Wir schaffen Wissen – heute für morgen

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Paul Scherrer Institut

Neutron Grating Interferometry

AUNIRA Workshop, Villigen-PSI, 1st October 2015

Outline

1. **Neutron Grating Interferometry:**
   a) **Setup**
   b) **Principle**
2. **Phase contrast and dark-field signals**
3. **Detection of nuclear scattering properties (applications)**
4. **Magnetic interaction**
5. **Magnetic investigations (applications)**
6. **Summary & Outlook**

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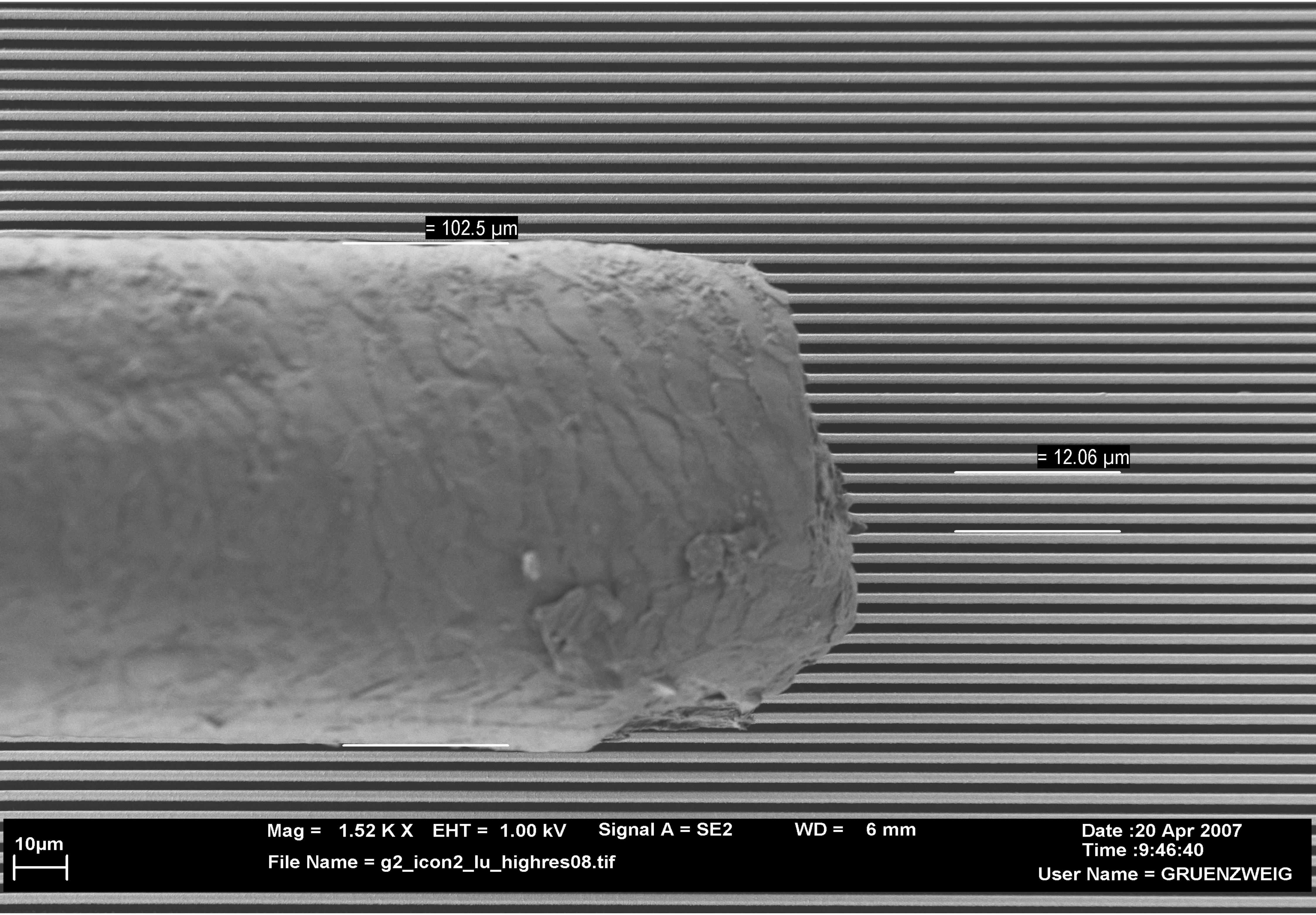
Neutron grating interferometry


= 102.5 µm
= 12.06 µm
10µm
Mag = 1.52 K X EHT = 1.00 kV Signal A = SE2 WD = 6 mm
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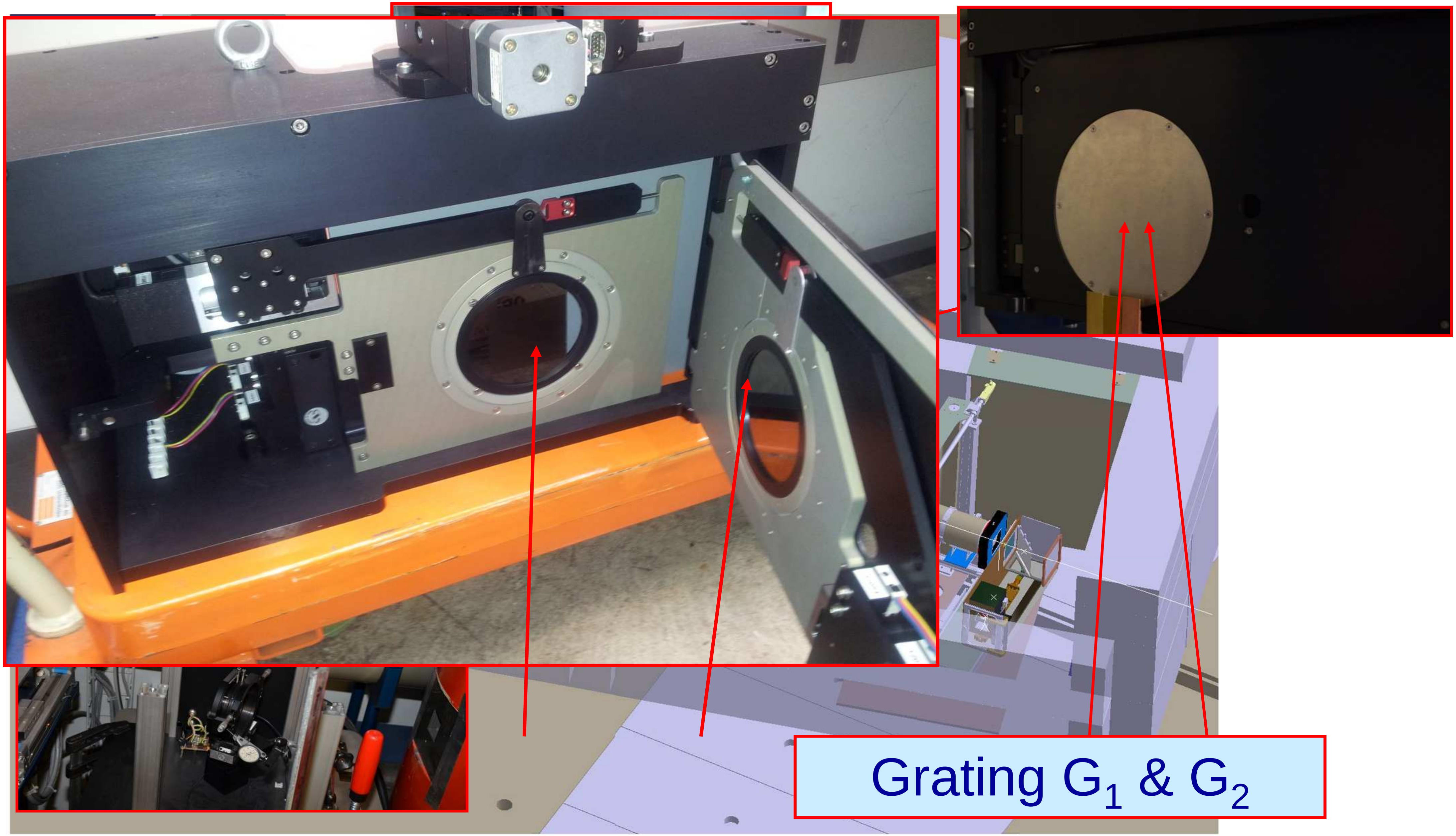
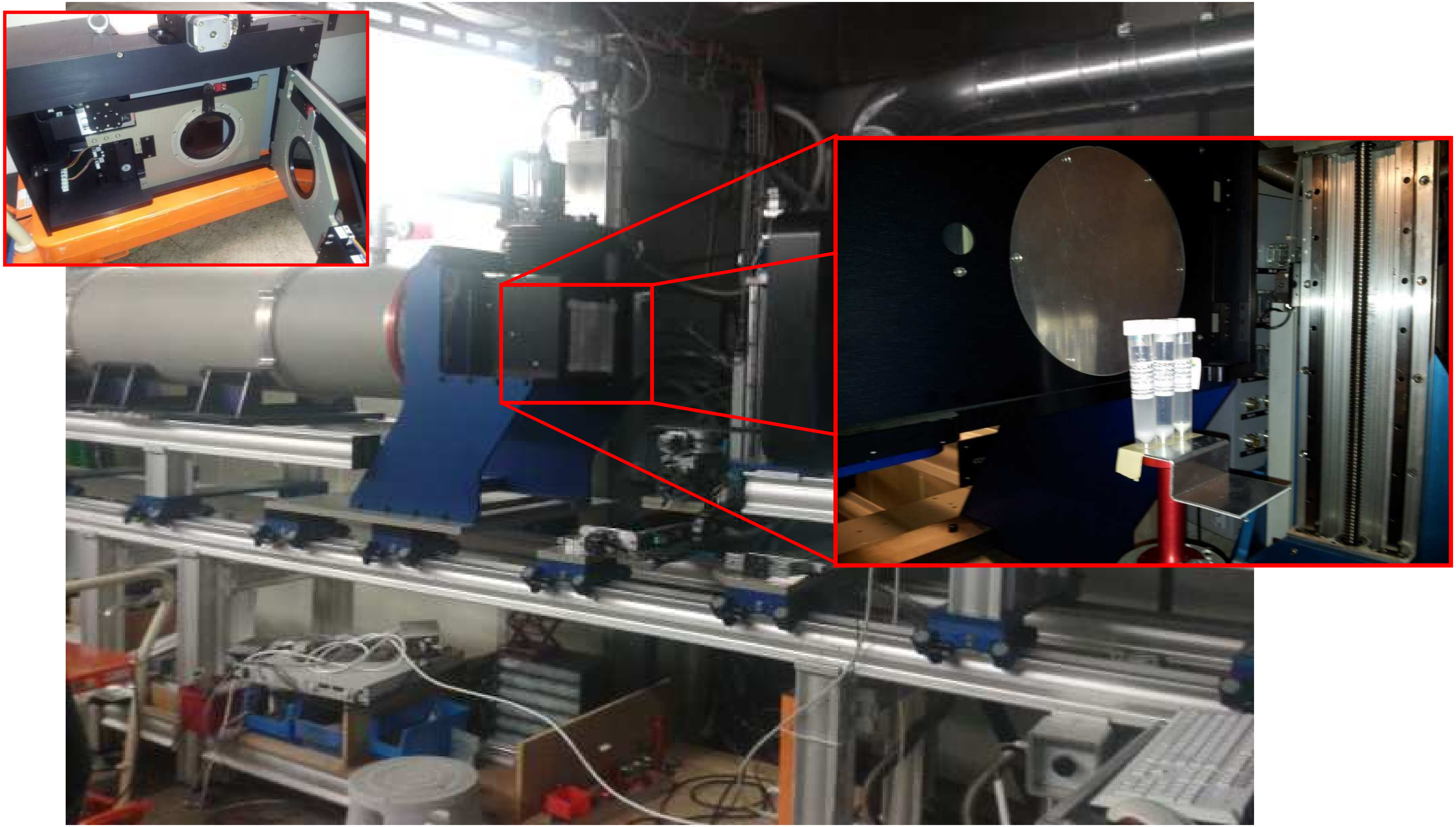
Date :20 Apr 2007
Time :9:46:40
User Name = GRUENZWEIG

Neutron grating interferometry



Neutron grating interferometry



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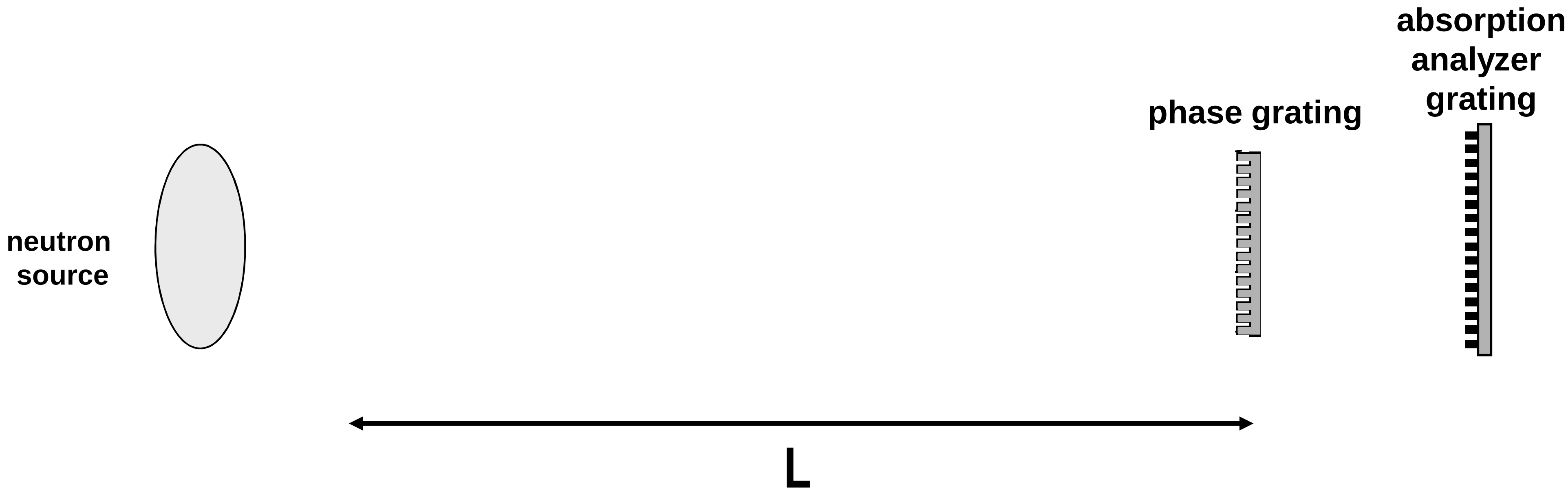
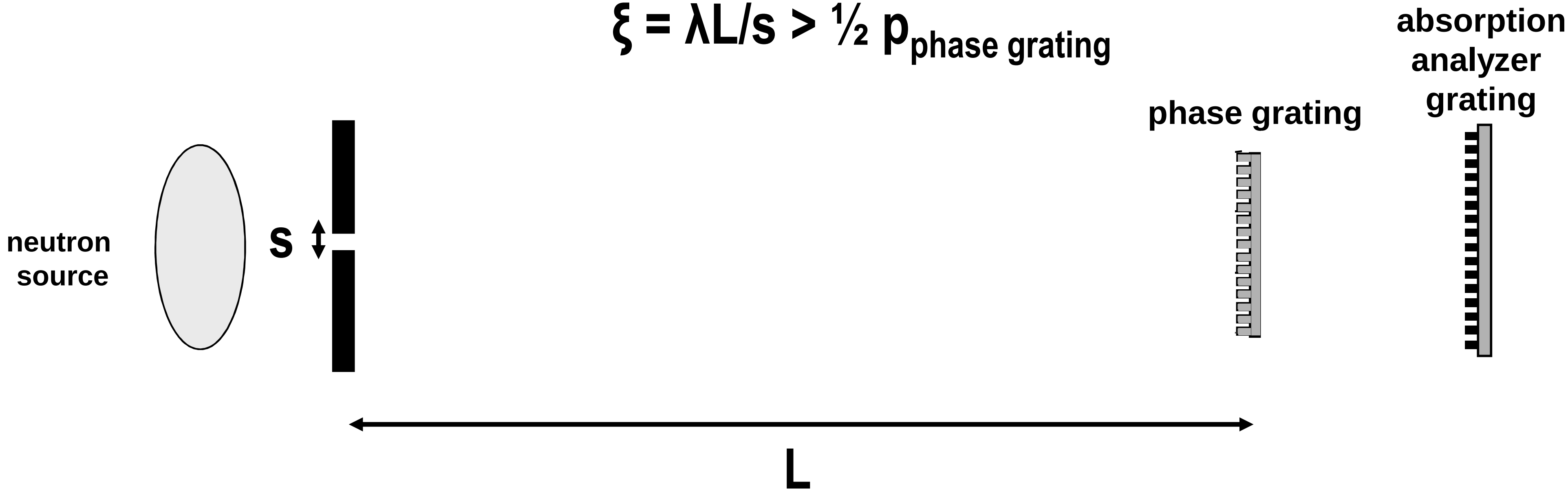
Neutron Grating Interferometry: Principle



