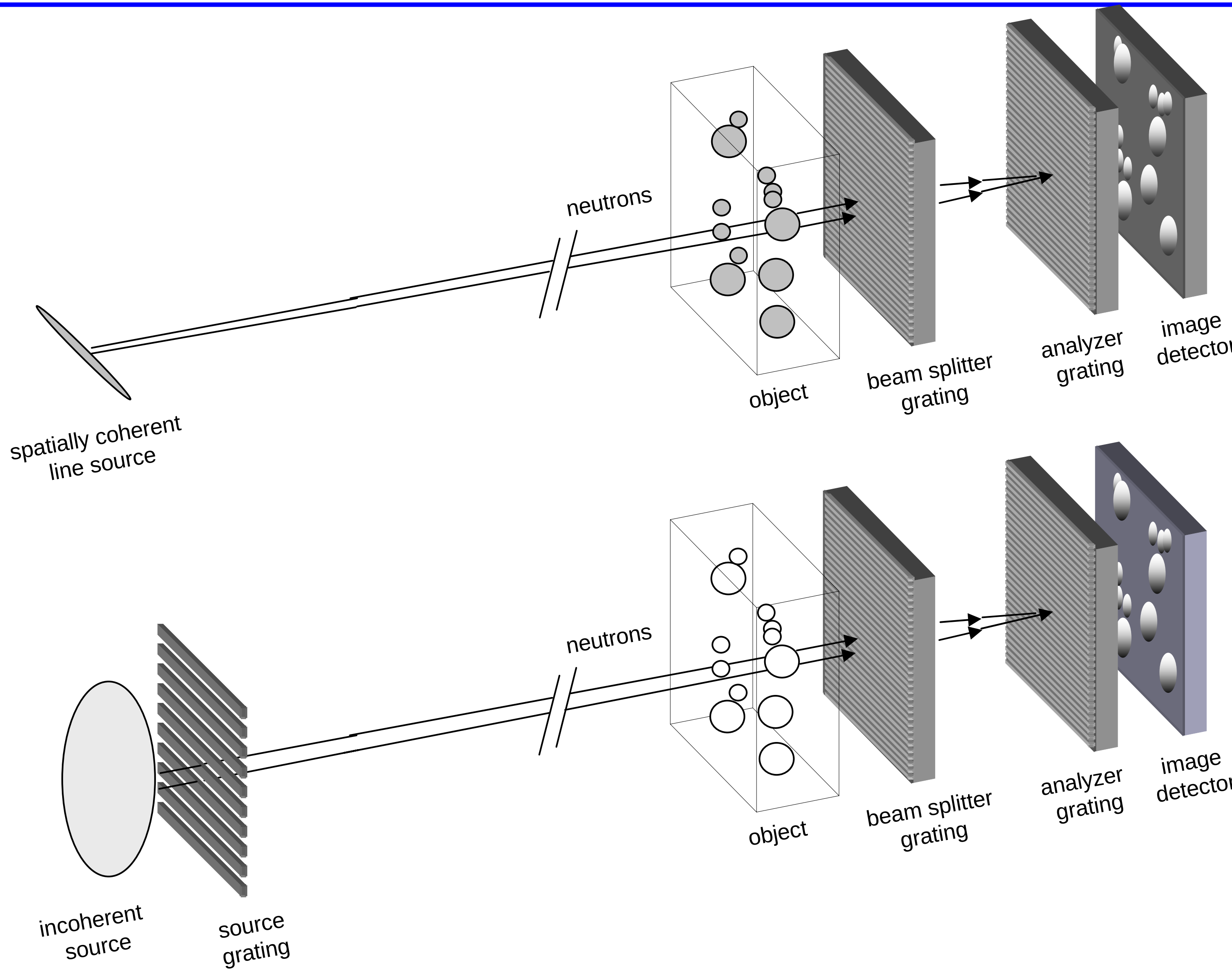
Higher efficiency with Talbot-Lau geometry

slit array/ grating



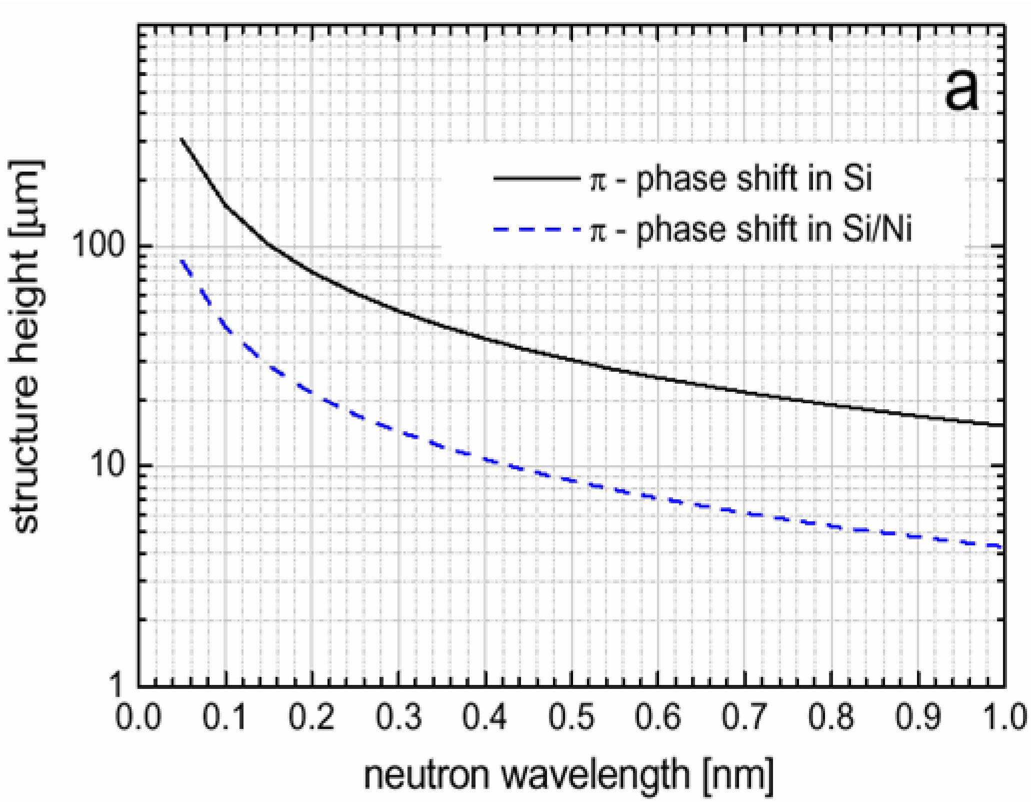
Decouples coherence from spatial resolution !