Neutron Grating Interferometry: Principle

Required
spatial coherence length

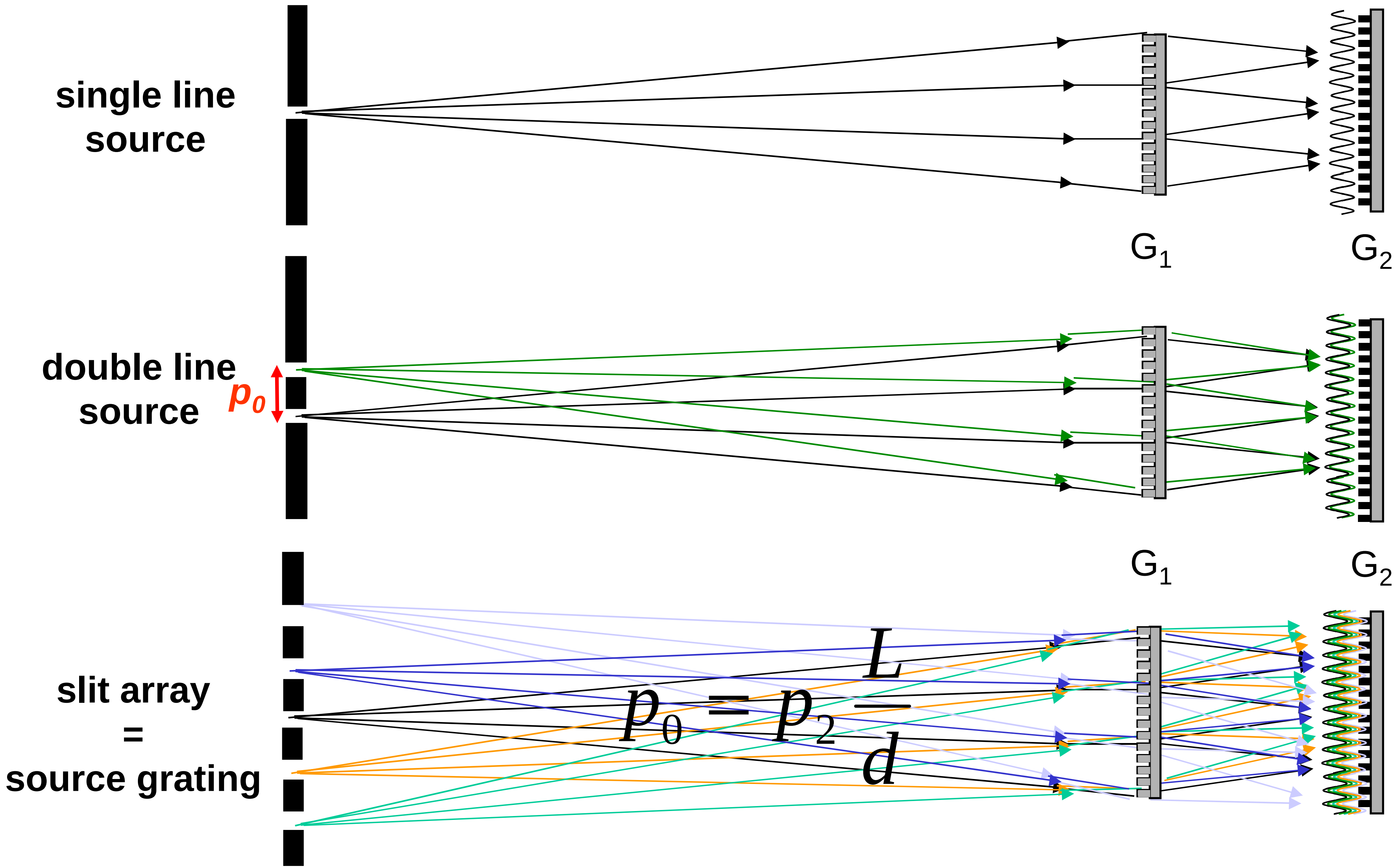
$$\xi = \lambda L/s > \tfrac{1}{2}\, p_{\text{phase grating}}$$



$$p_{\text{phase grating}} = 8\ \mu m, \quad L = 5.23\ m, \quad \lambda = 4\ \text{Å},$$

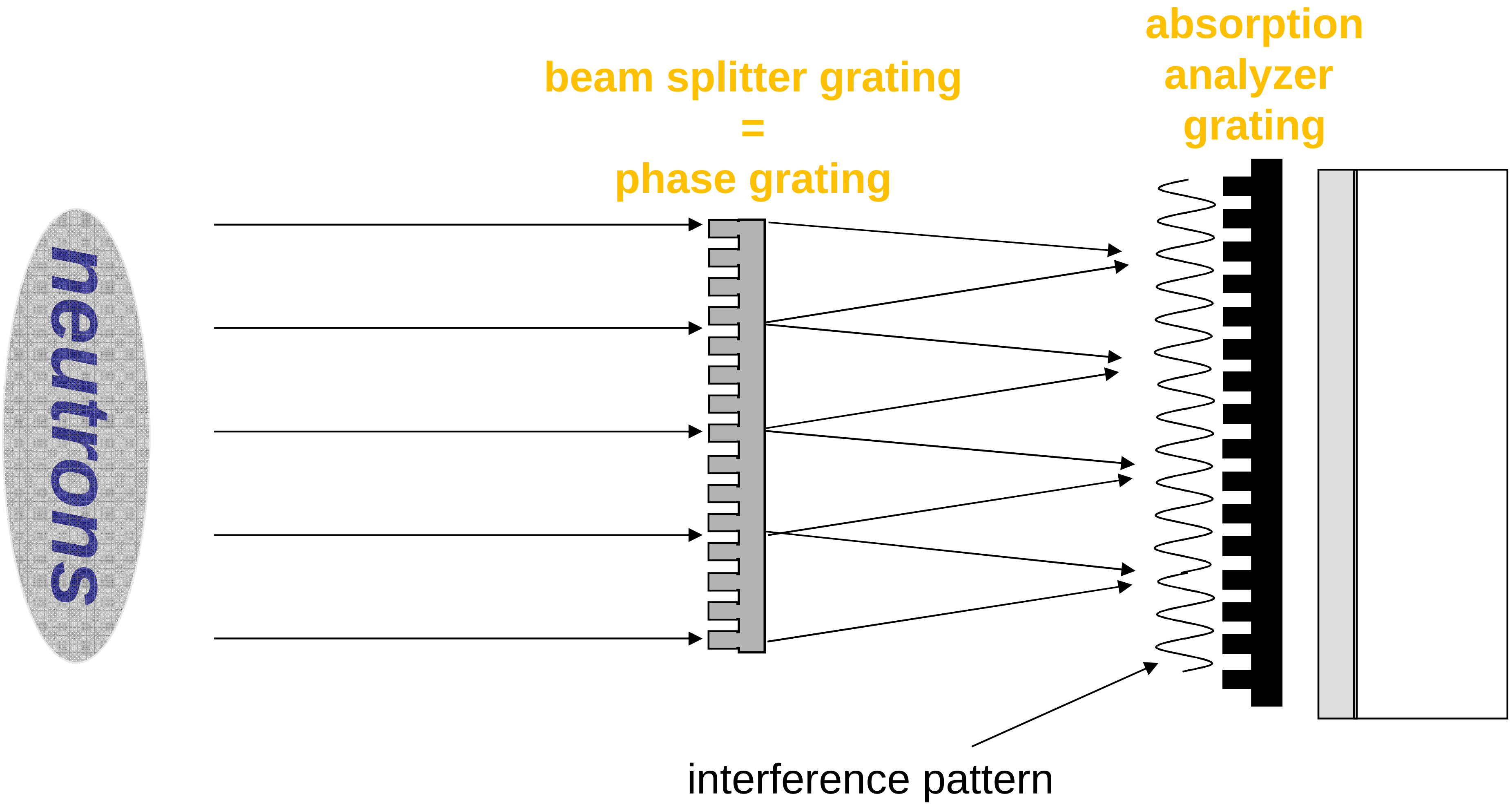
$$\Rightarrow\ s \sim 500\ \mu m$$

Neutron Grating Interferometry: Principle



$$p_0 = p_2 \frac{L}{d}$$

Neutron Grating Interferometry: Principle



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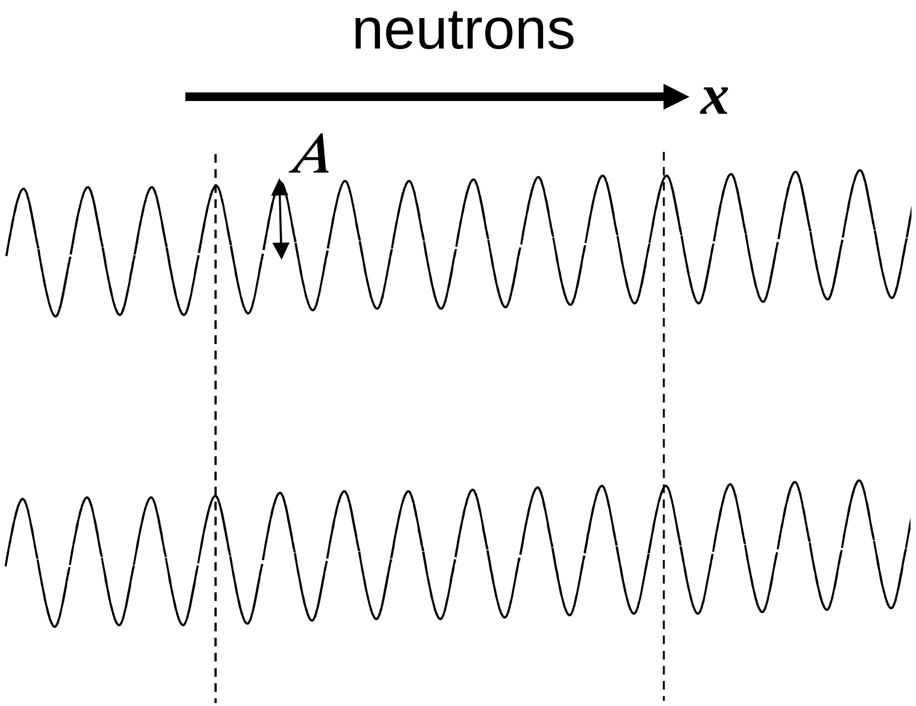
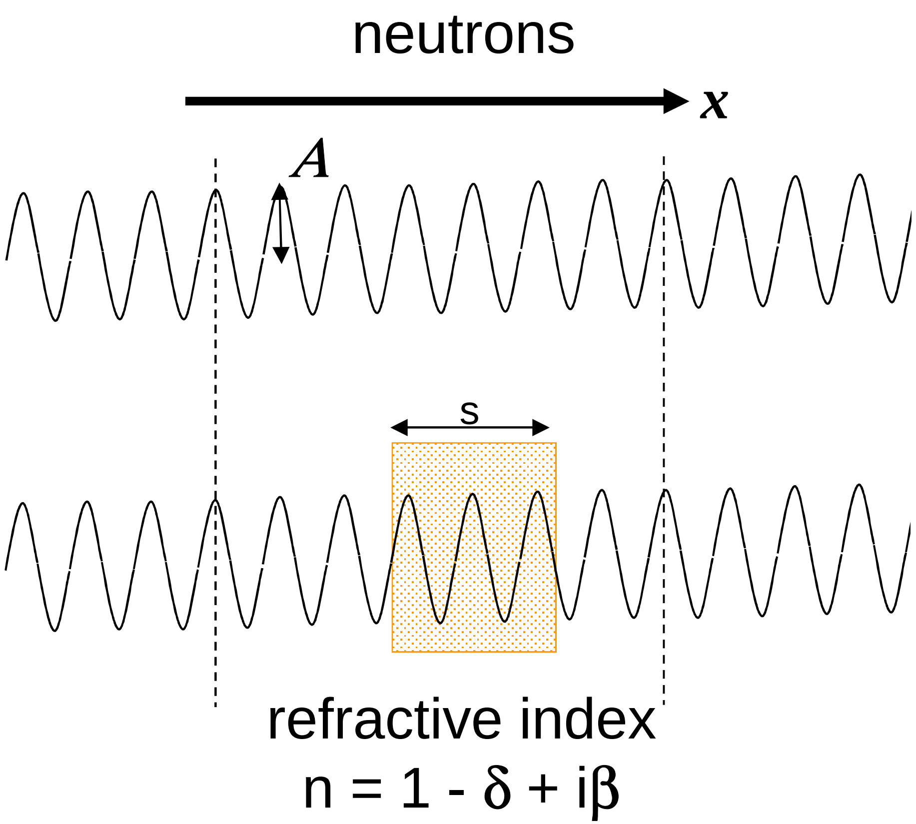
Phase contrast imaging:



$$\Psi_{before} = A \cdot e^{-i(\omega t - kx)}$$

Phase contrast imaging:



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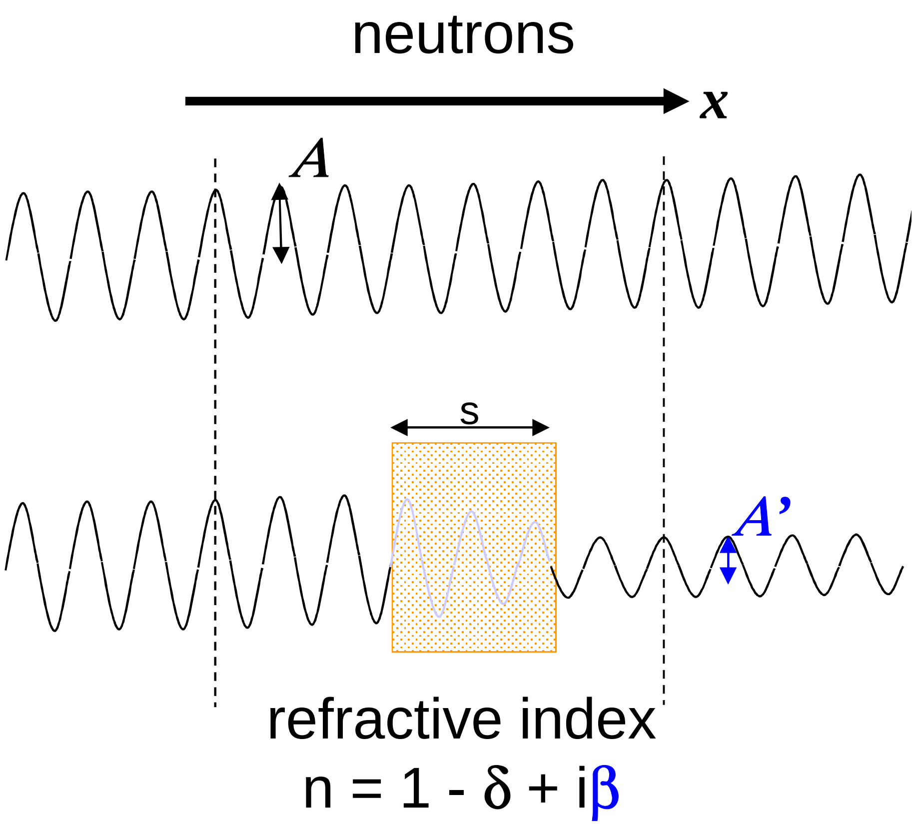