Talbot-Lau grating interferomter

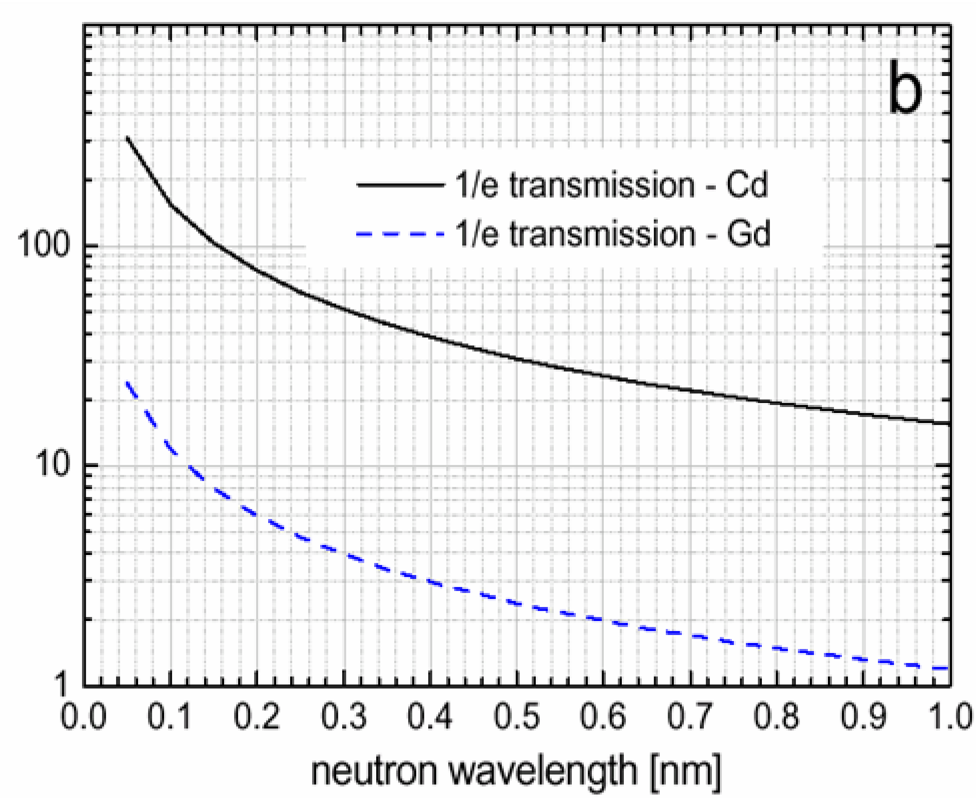


Gratings for neutron applications

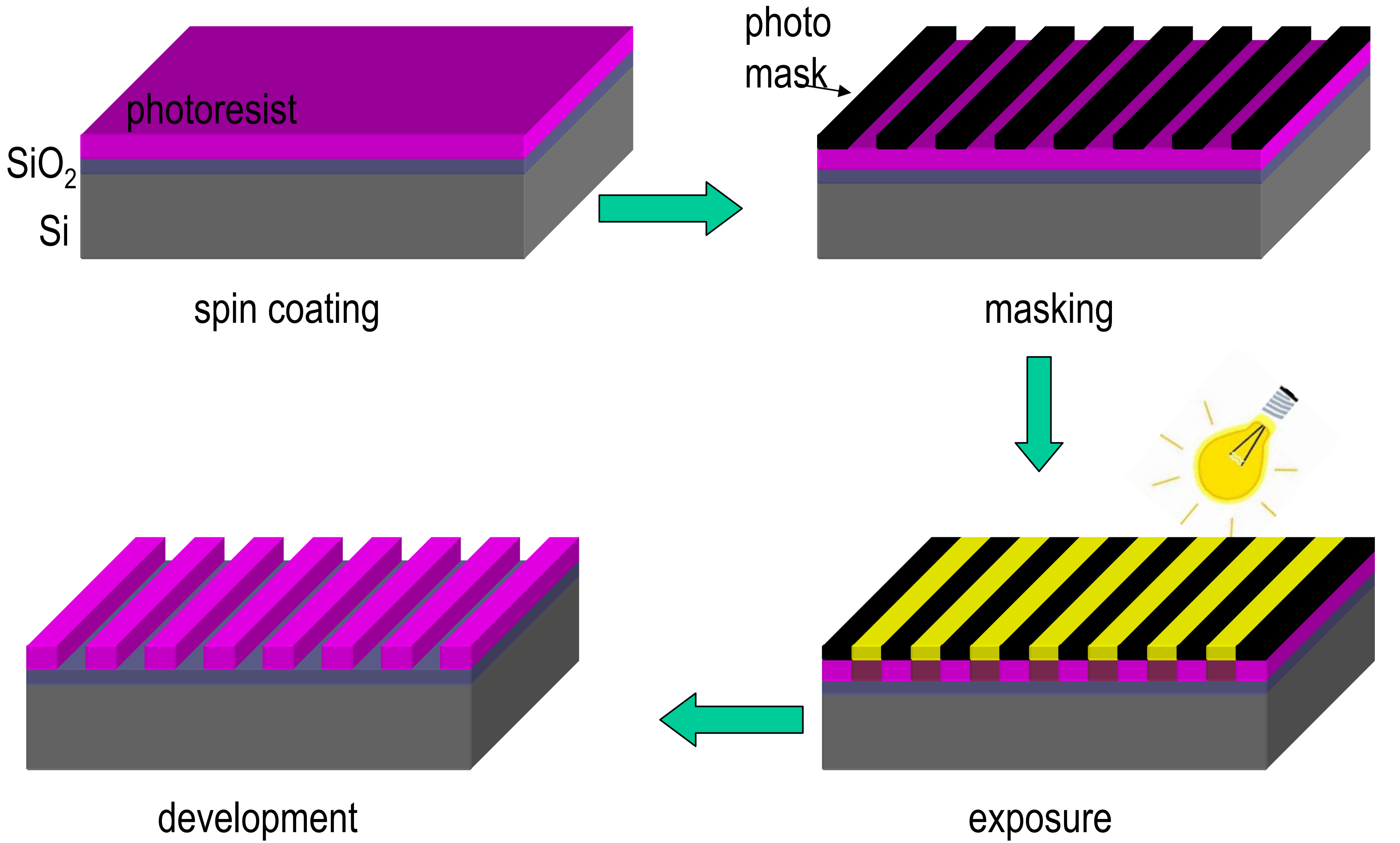
phase grating G1



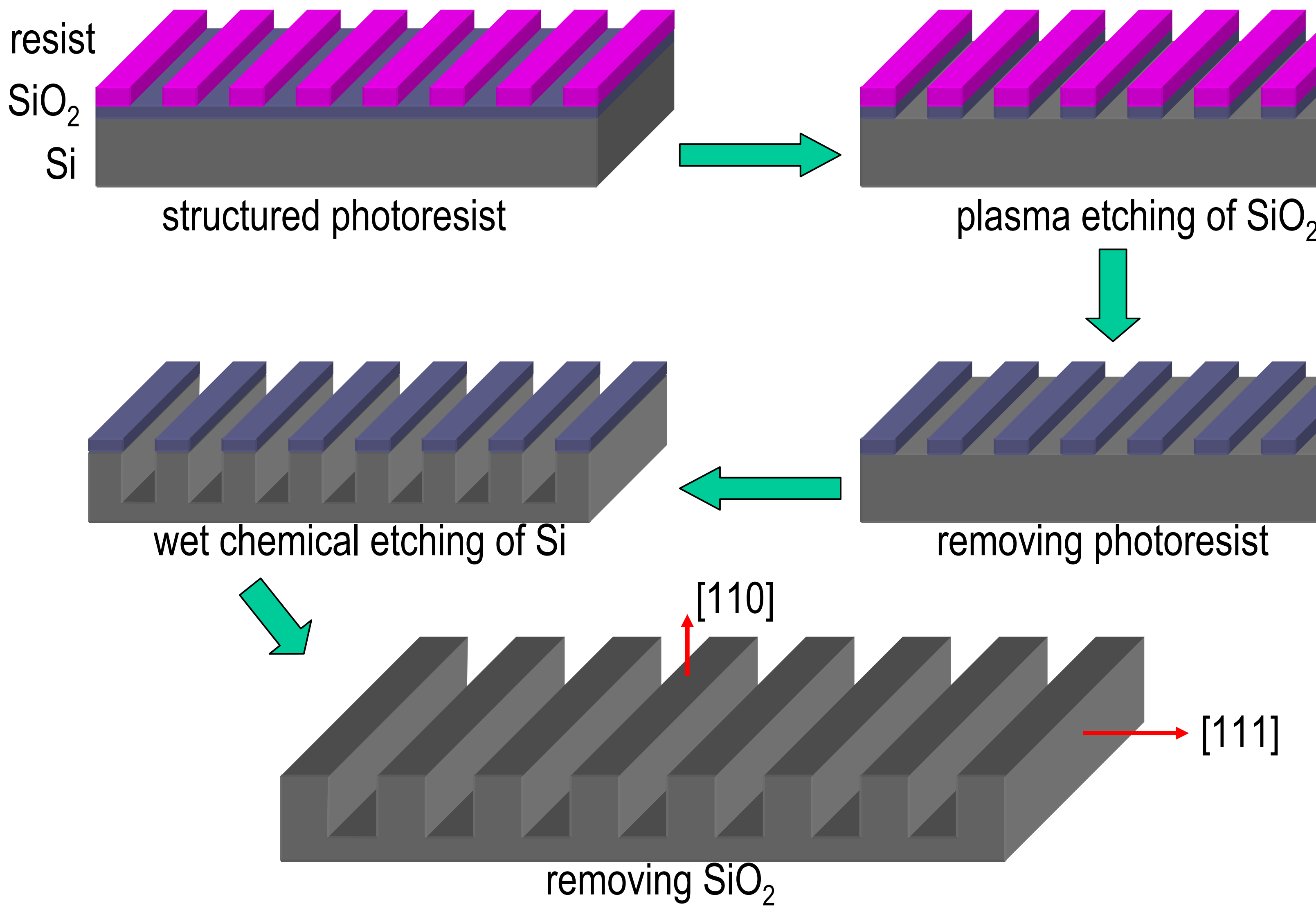
absorption gratings G0/G2



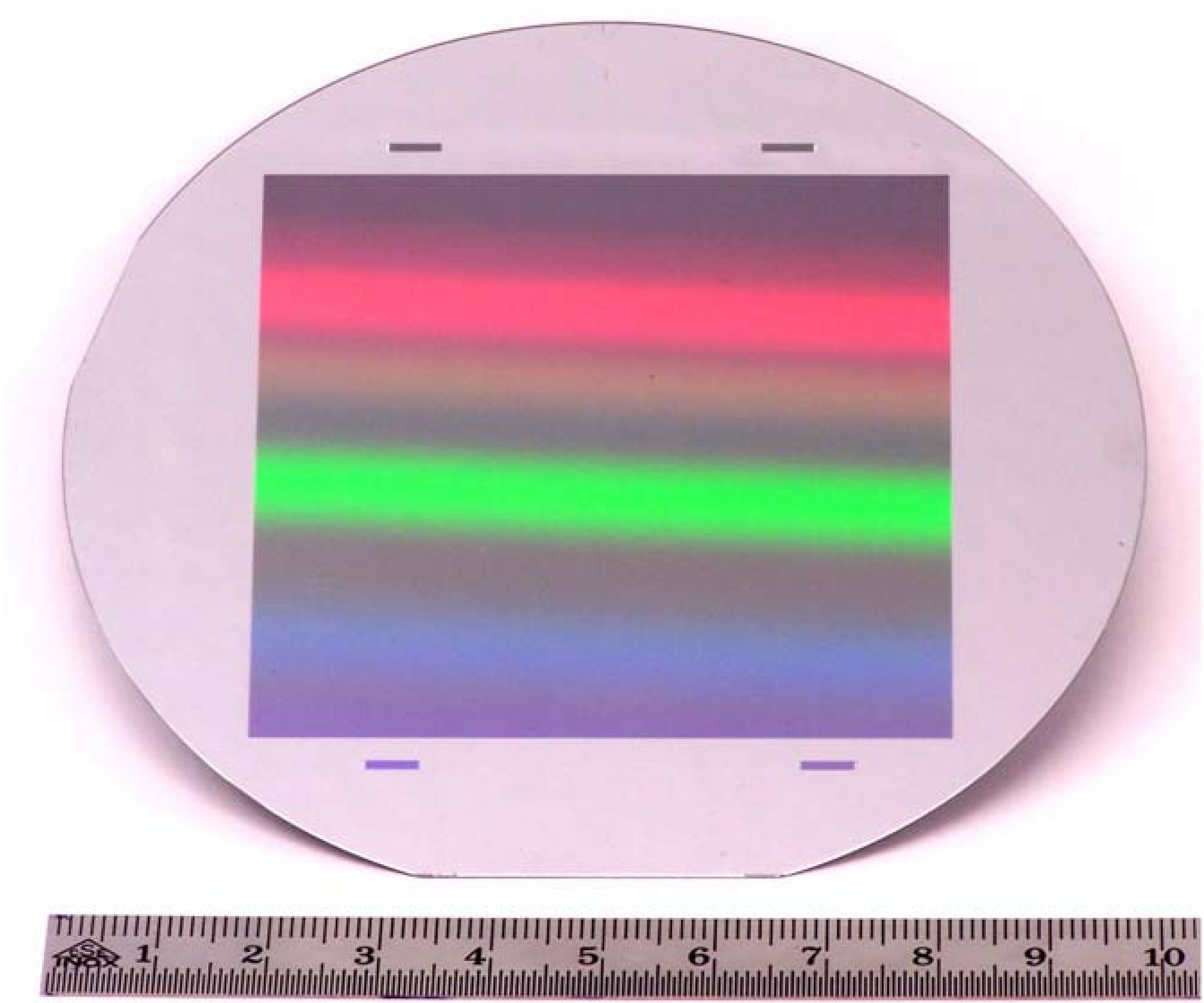
Fabrication (Si gratings)

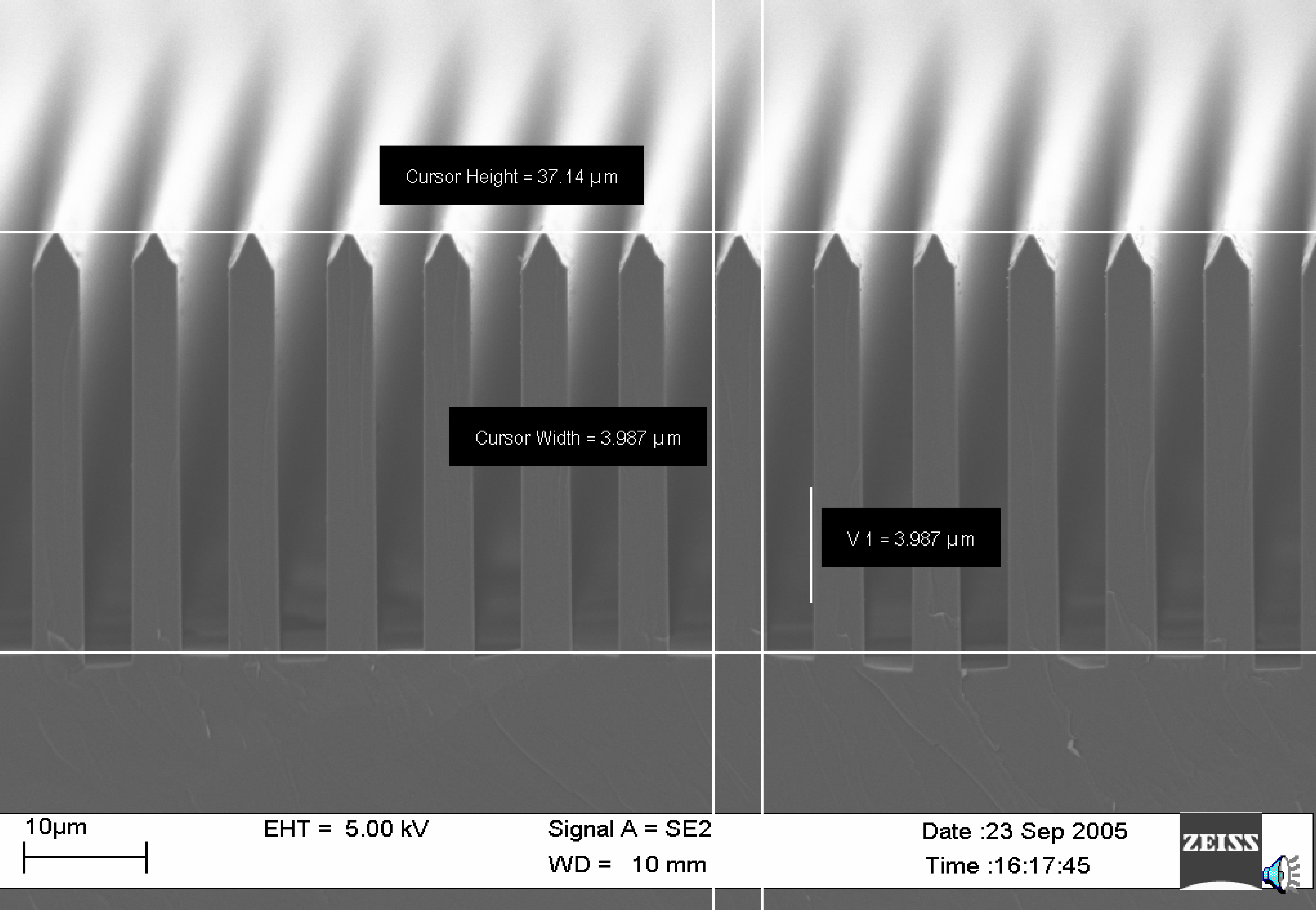


Fabrication (Si gratings)



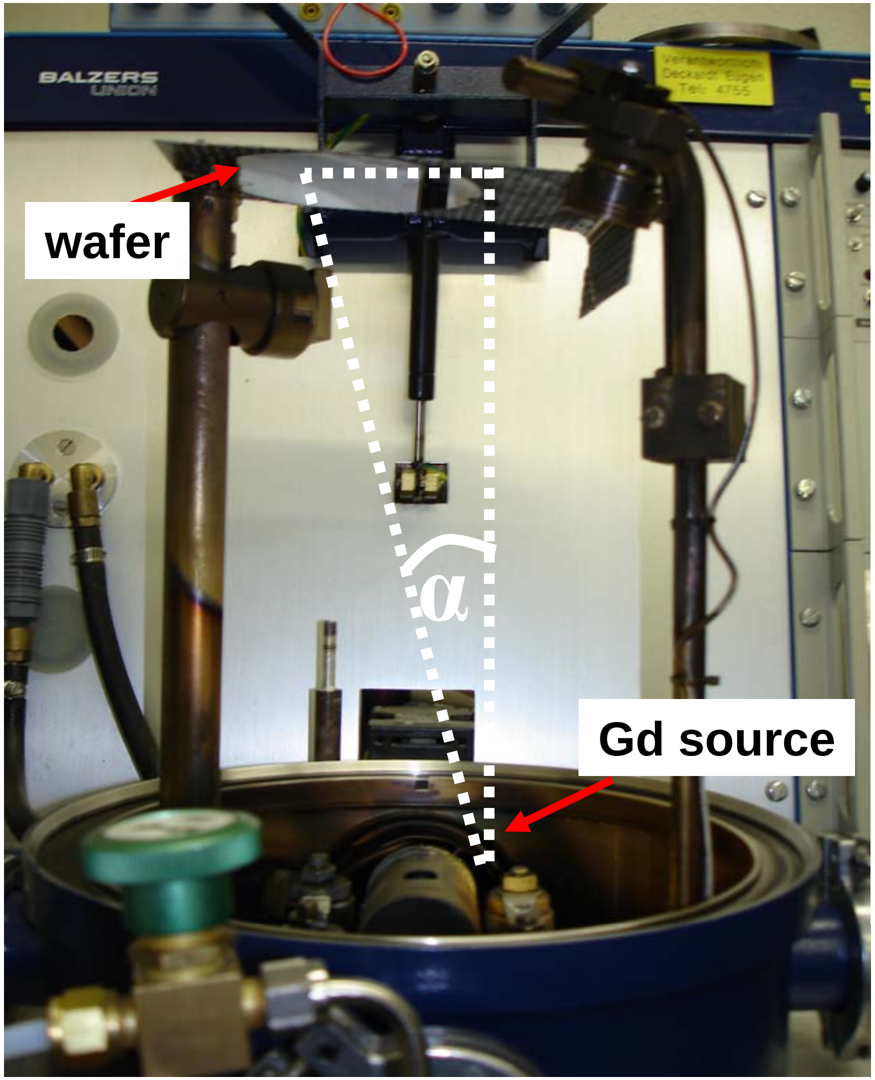
Fabrication (Si gratings)