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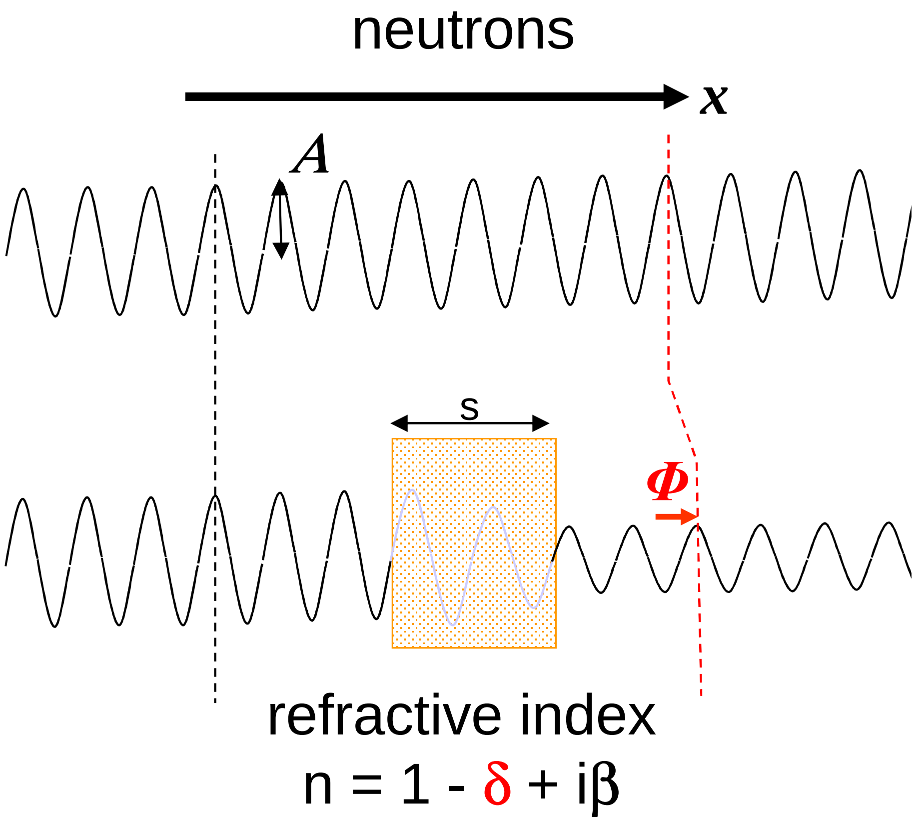

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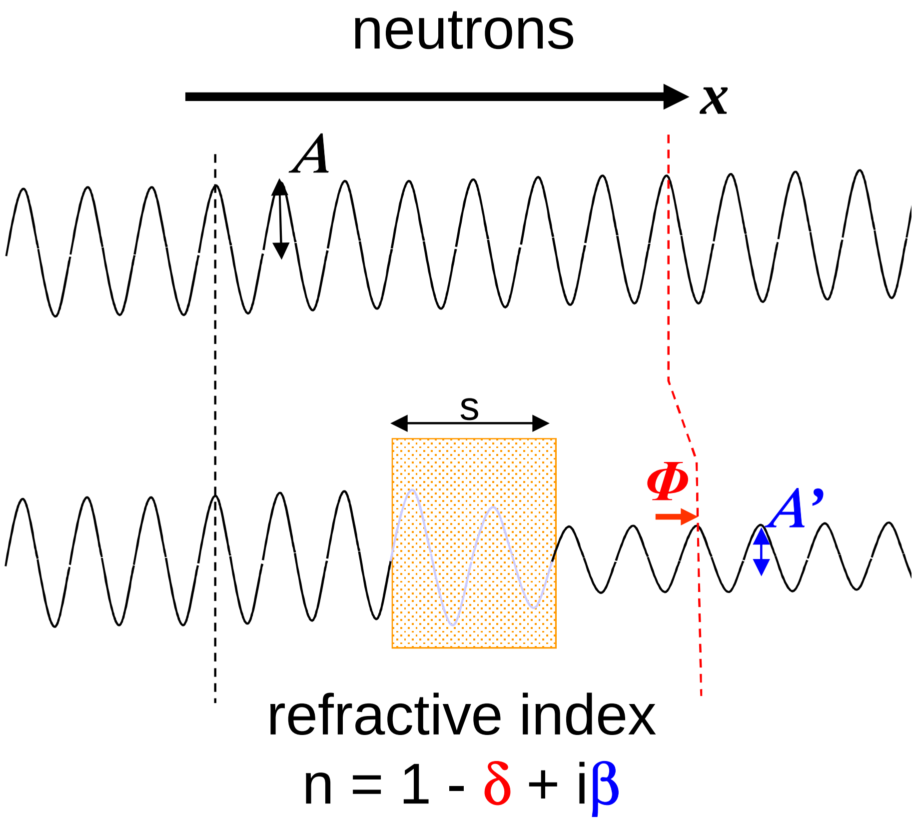
Phase contrast imaging:



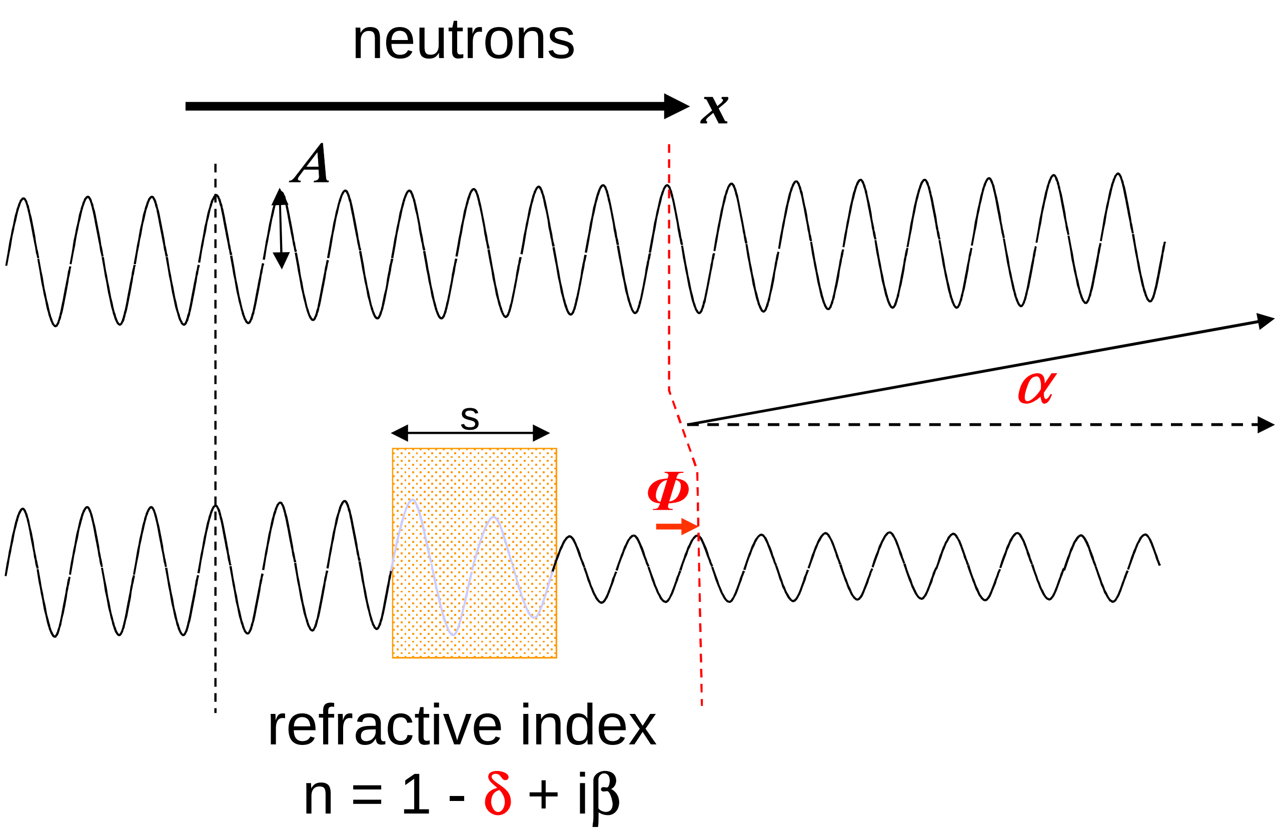
$$\Psi_{before} = A \cdot e^{-i(\omega t - kx)}$$

$$\Psi_{after} = \underbrace{e^{-i(2\pi\delta/\lambda)s}}_{\Phi} \cdot \underbrace{e^{-(2\pi\beta/\lambda)s}}_{A'/A} \cdot \Psi_{before}$$

Phase image

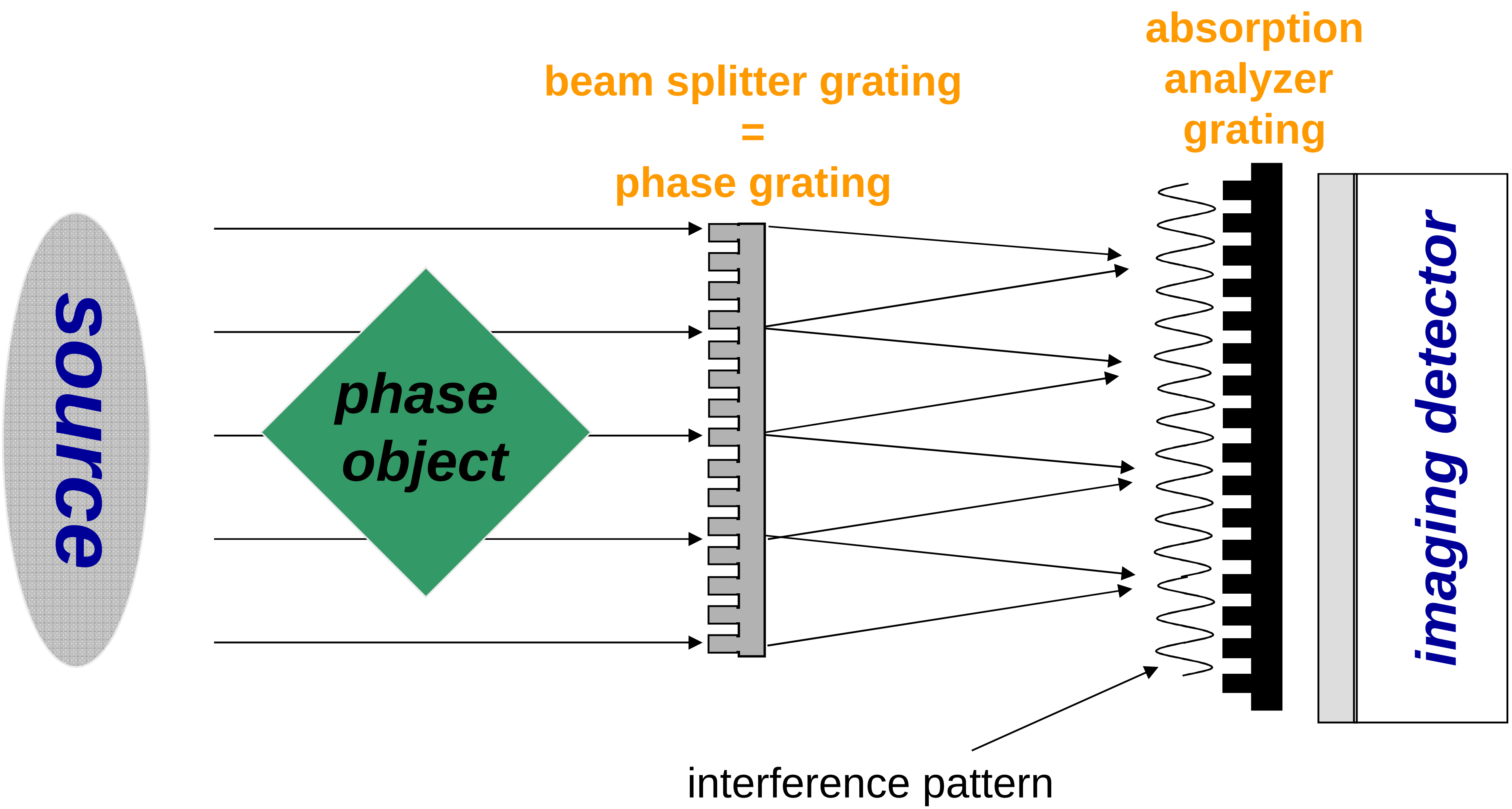
Attenuation image

Phase contrast imaging:

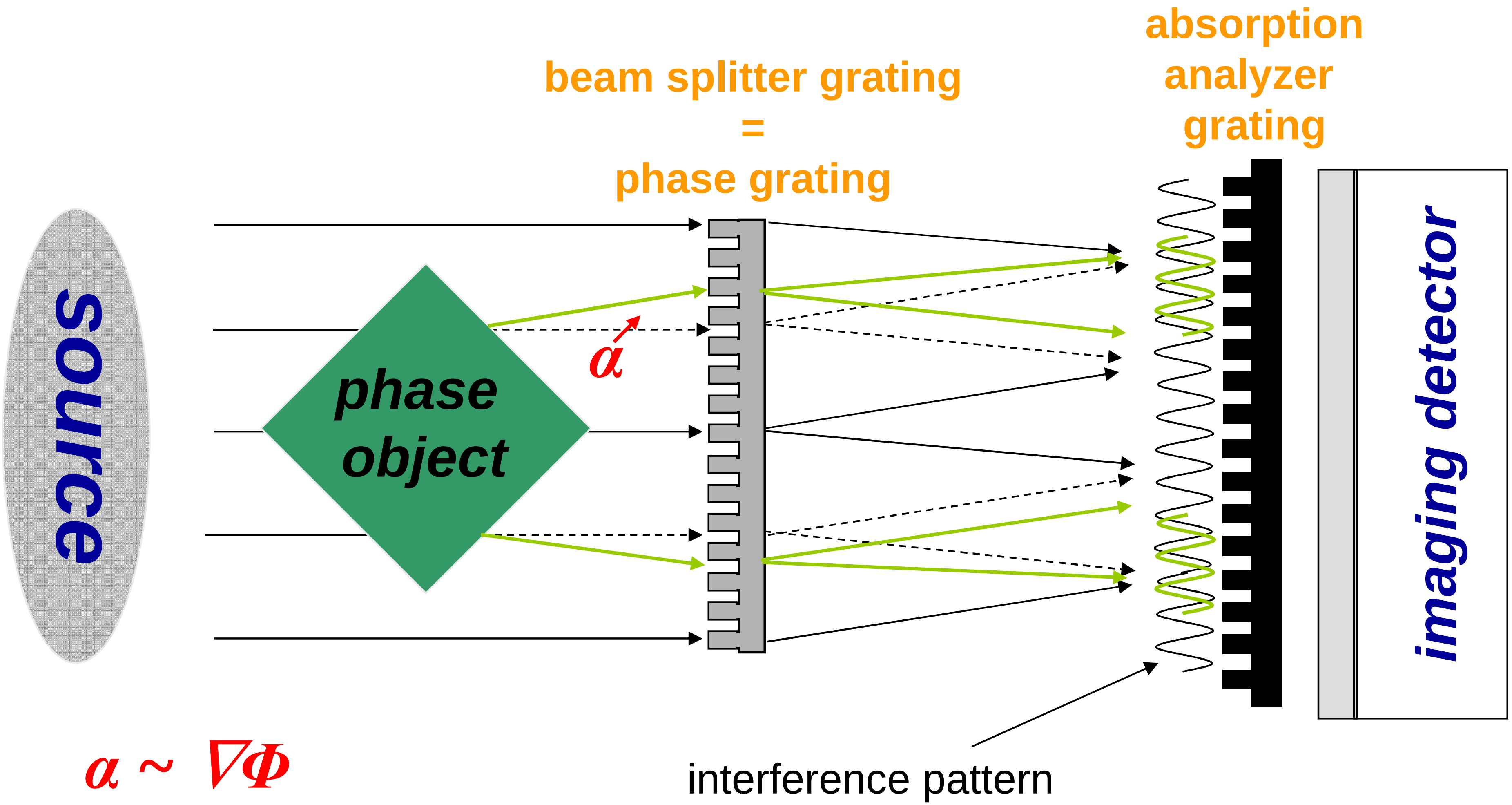


$$\nabla\Phi \sim \alpha$$

Phase contrast imaging:

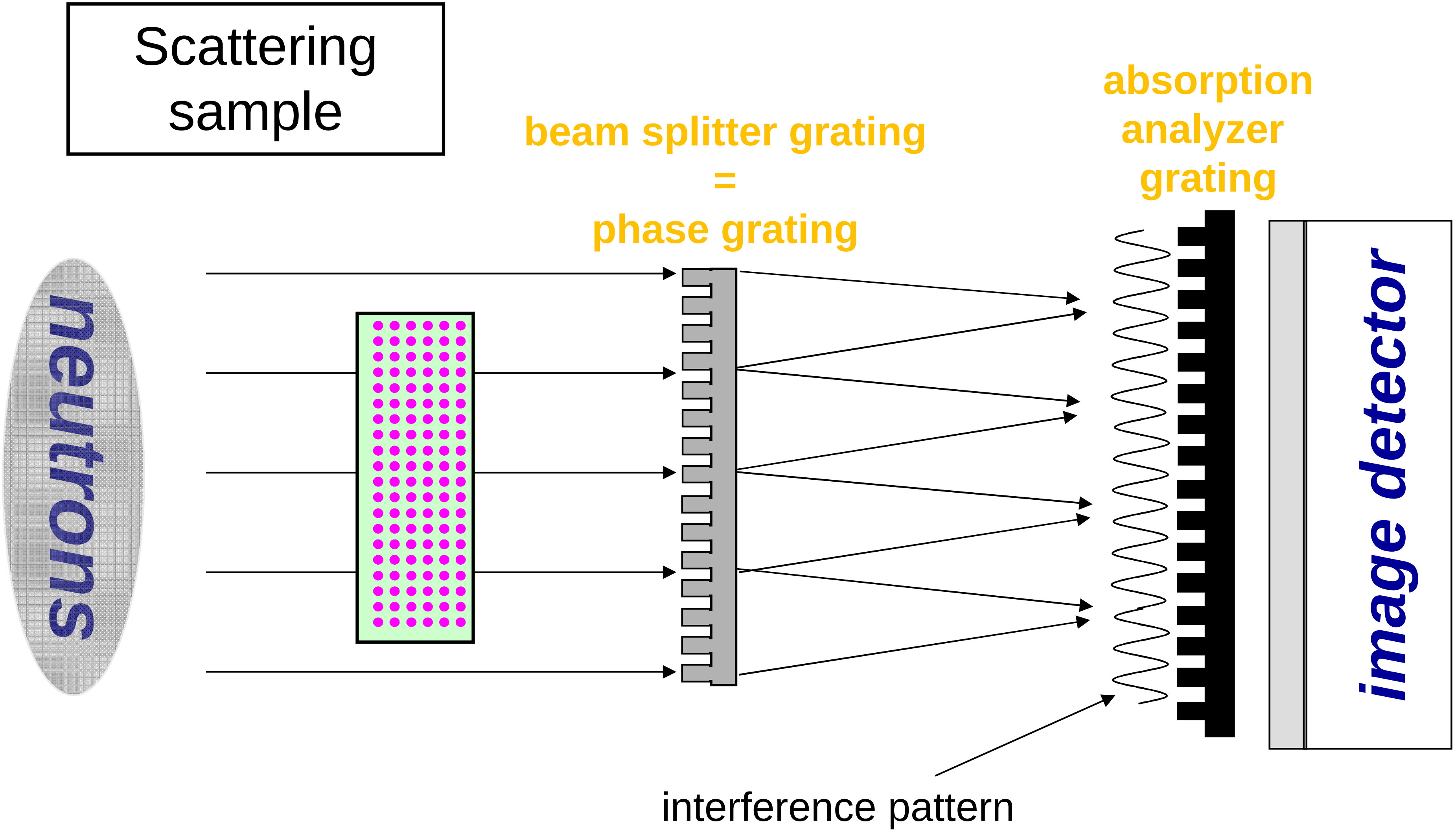


Phase contrast imaging:



$\alpha \sim \nabla\Phi$

Dark-field imaging:



Dark-field imaging:

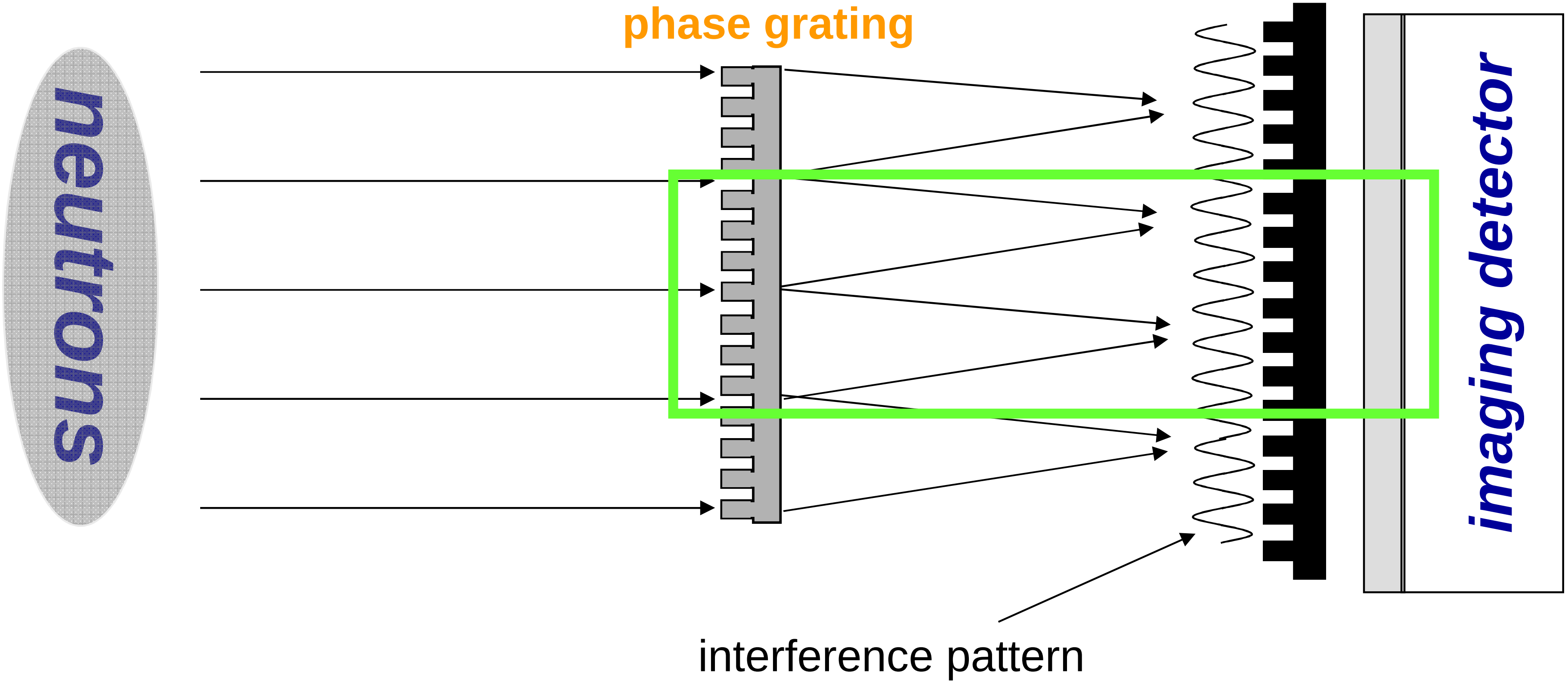
Scattering

neutrons

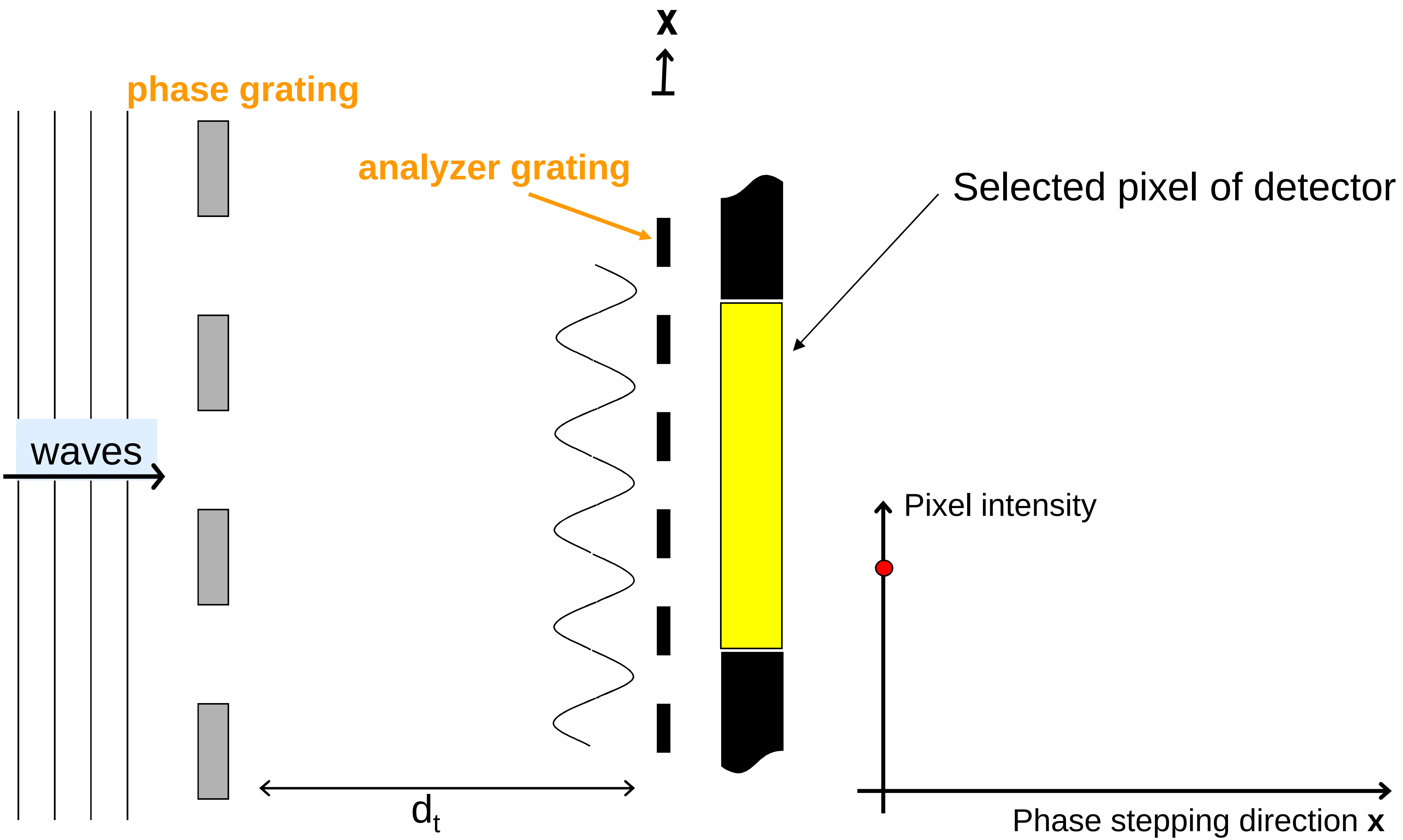
How to analyse these changes in the interference pattern?

Phase contrast and dark-field signals

Open beam image



Phase contrast and dark-field signals



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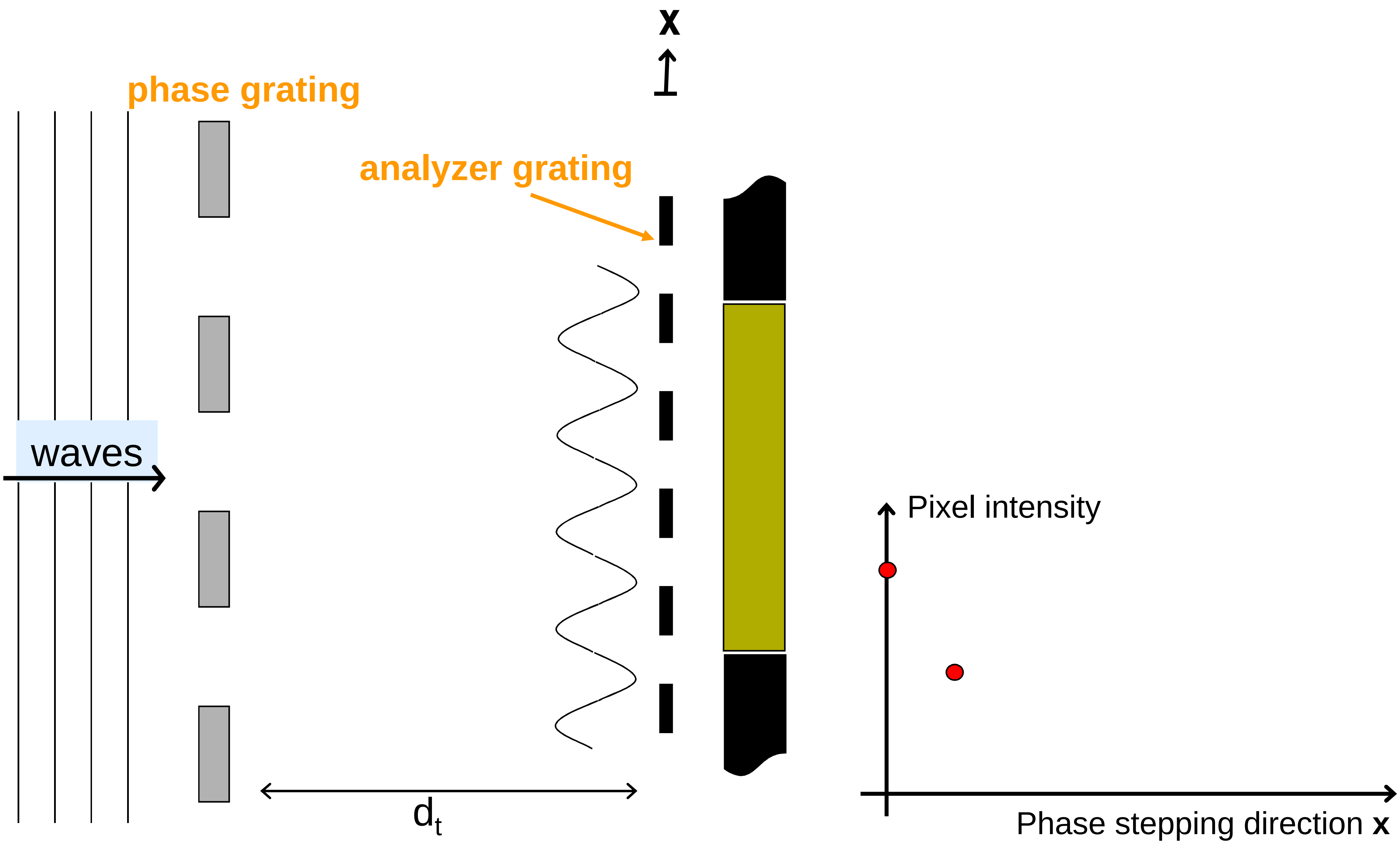