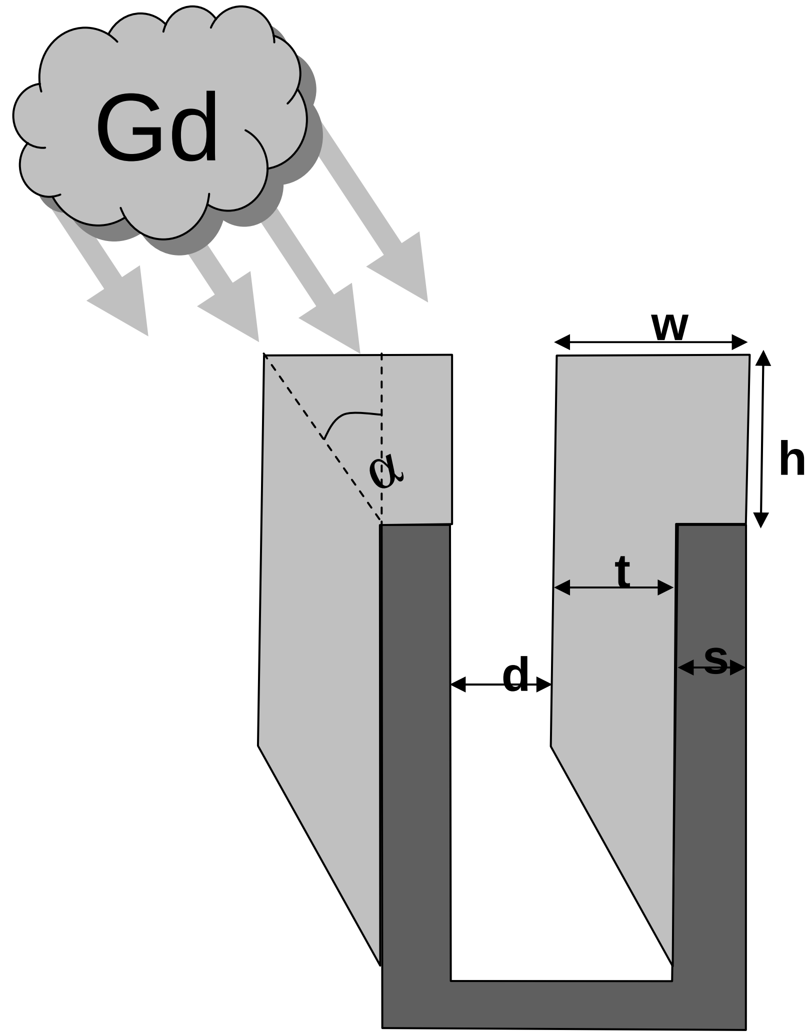


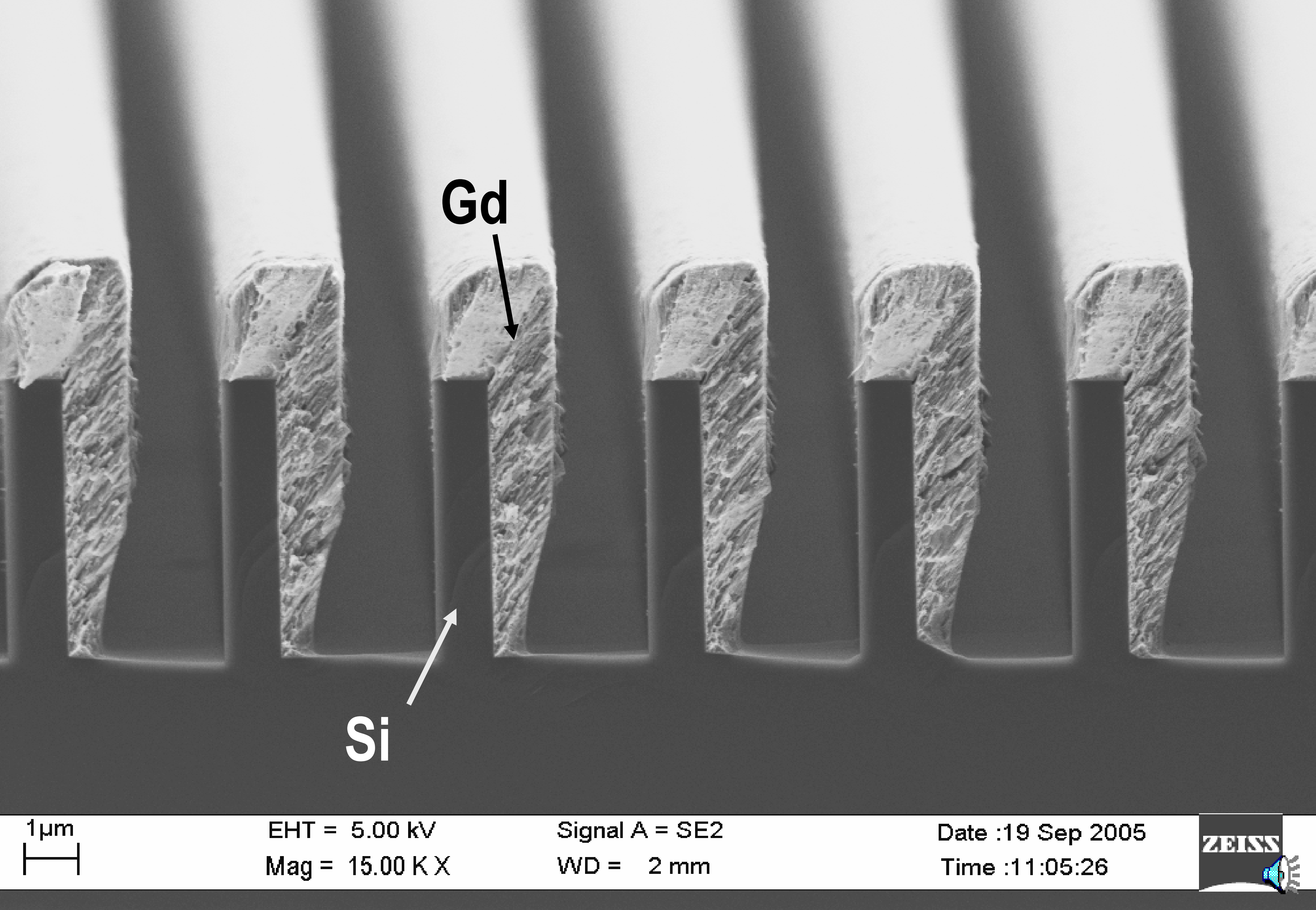


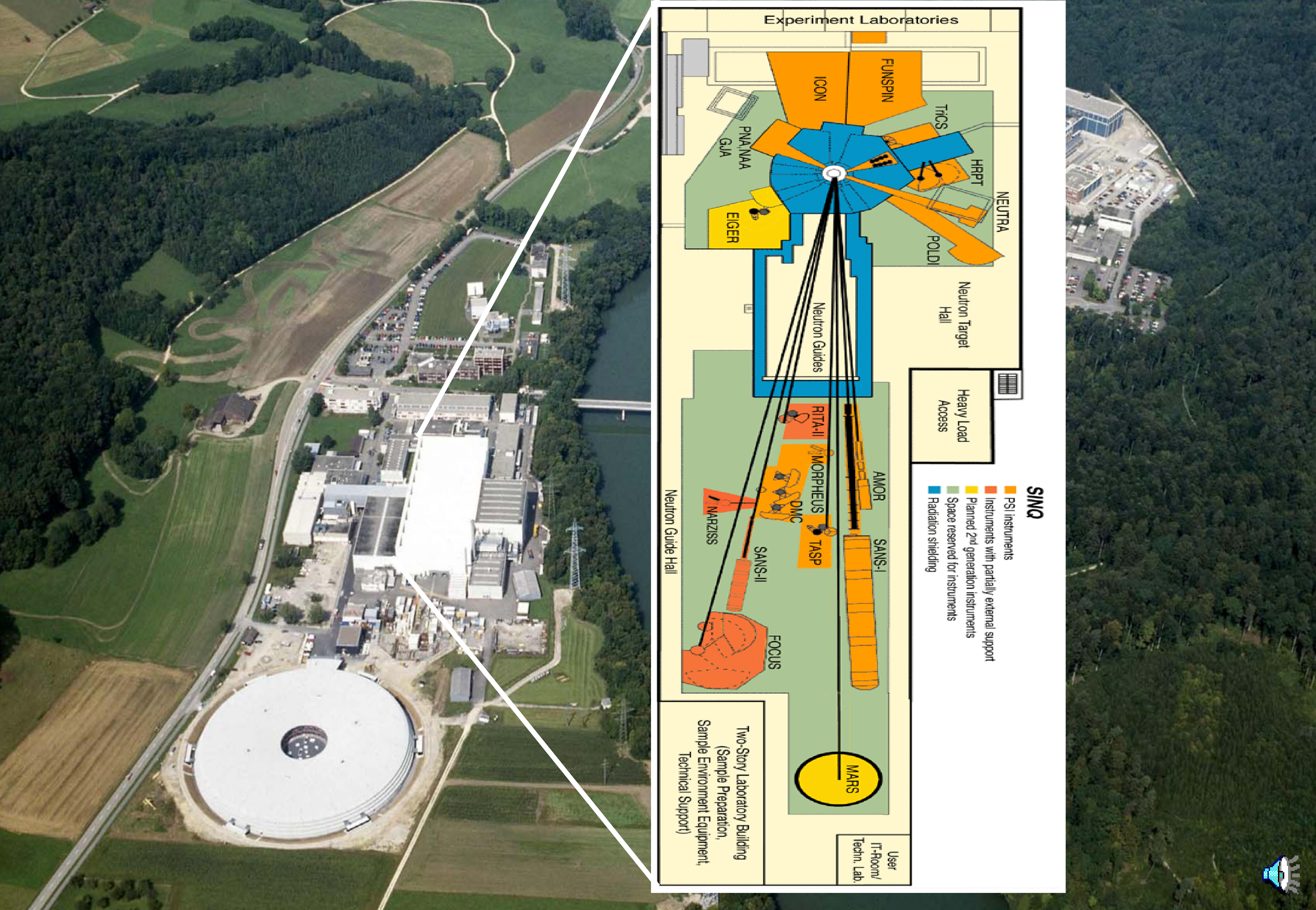
Cursor Height = 37.14 µm
Cursor Width = 3.987 µm
V 1 = 3.987 µm
10µm
EHT = 5.00 kV
Signal A = SE2
WD = 10 mm
Date :23 Sep 2005
Time :16:17:45

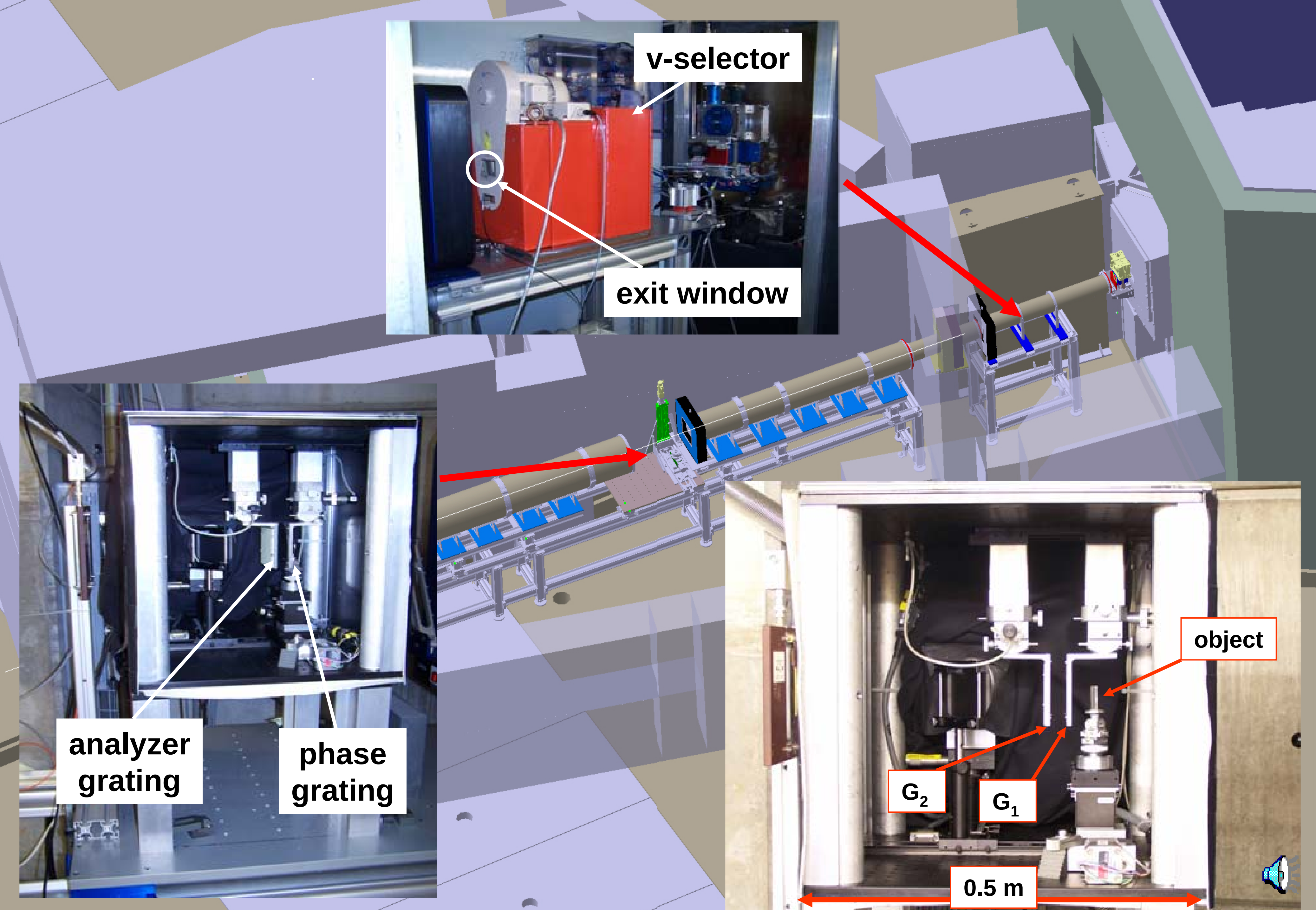
Fabrication (Si + Gd gratings)



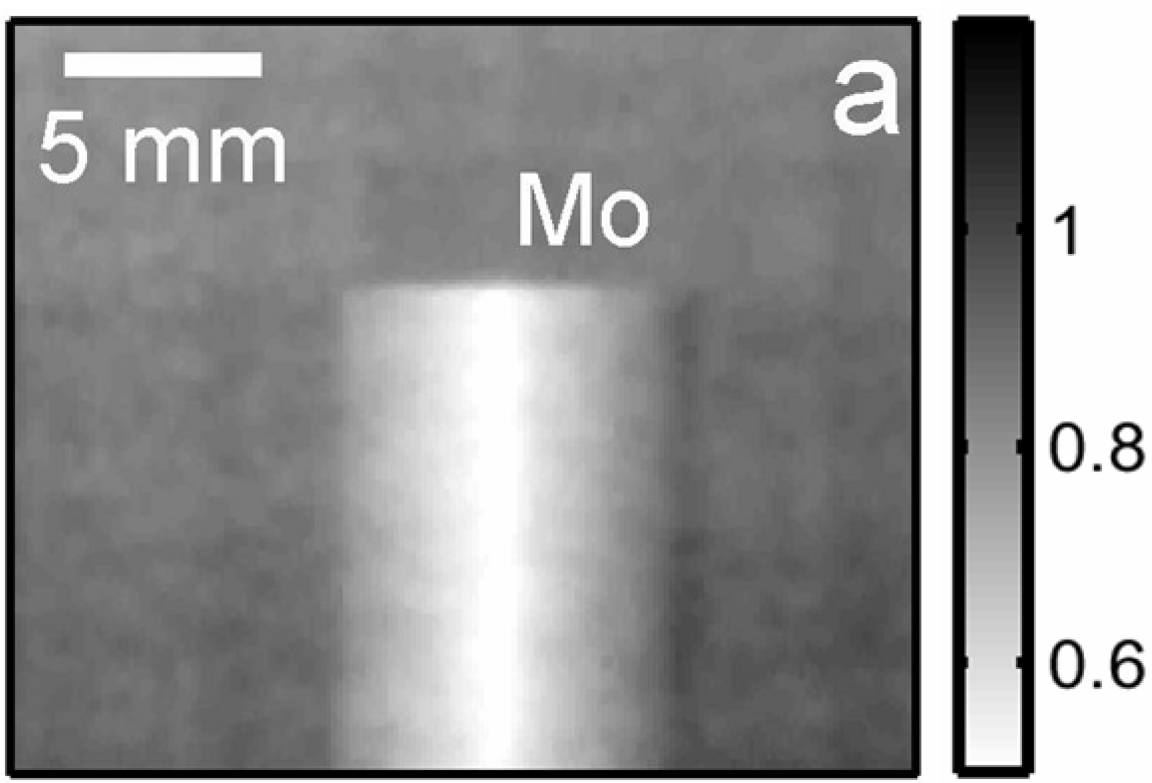



Gd
Si
1µm
EHT = 5.00 kV
Mag = 15.00 K X
Signal A = SE2
WD = 2 mm
Date :19 Sep 2005
Time :11:05:26
ZEISS


Experiment Laboratories
ICON
FUNSPIN
TriCS
PNA,NAA
GJA
HRPT
NEUTRA
POLDI
EIGER
Neutron Target Hall
Neutron Guides
Heavy Load Access
RITA-II
MORPHEUS
AMOR
DMC
NARZISS
TASP
SANS-I
SANS-II
FOCUS
MARS
Neutron Guide Hall
Two-Story Laboratory Building (Sample Preparation, Sample Environment Equipment, Technical Support)
User IT-Room/ Techn. Lab.
SINQ
PSI instruments
Instruments with partially external support
Planned 2nd generation instruments
Space reserved for instruments
Radiation shielding