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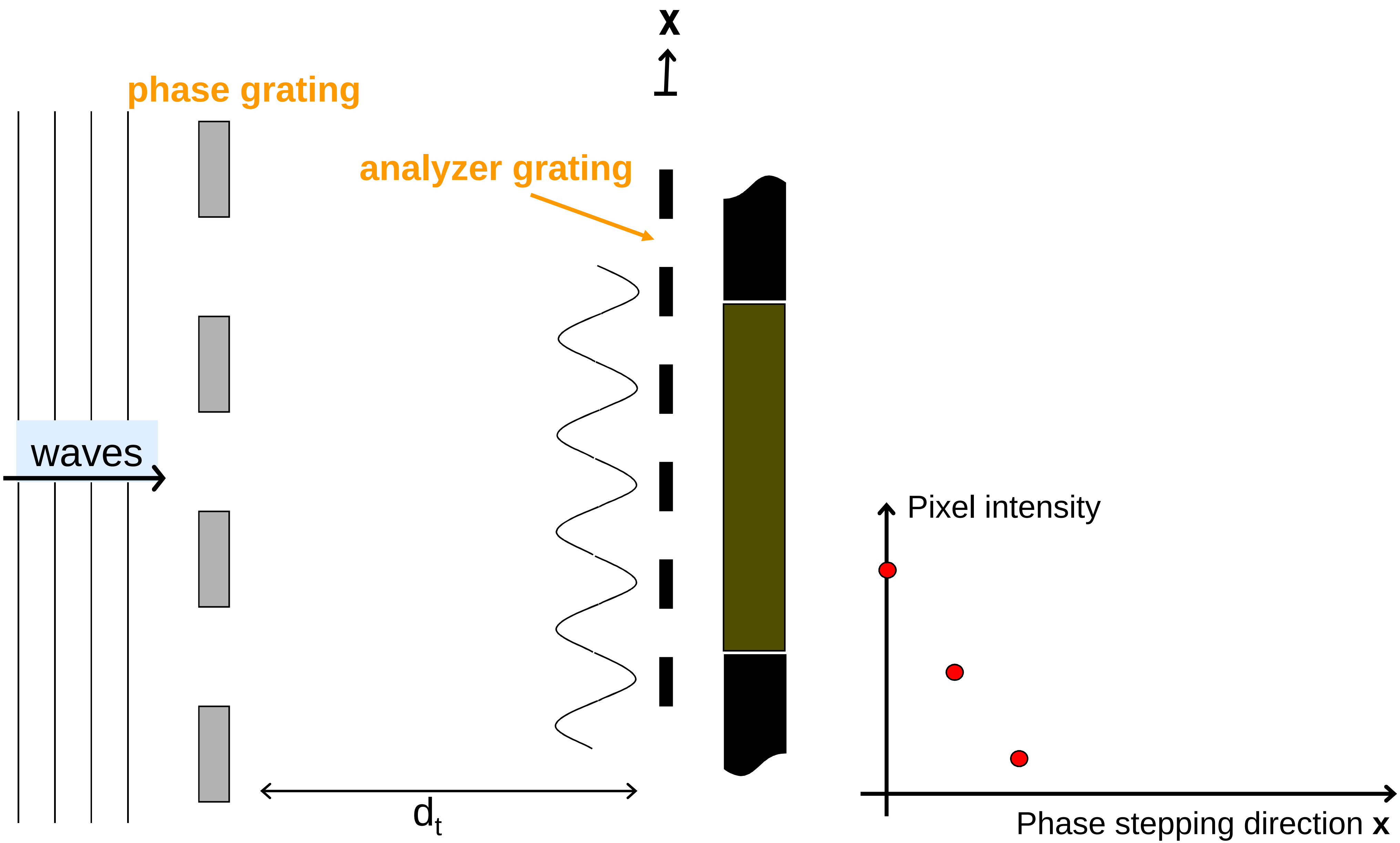

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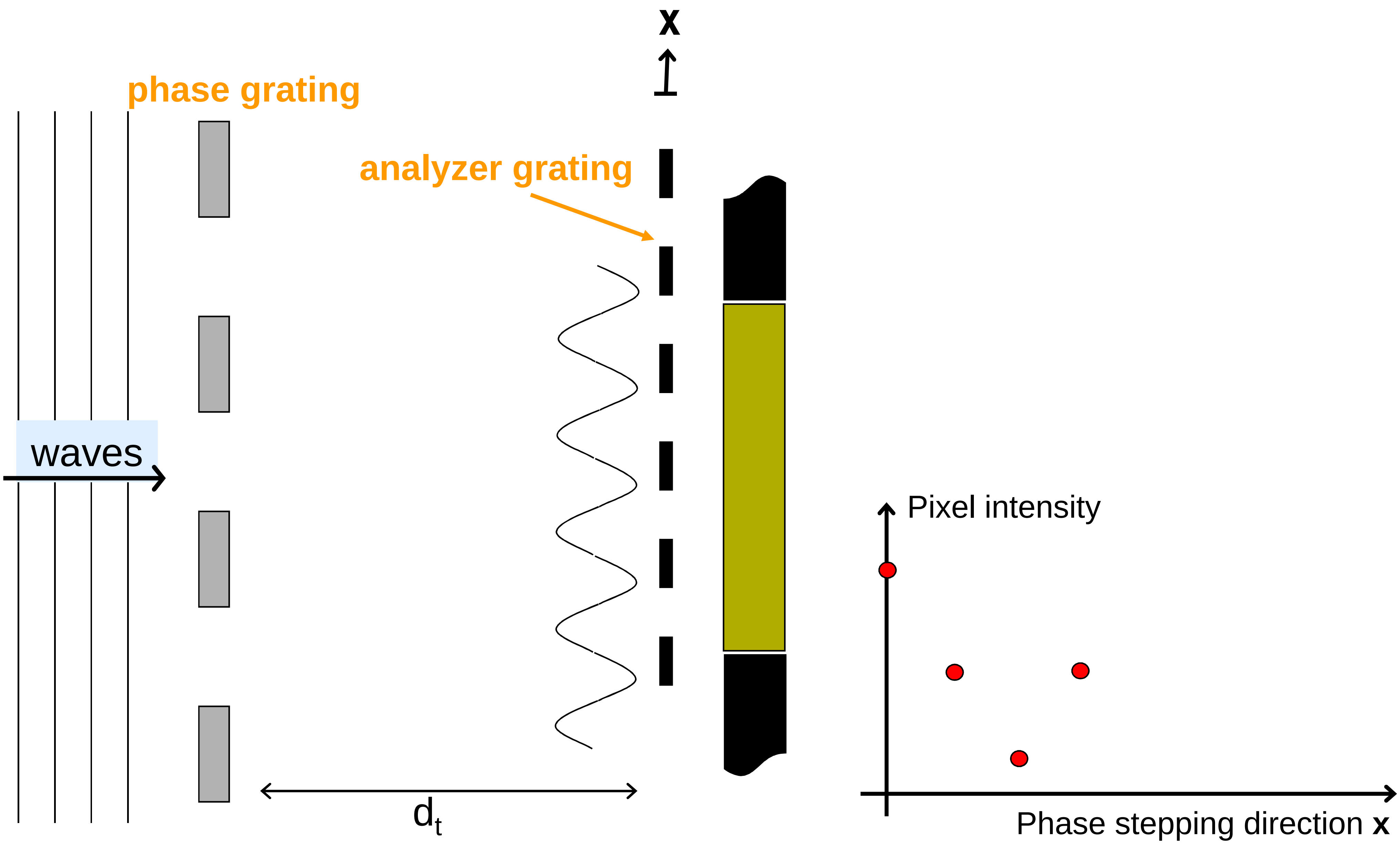

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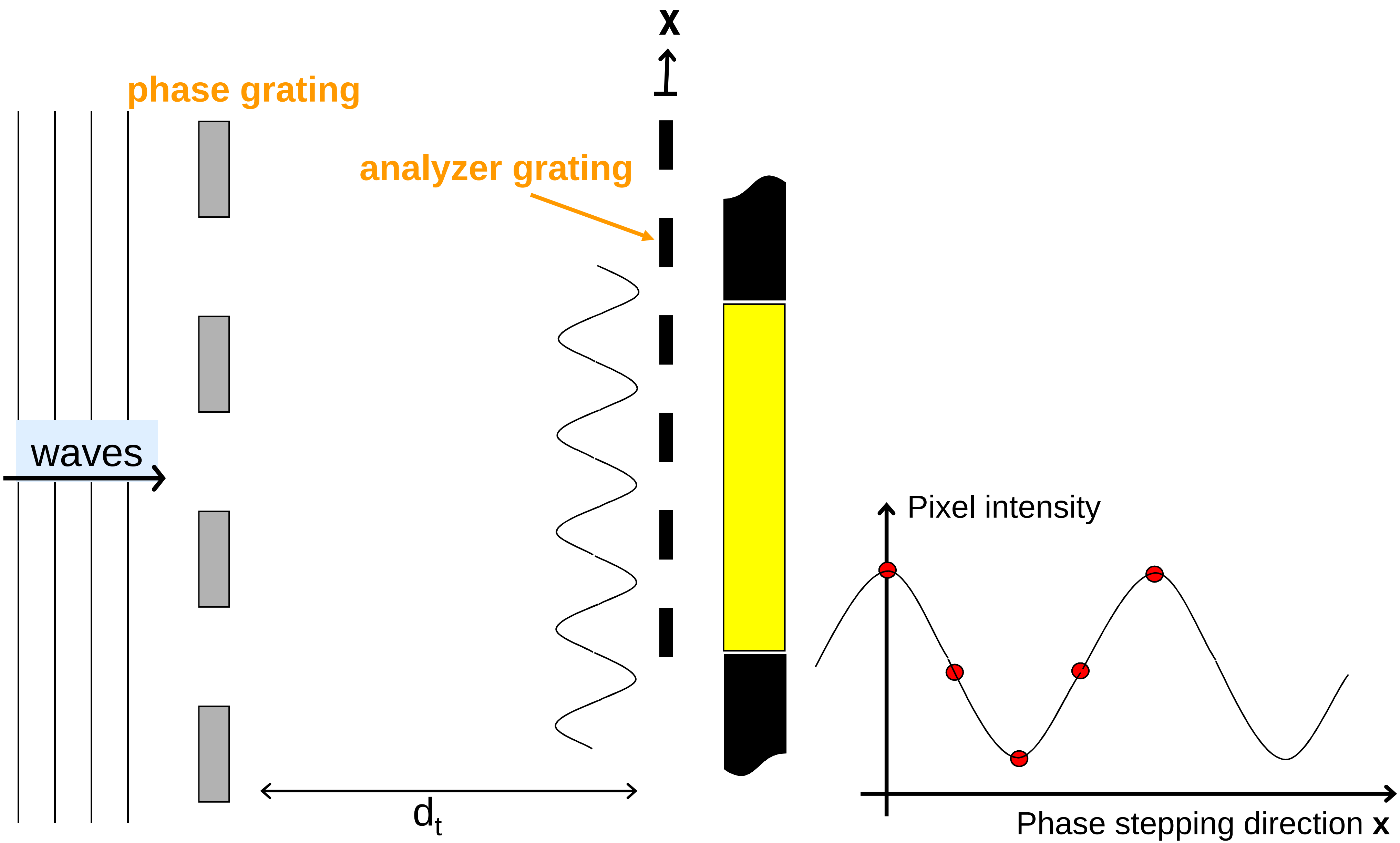

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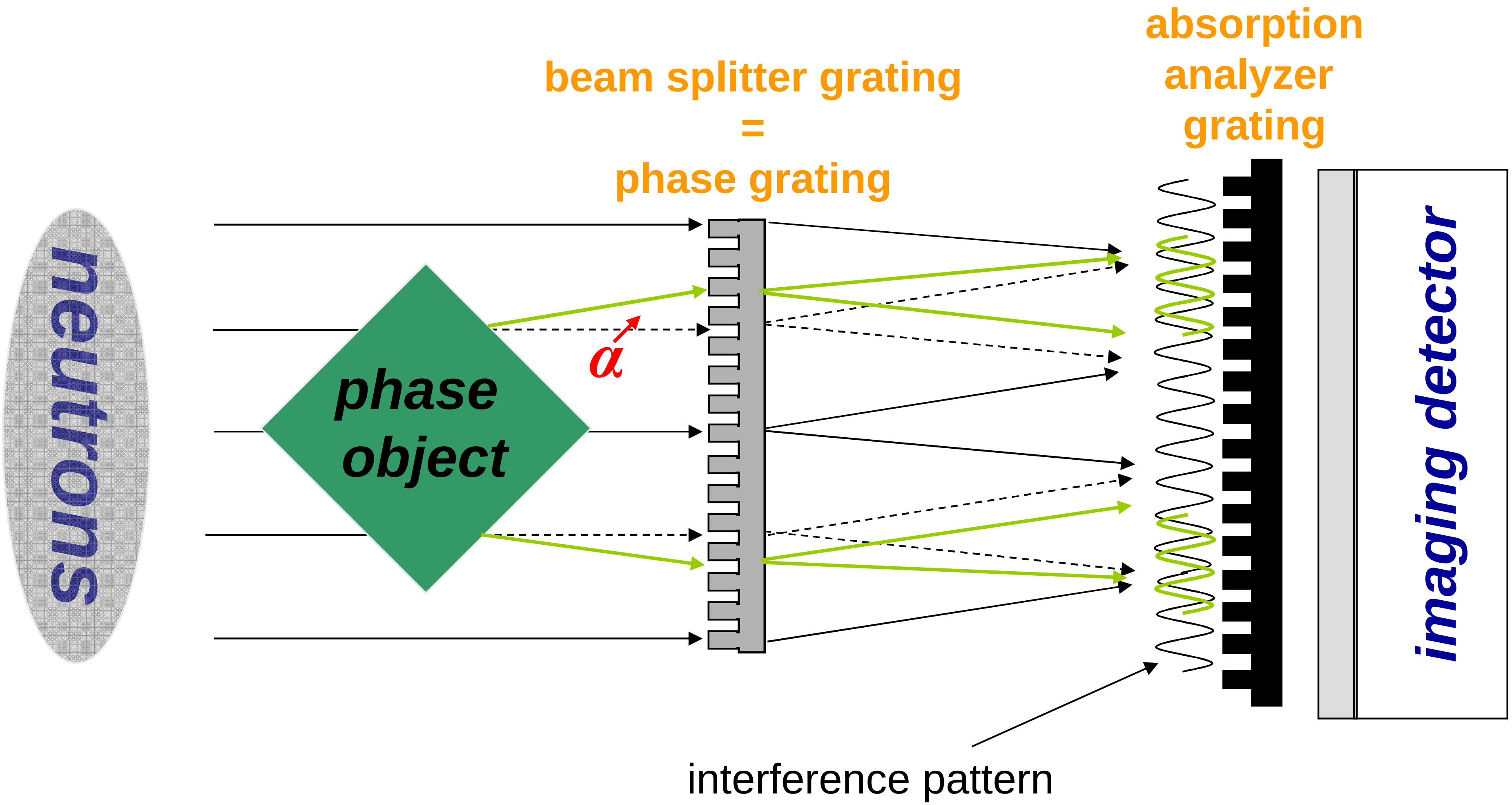