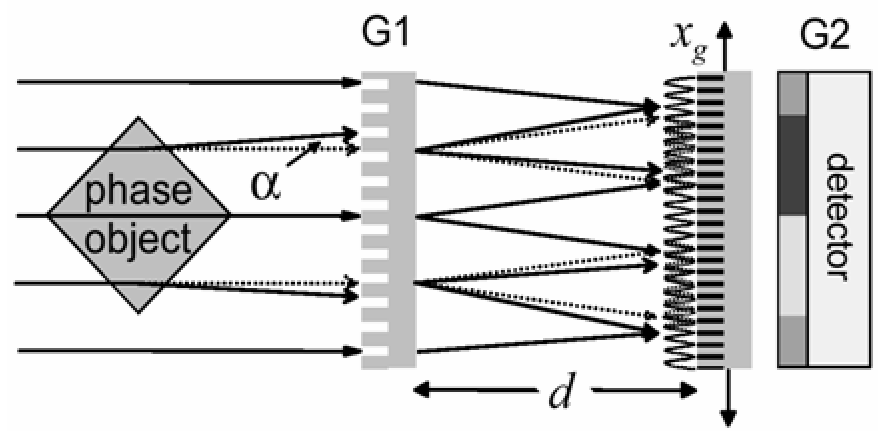

v-selector
exit window
analyzer grating
phase grating
object
G2
G1
0.5 m

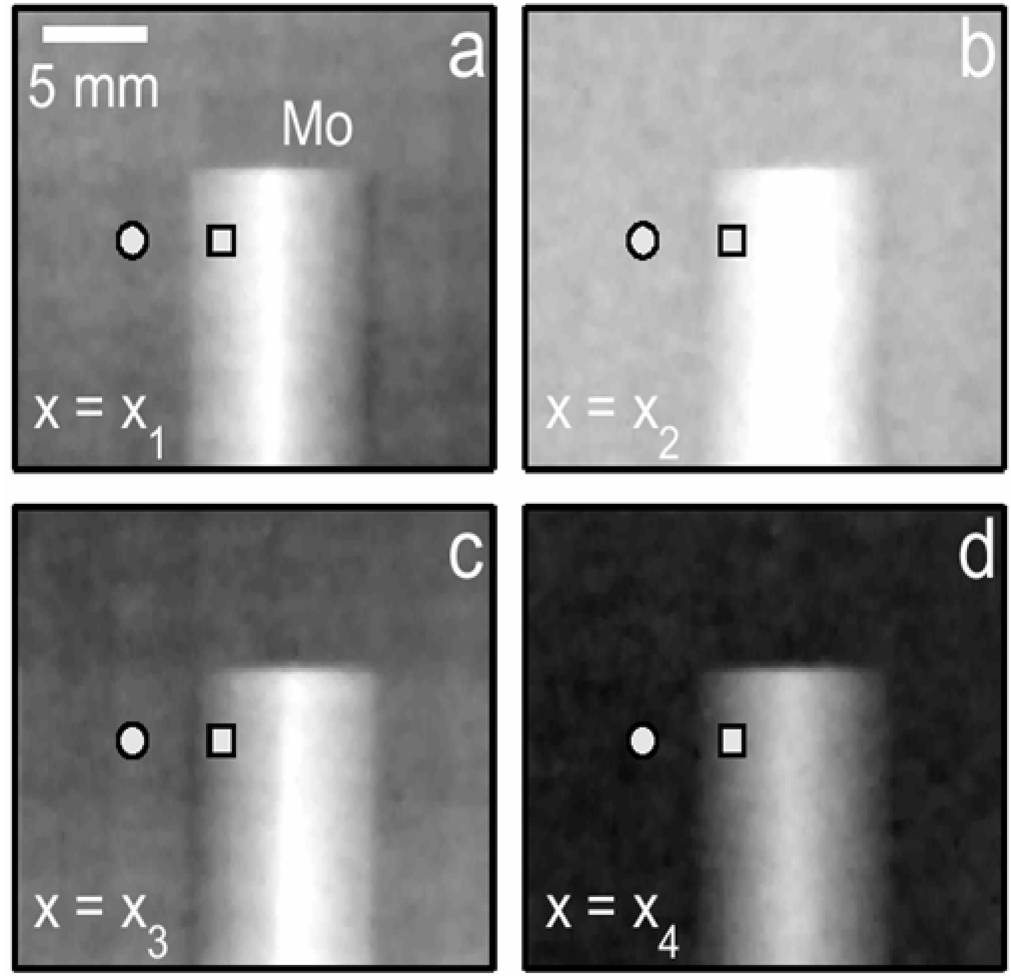
First neutron phase contrast results

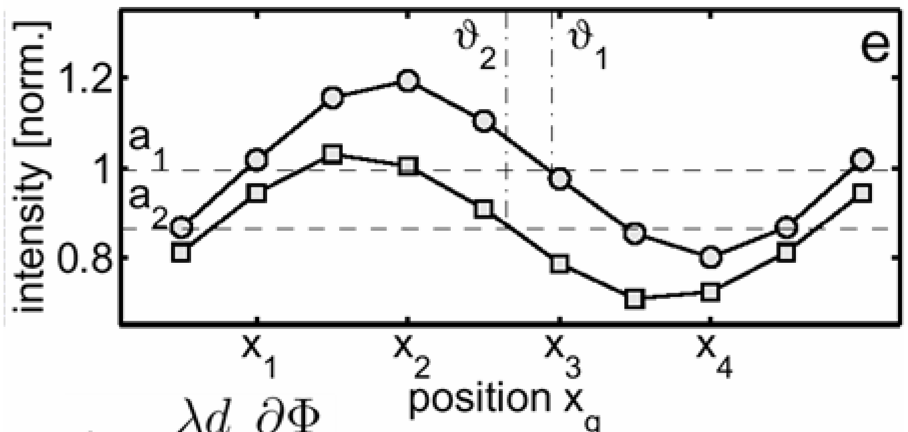


L/D ~ 250, exposure time per image: 10 sec, spatial resolution ~ 250 micron

First neutron phase contrast results



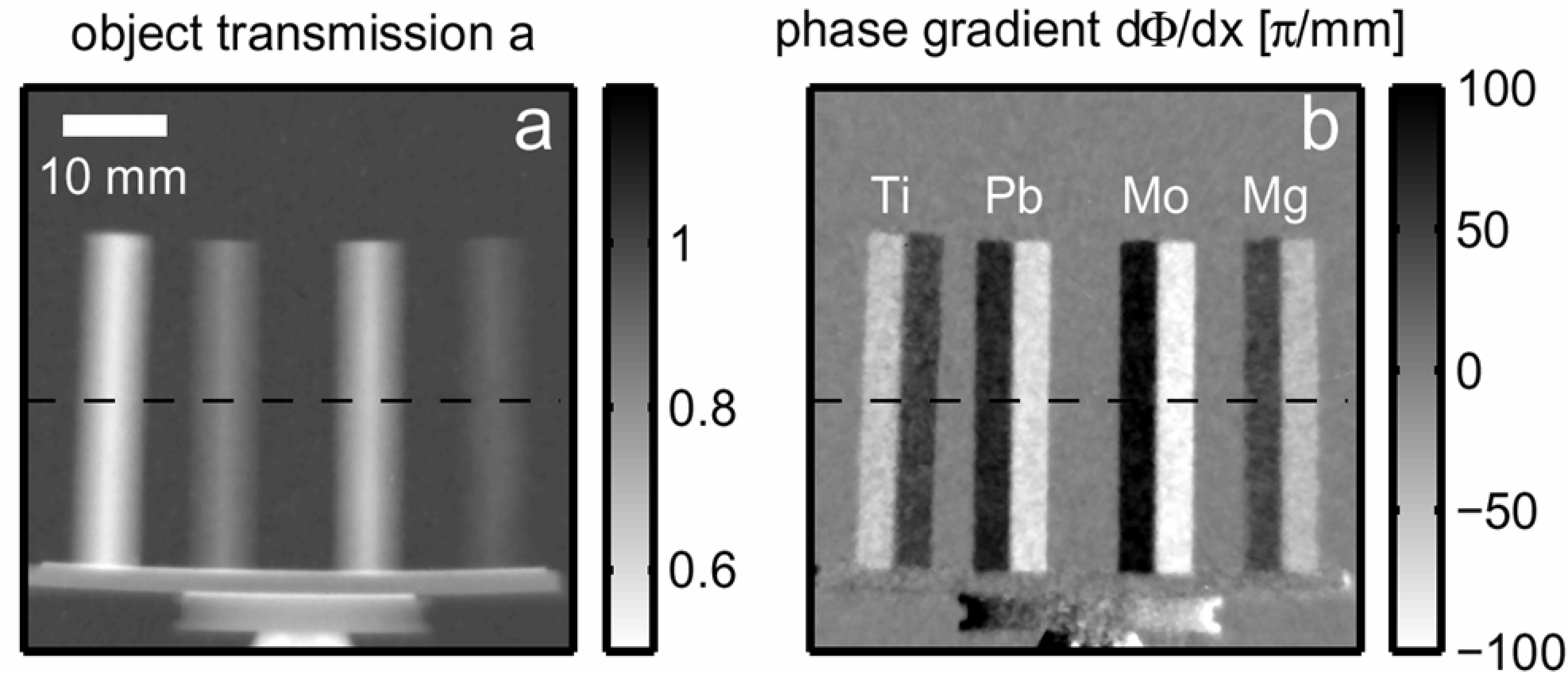




$$\vartheta = \frac{\lambda d}{p_2} \frac{\partial \Phi}{\partial x}$$