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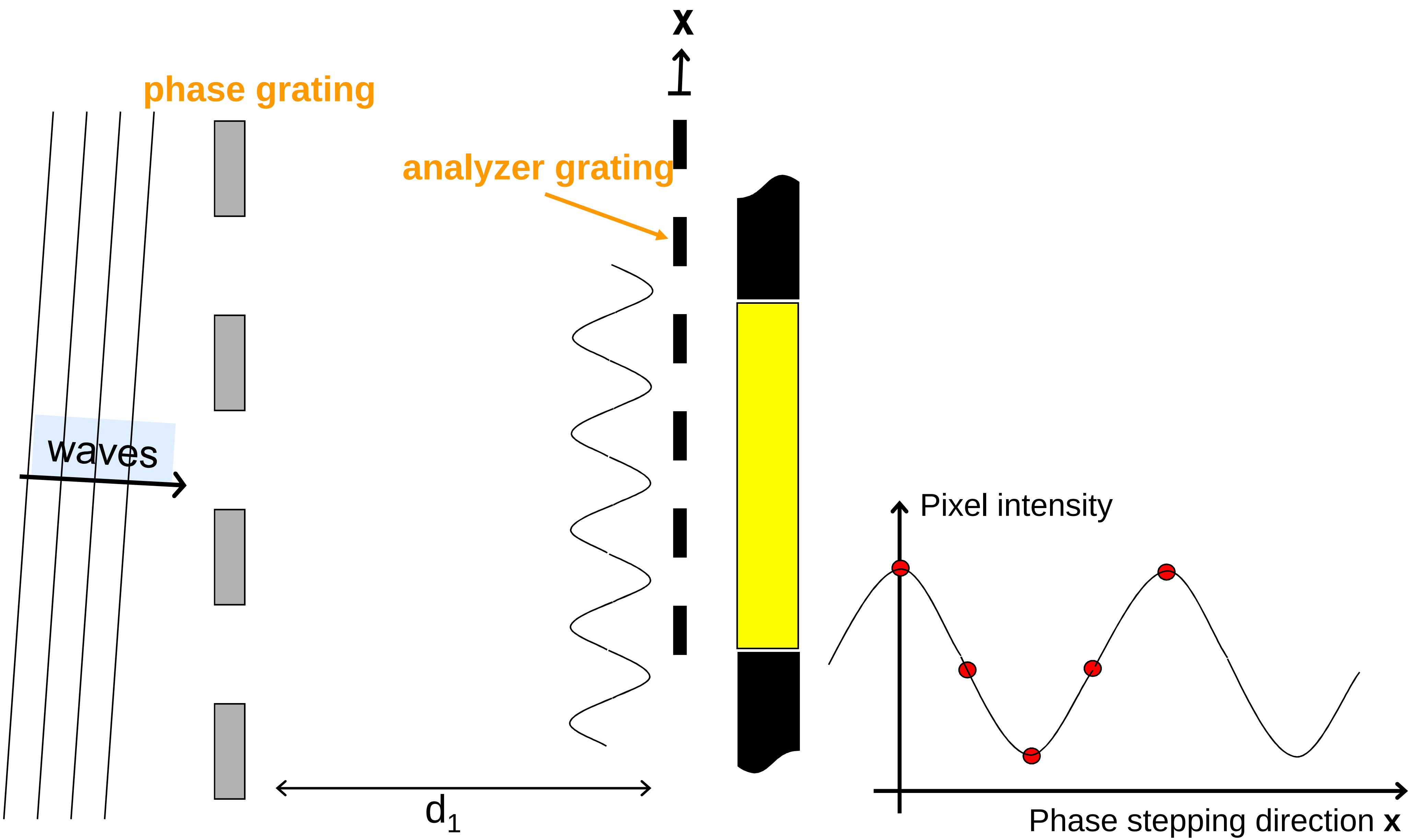
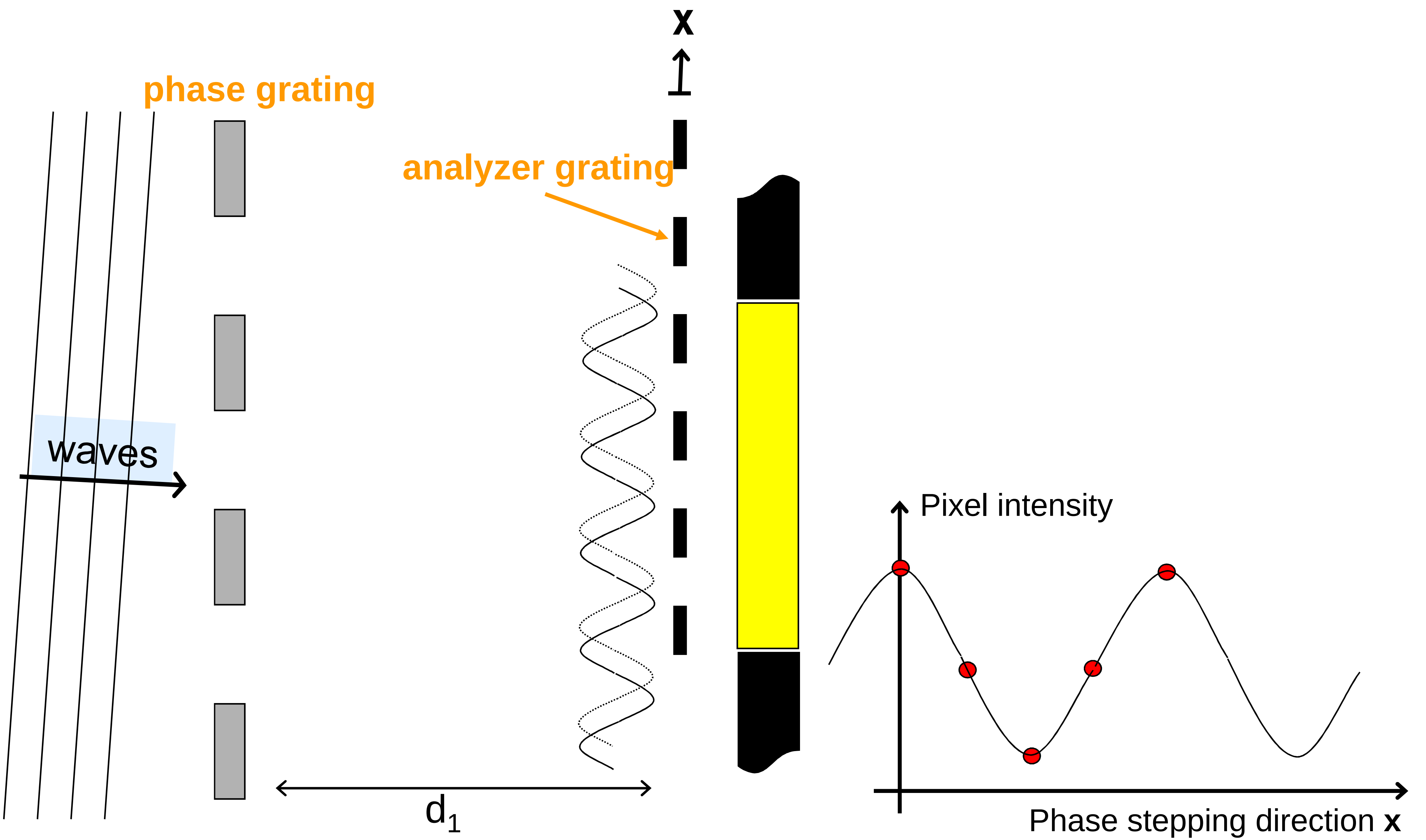


Phase contrast and dark-field signals



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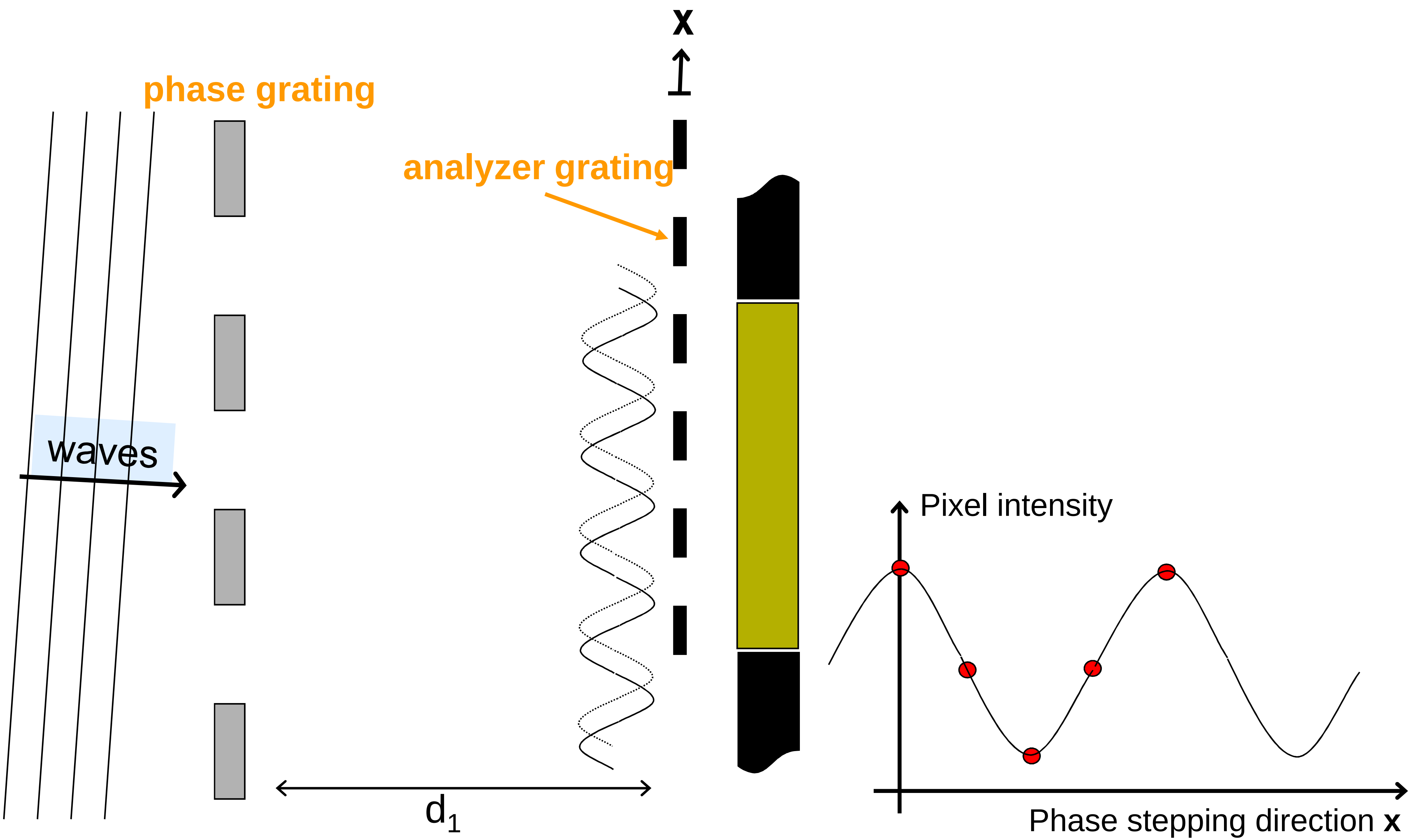

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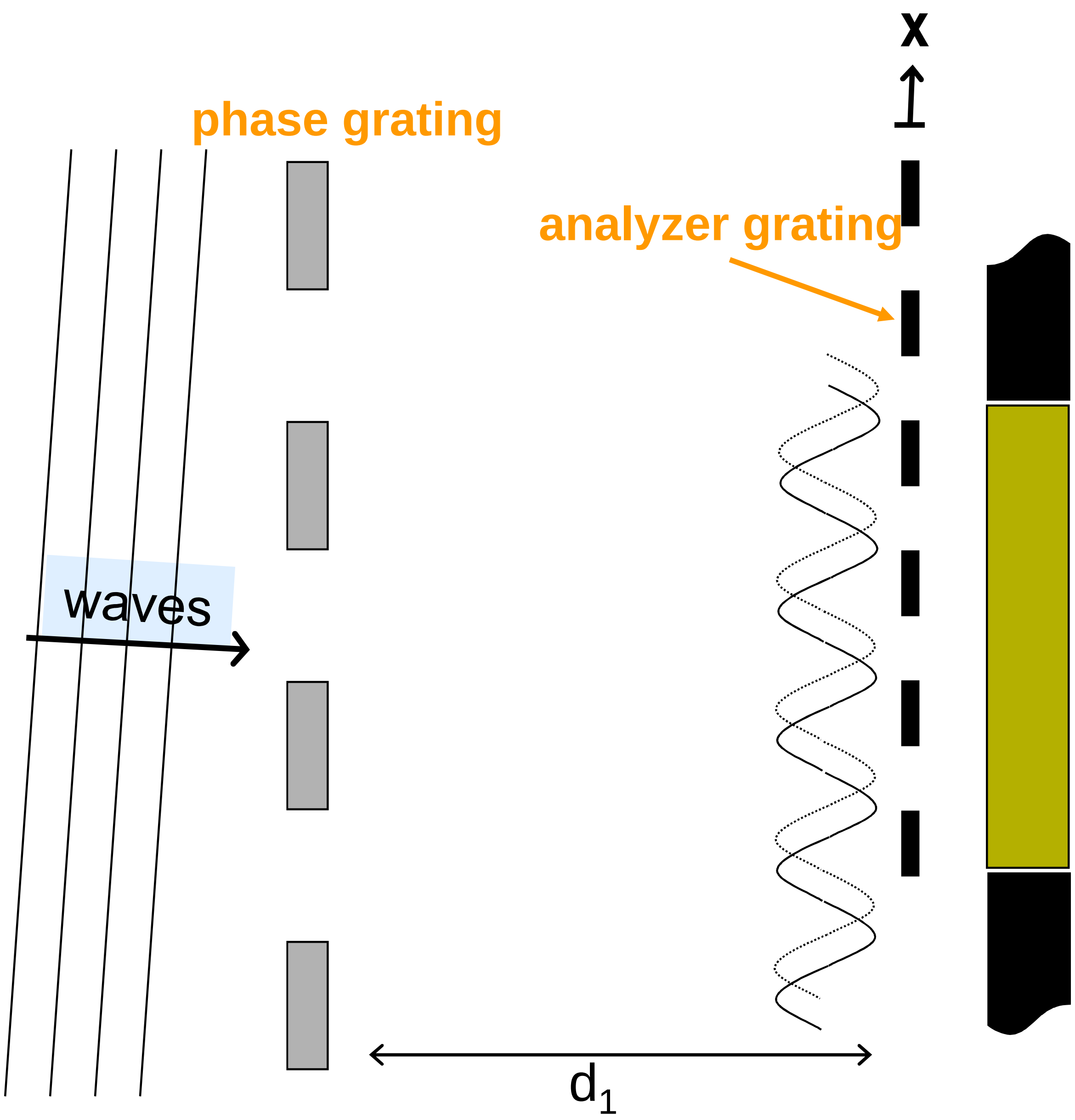
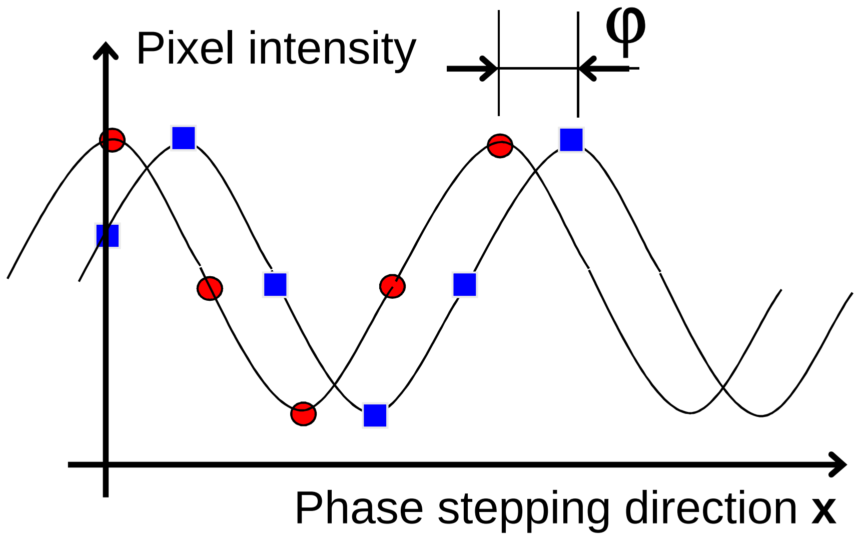
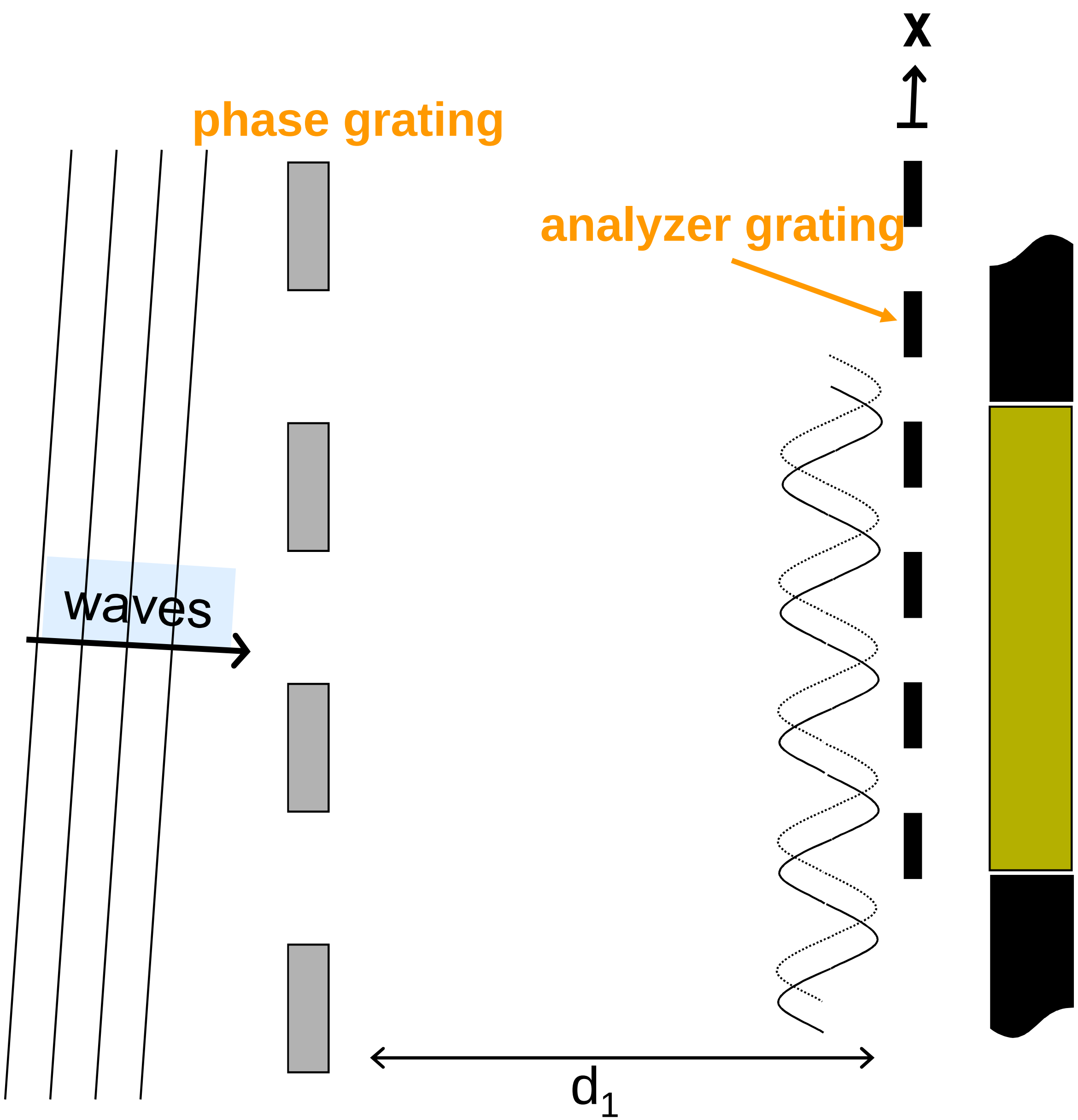


$$\frac{\partial \Phi}{\partial x} = \frac{p_2}{\lambda \cdot d_1} \cdot \varphi$$

differential phase contrast



Phase contrast and dark-field signals



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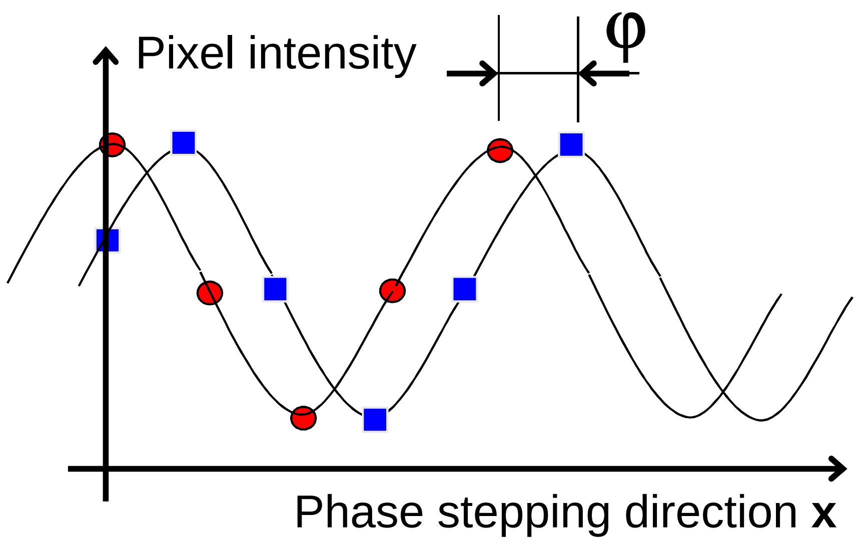
differential phase contrast



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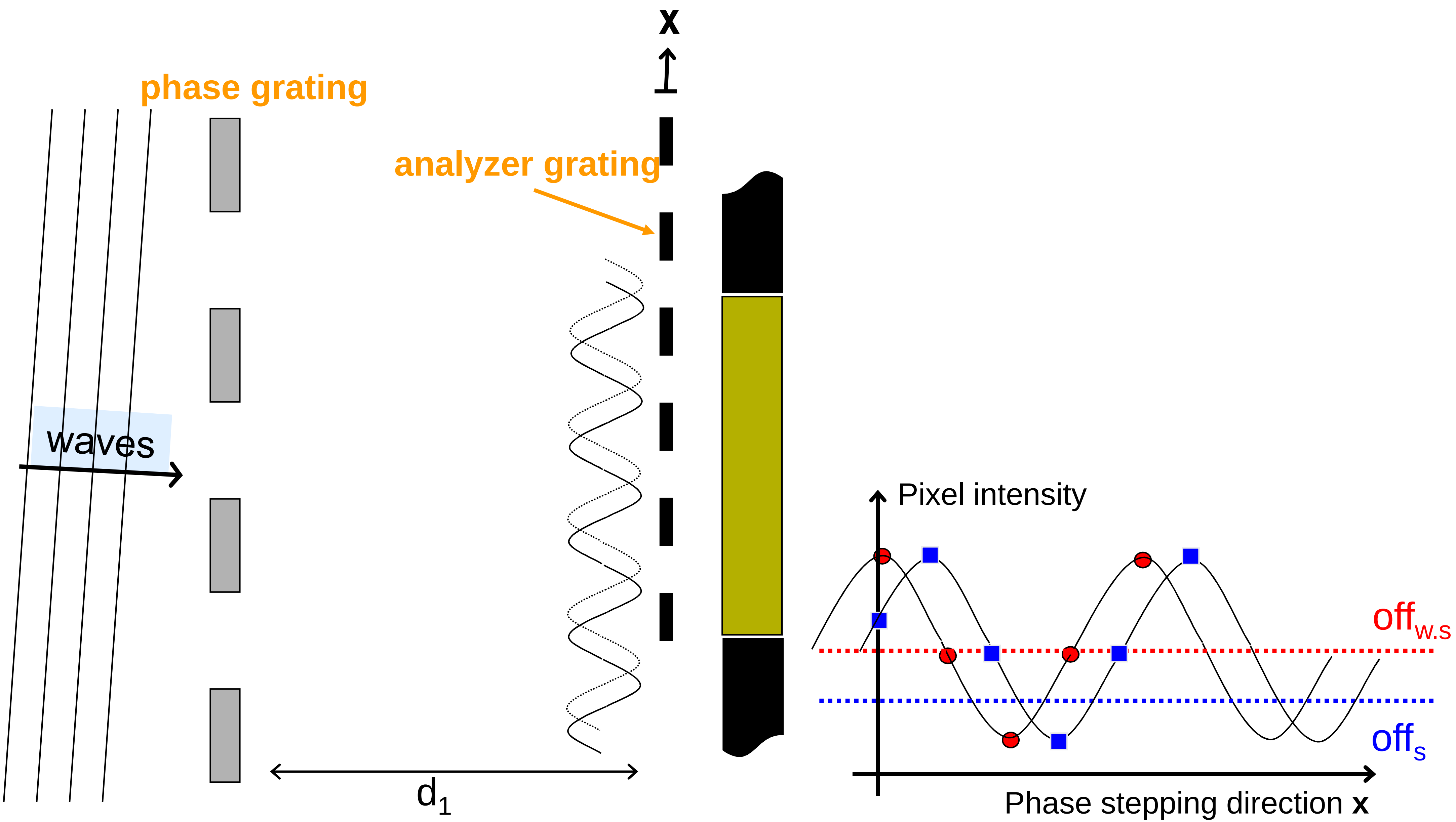

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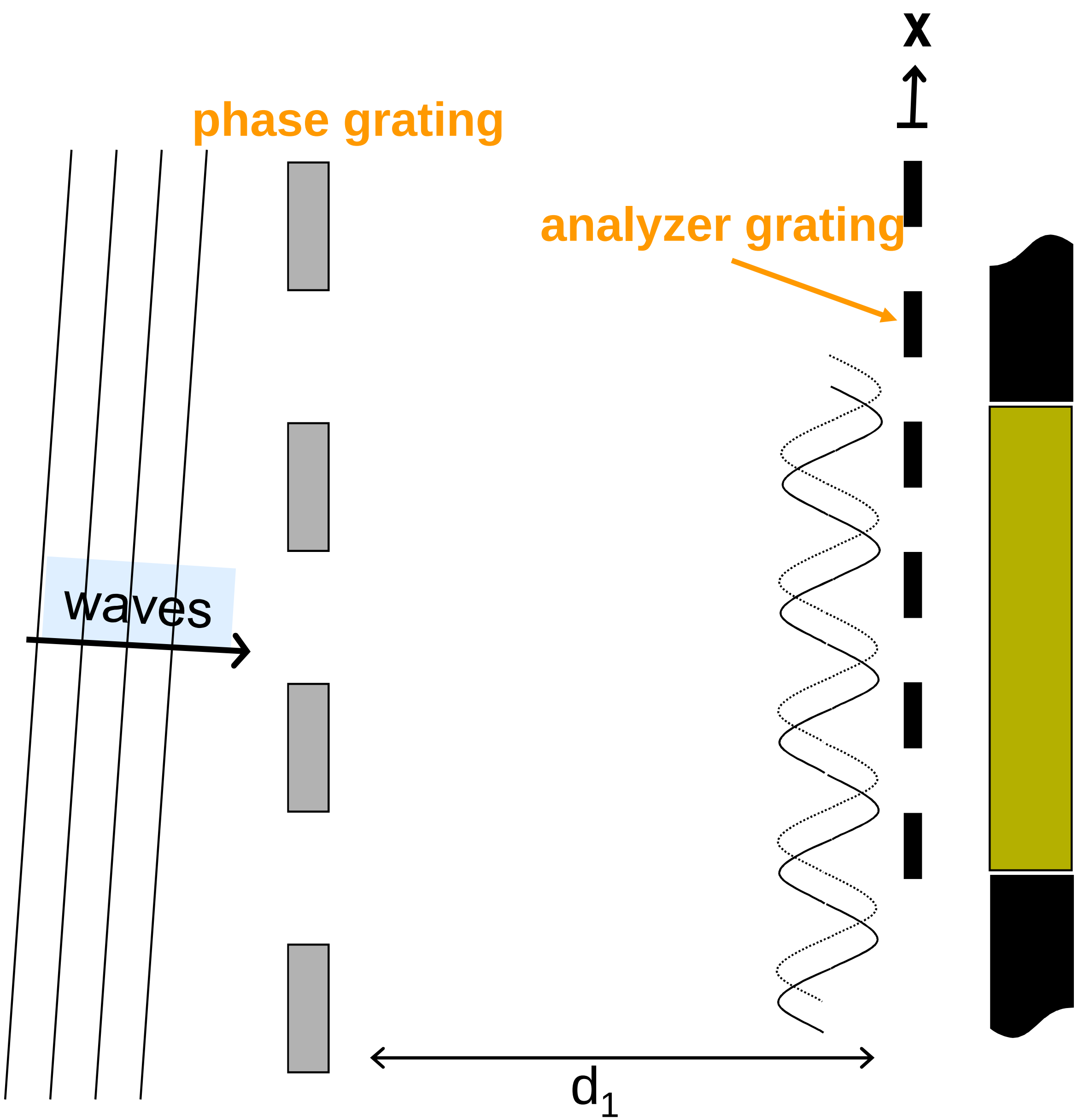
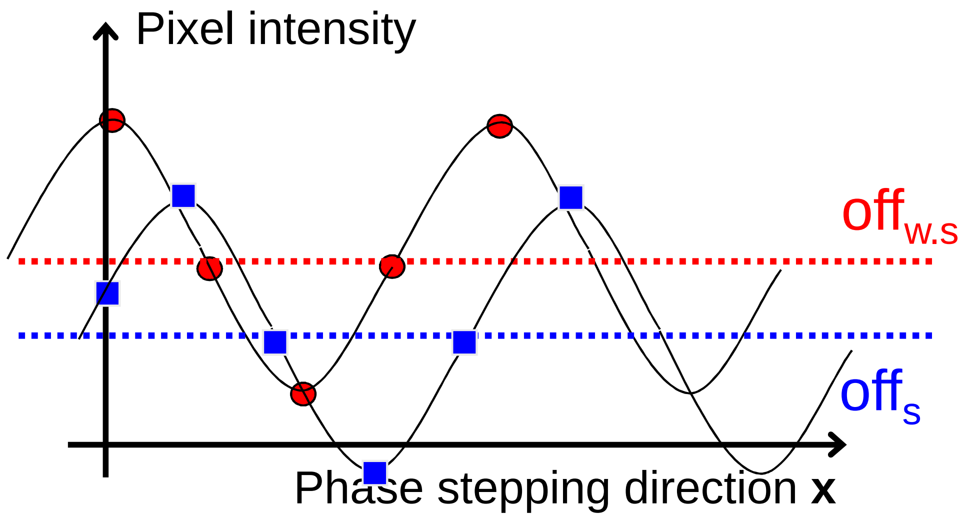
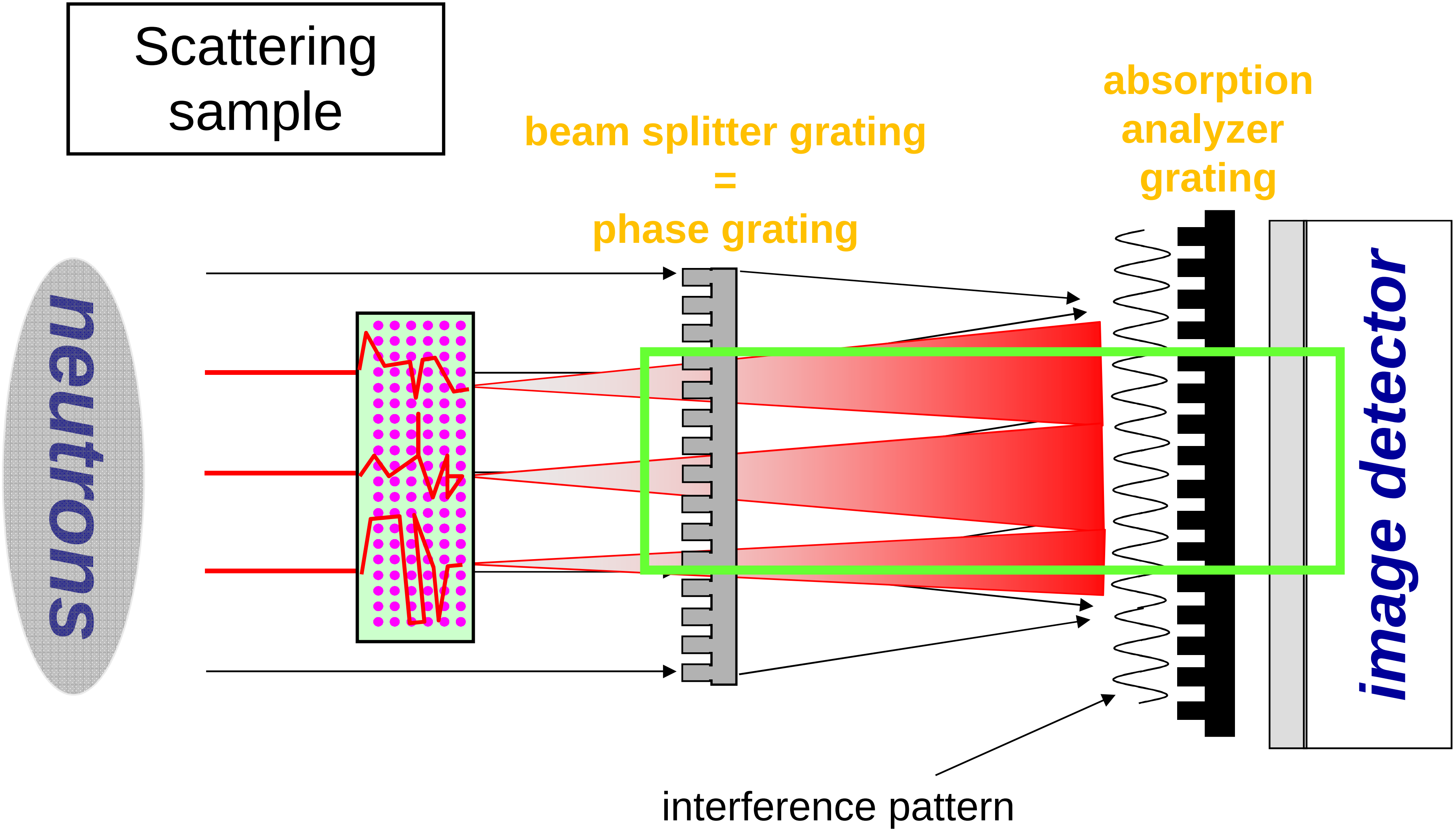