Phase stepping

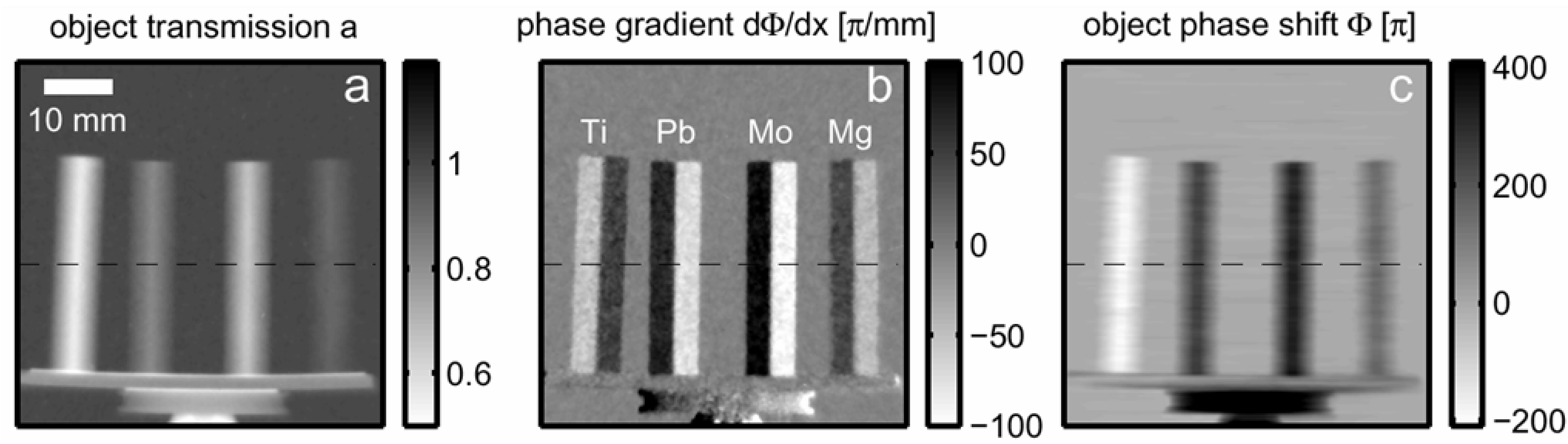
First neutron phase contrast results



L/D ~ 250, total exposure time ~ 100 sec, spatial resolution ~ 250 micron

First neutron phase contrast results

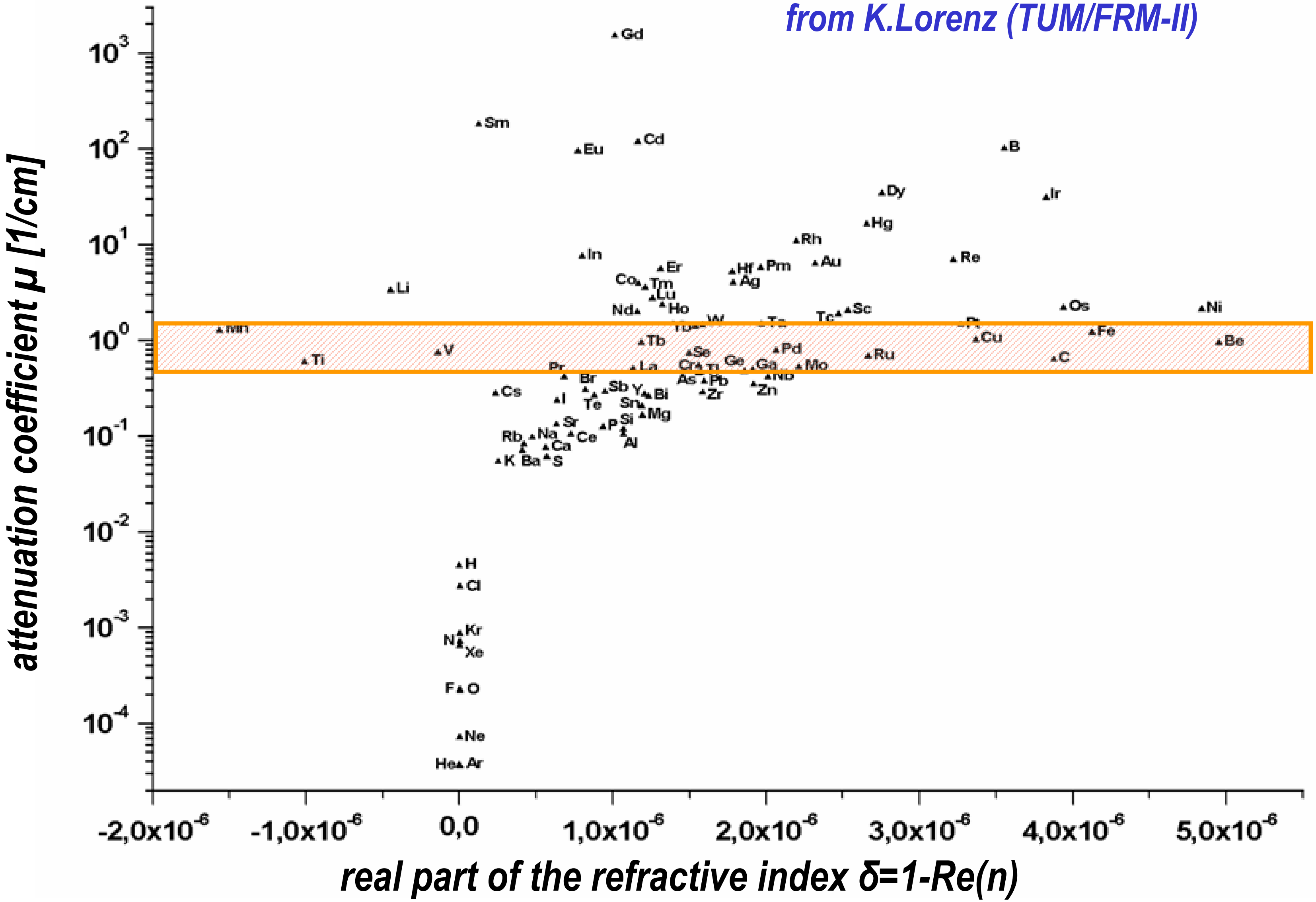
Quantitative ✓



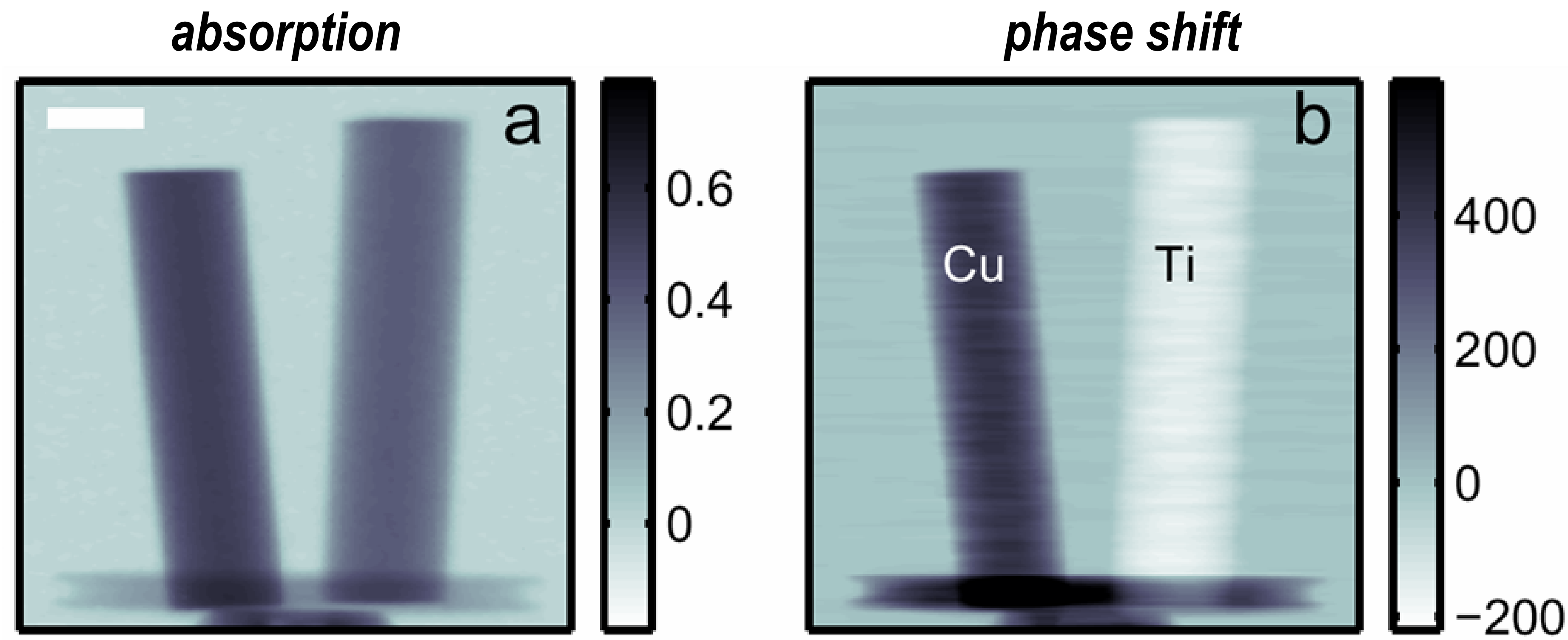
L/D ~ 250, total exposure time ~ 100 sec, spatial resolution ~ 250 micron

Absorption vs. Phase Contrast

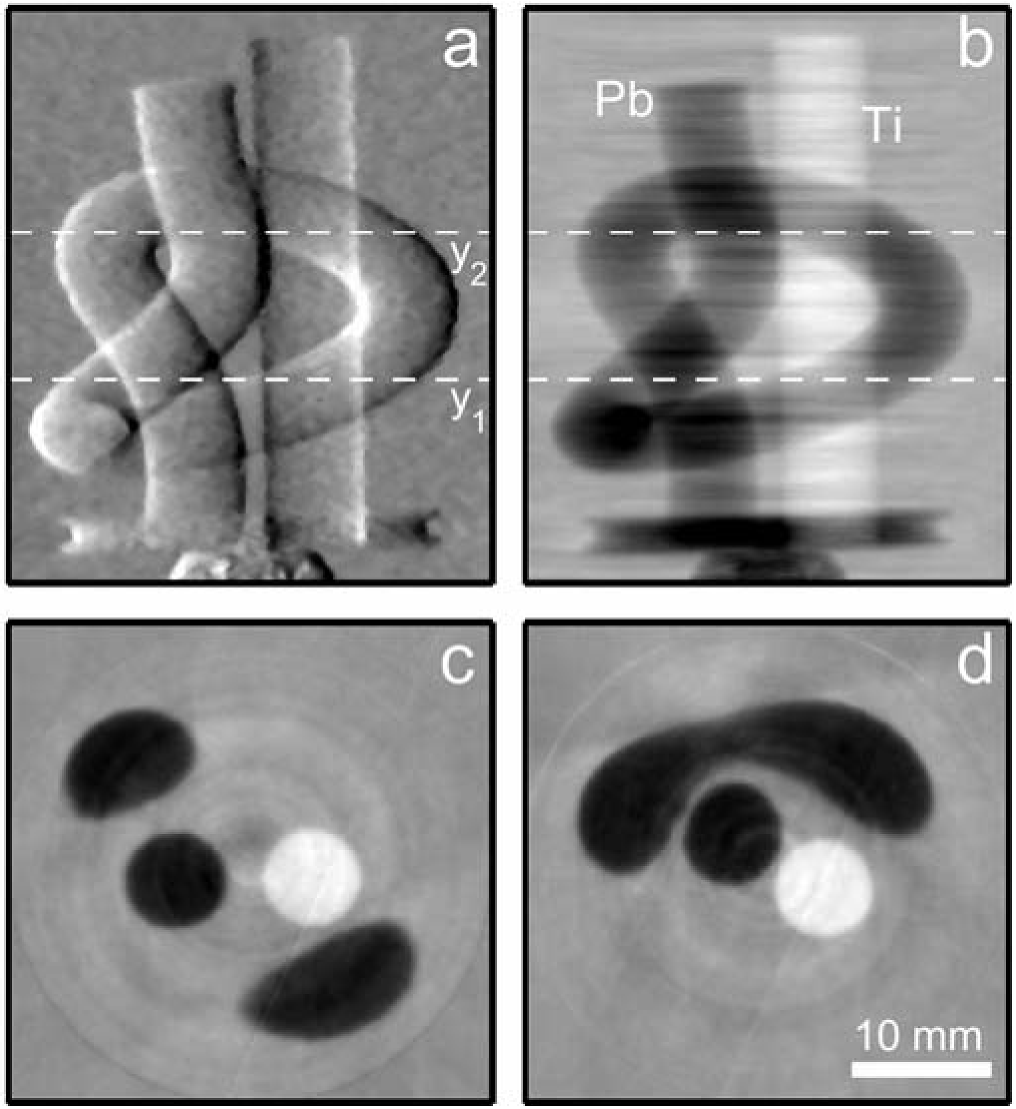
from K.Lorenz (TUM/FRM-II)



Absorption vs. Phase Contrast



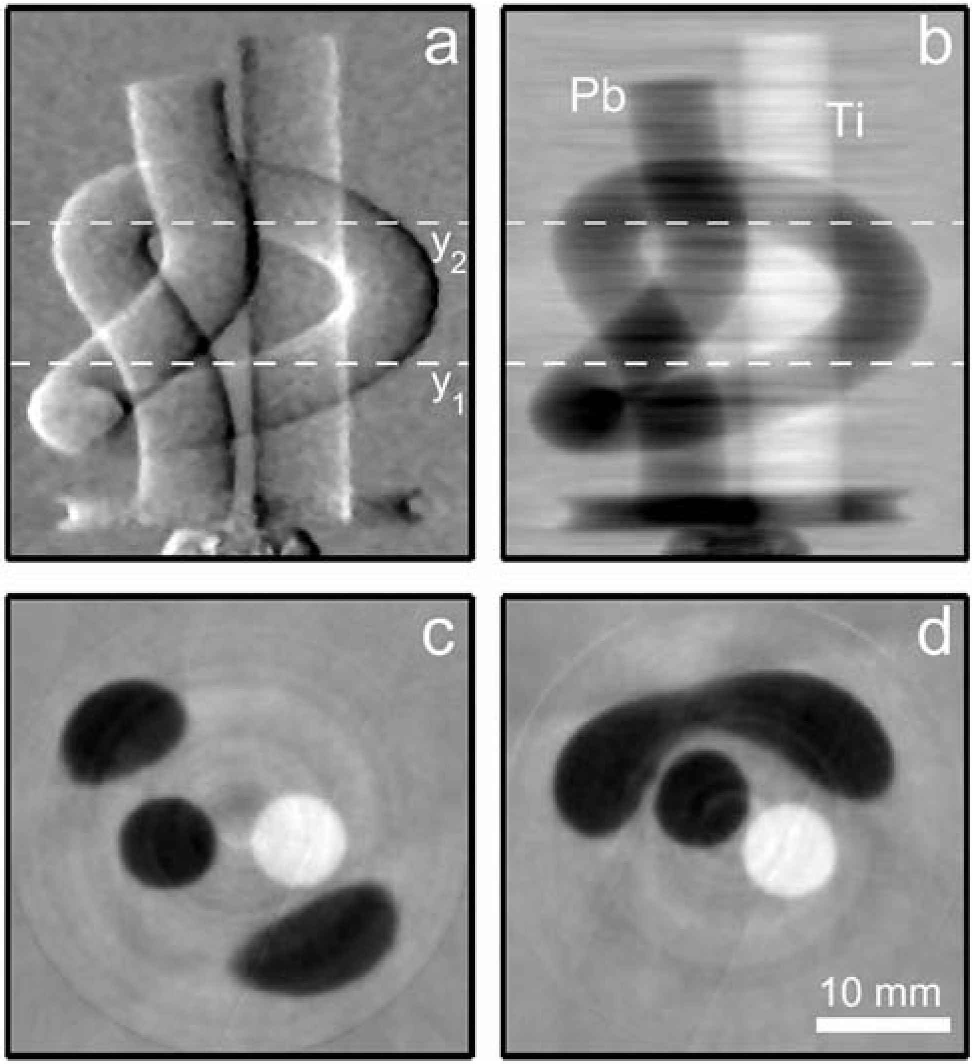
Neutron phase contrast tomography

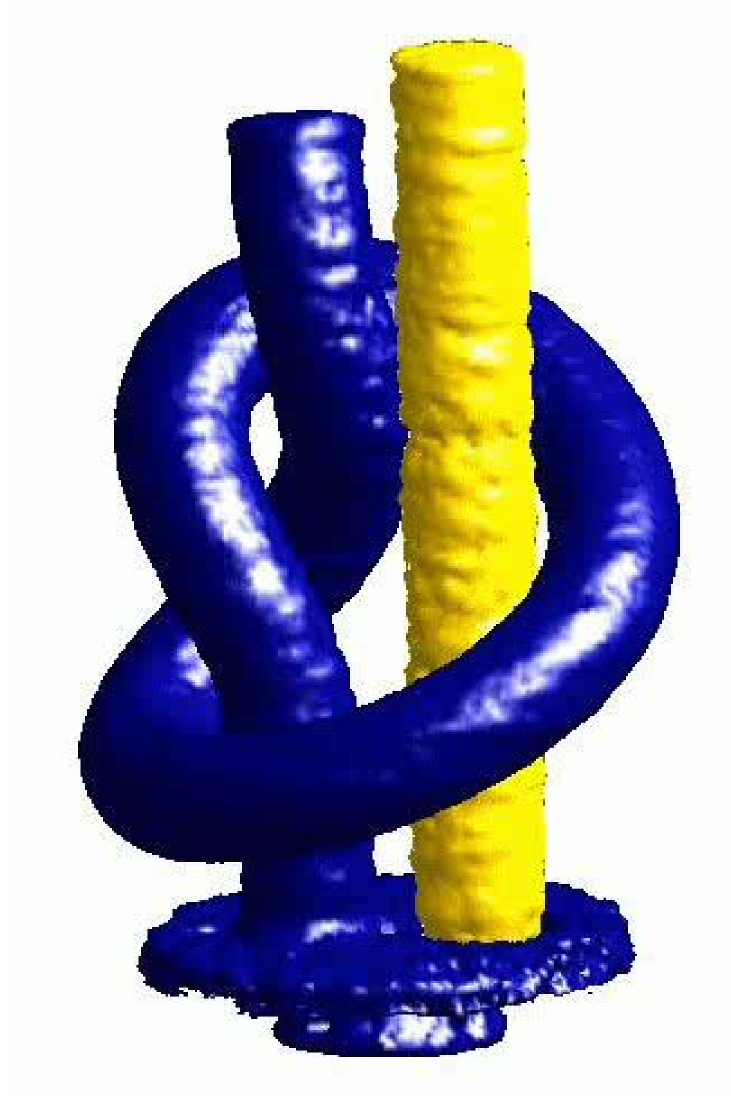


180 Phase Projections,
10 images á 10 sec

CT reconstruction:
$\delta(x,y,z) \sim b_c(x,y,z)$,
512 slices

Neutron phase contrast tomography





Efficiency ?

VOLUME 91, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2003

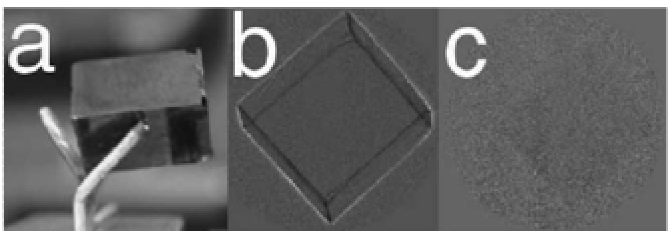
Quantitative Phase Radiography with Polychromatic Neutrons

P. J. McMahon,[1,*] B. E. Allman,[1,†] D. L. Jacobson,[2] M. Arif,[2] S. A. Werner,[2] and K. A. Nugent[1,‡]

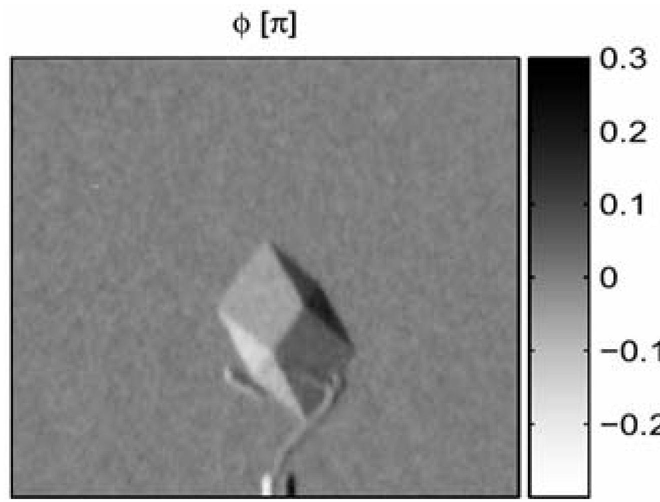
[1]*School of Physics, University of Melbourne, Victoria 3010, Australia*

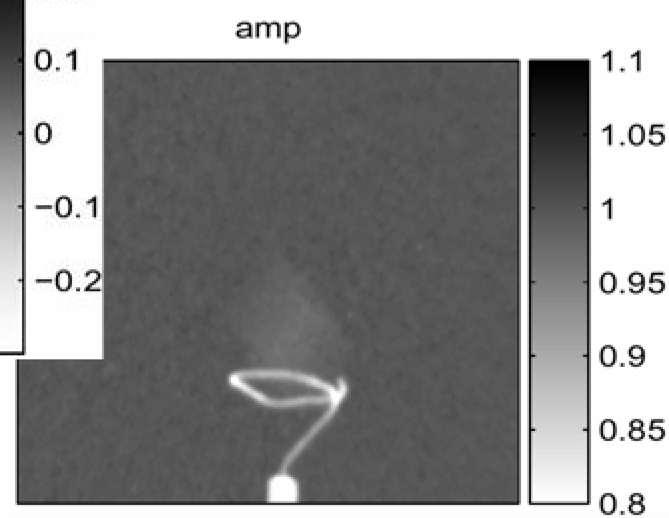
[2]*Physics Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*

(Received 23 June 2003; published 1 October 2003)



the sample in order to allow a suitable redistribution of intensity. An example of the intensity recorded at this position for a 12 h exposure is shown in Fig. 2(b). This image was normalized by an image of the field recorded over a similar period without the sample in position in





Total exp. time: 100 sec (SINQ)

Comparison to other methods

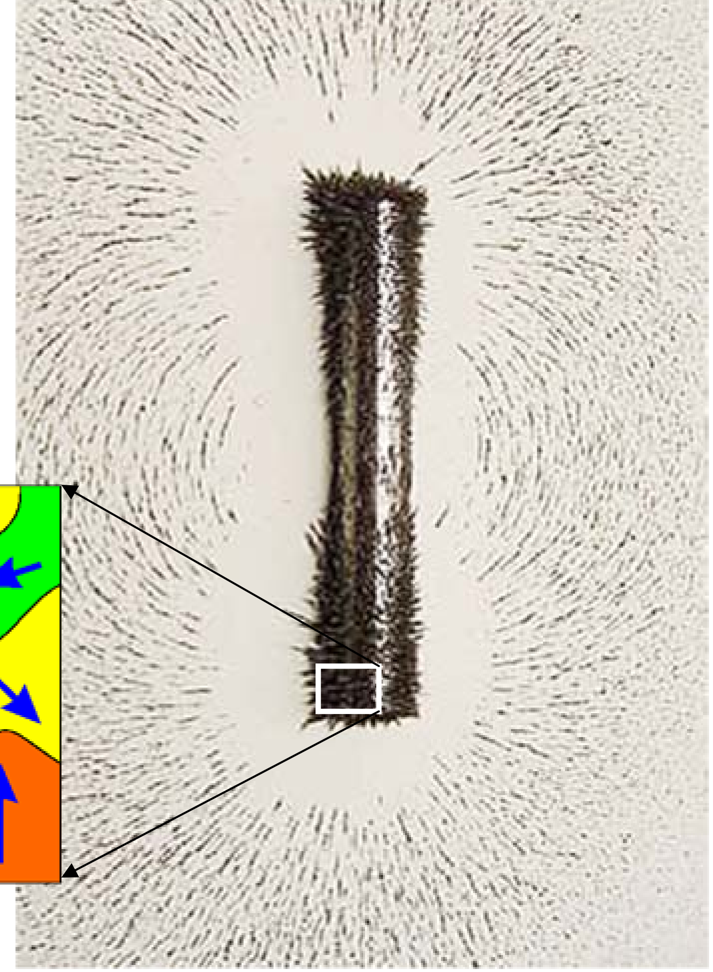
Method	Measured quantity		
Crystal Interferometer	Phase Φ	•highest phase sensitivity	•mechanical instability •monochromatic •limited FOV (Crystals) •low efficiency
Grating Interferometer	Phase gradient $\nabla\Phi$	•good phase sensitivity •polychromatic •large fields of view •very efficient	•requires gratings
Fresnel Propagation	Laplace of phase $\Delta\Phi$	•simple •polychromatic	•low efficiency •requires high resolution detector •low phase sensitivity

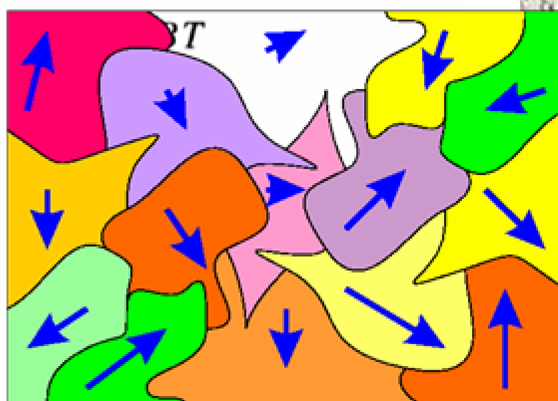
The Future ?

Interaction	Potential	Phase shift
Nuclear ✓	$\frac{2\pi\hbar^2}{m} b_c \delta(\boldsymbol{r})$	$-N b_c \lambda D$
Magnetic	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(\boldsymbol{r})$	$\pm \frac{\mu B m \lambda D}{2\pi\hbar^2}$
Gravitation	$m\boldsymbol{g} \cdot \boldsymbol{r}$	$\frac{m^2 g \lambda A \sin\alpha}{2\pi h^2}$
Coriolis	$-\hbar\boldsymbol{\omega}(\boldsymbol{r} \times \boldsymbol{k})$	$\frac{2m}{\hbar} \boldsymbol{\omega}_e \cdot \boldsymbol{A}$
Aharonov–Casher (Schwinger)	$-\boldsymbol{\mu} \cdot (\boldsymbol{v} \times \boldsymbol{E})/c$	$\pm \frac{2\mu}{\hbar c} \boldsymbol{E} \cdot \boldsymbol{D}$
Scalar Aharonov–Bohm	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(t)$	
Magnetic Josephson	$-\boldsymbol{\mu} \cdot \boldsymbol{B}(t)$	
Fizeau	—	
Geometry (Berry)	—	

3D domain structure ?

=> User instrument !





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