$$TI = \frac{off_s}{off_{w.s}}$$

attenuation contrast



Phase contrast and dark-field signals



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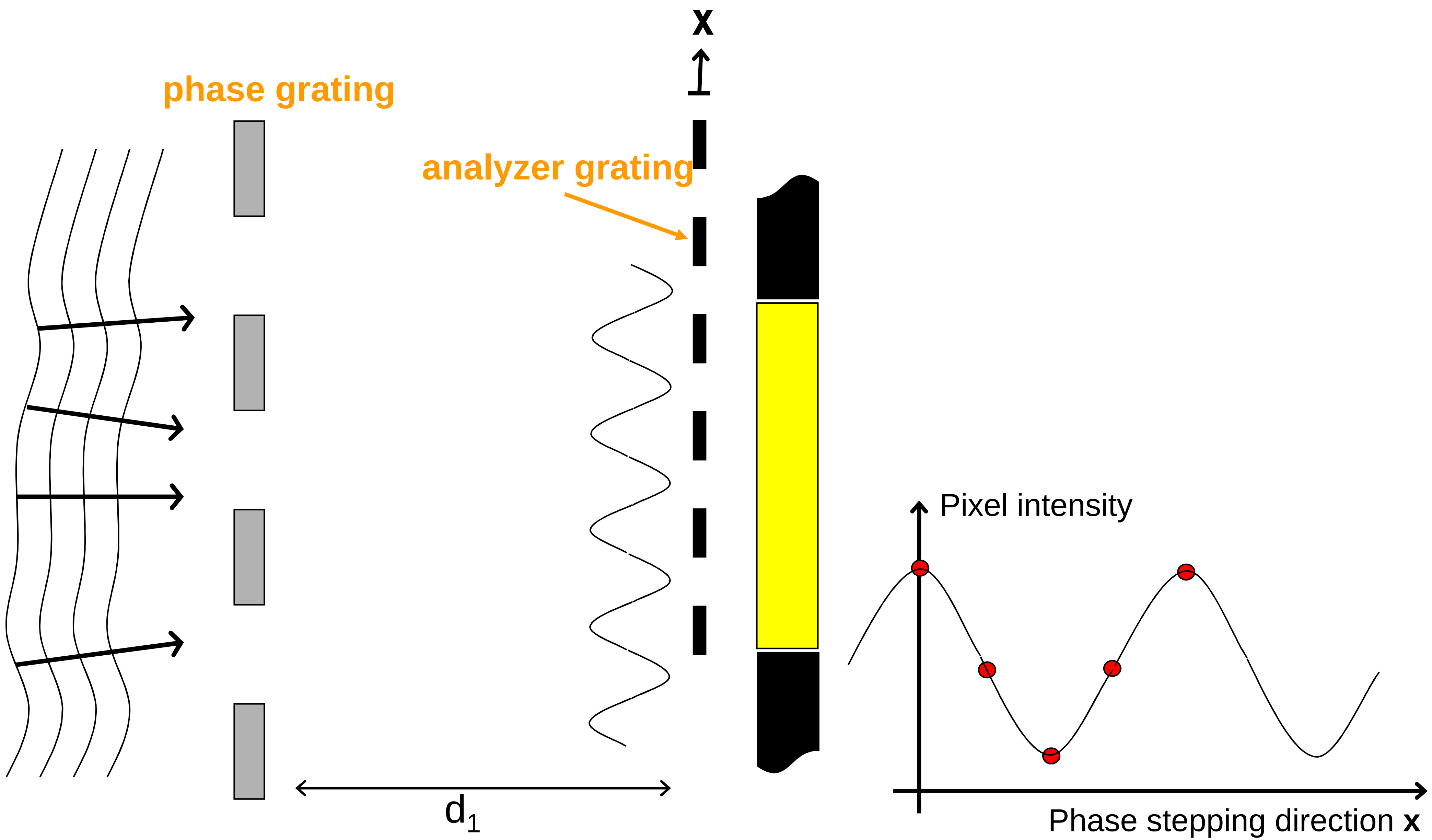

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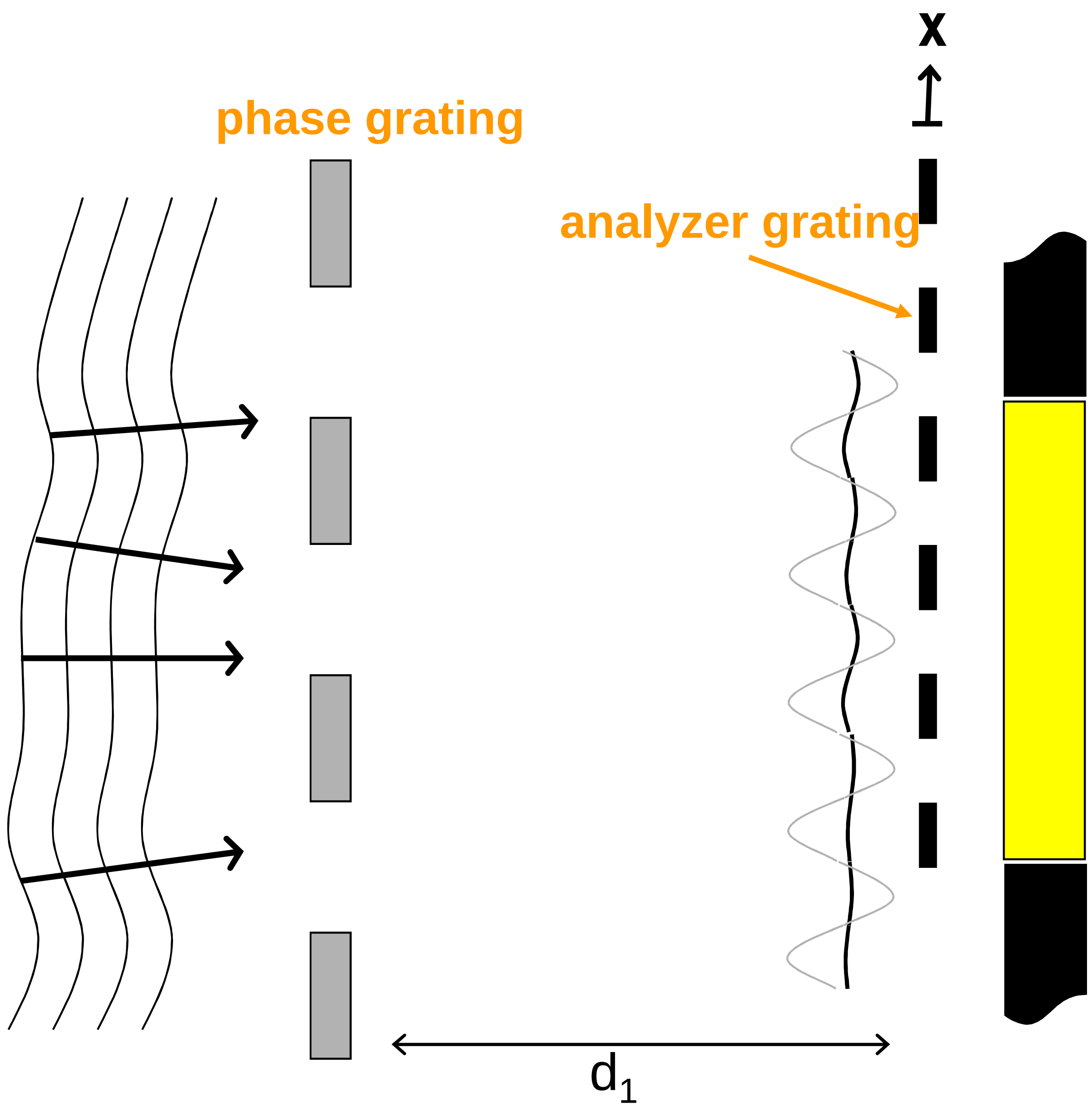
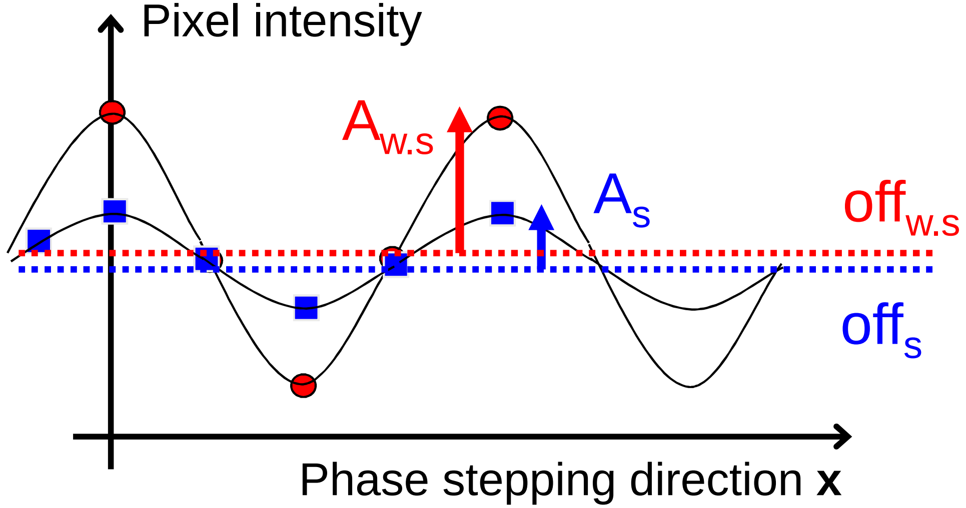


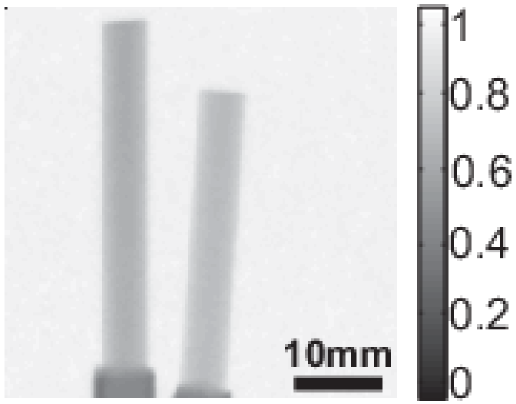
$$DFI = \frac{\frac{A_s}{off_s}}{\frac{A_{w.s}}{off_{w.s}}} = \frac{A_s \cdot off_{w.s}}{A_{w.s} \cdot off_s}$$

dark-field image

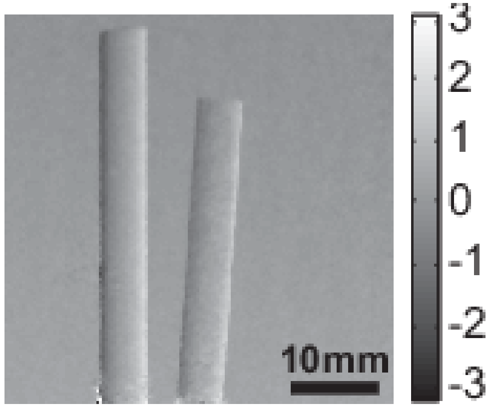


Phase contrast and dark-field signals

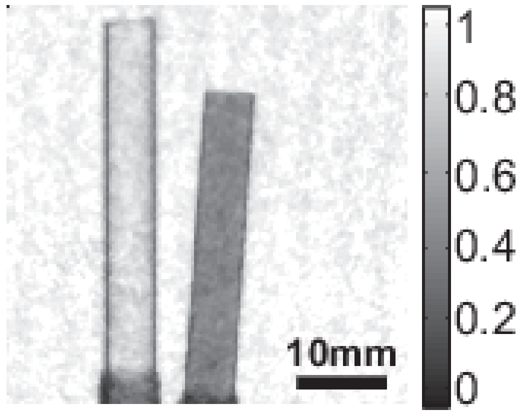
TI



DPCI



DFI



Simultaneously three different types of image / data sets

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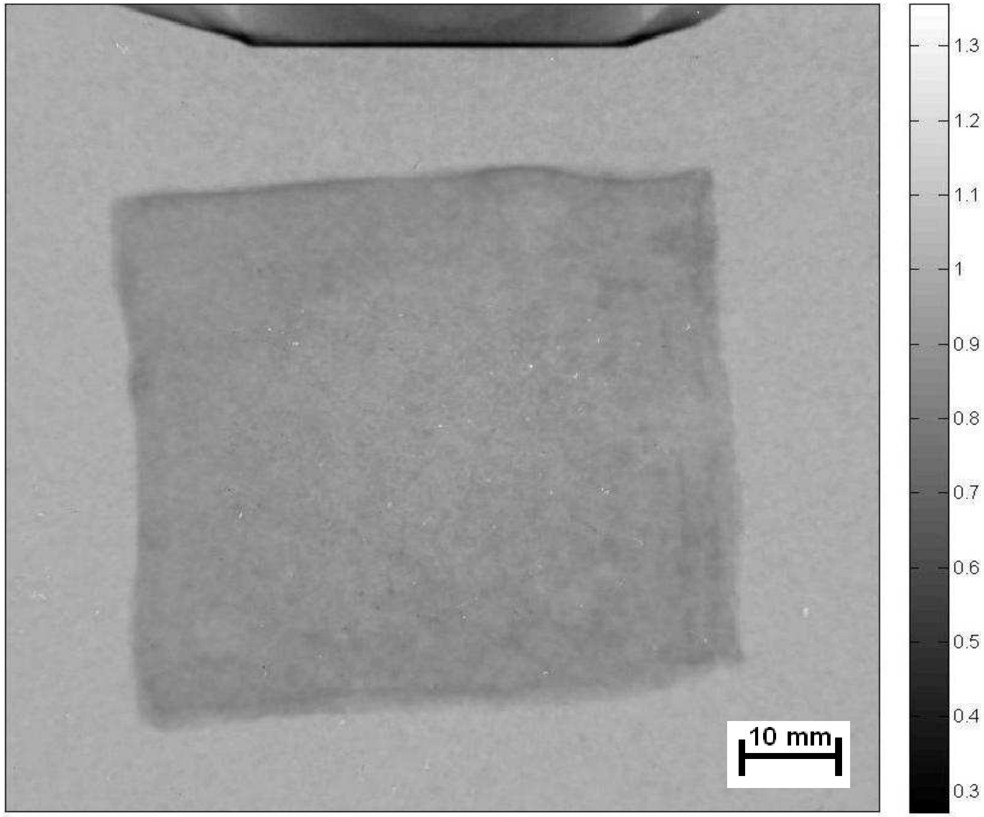
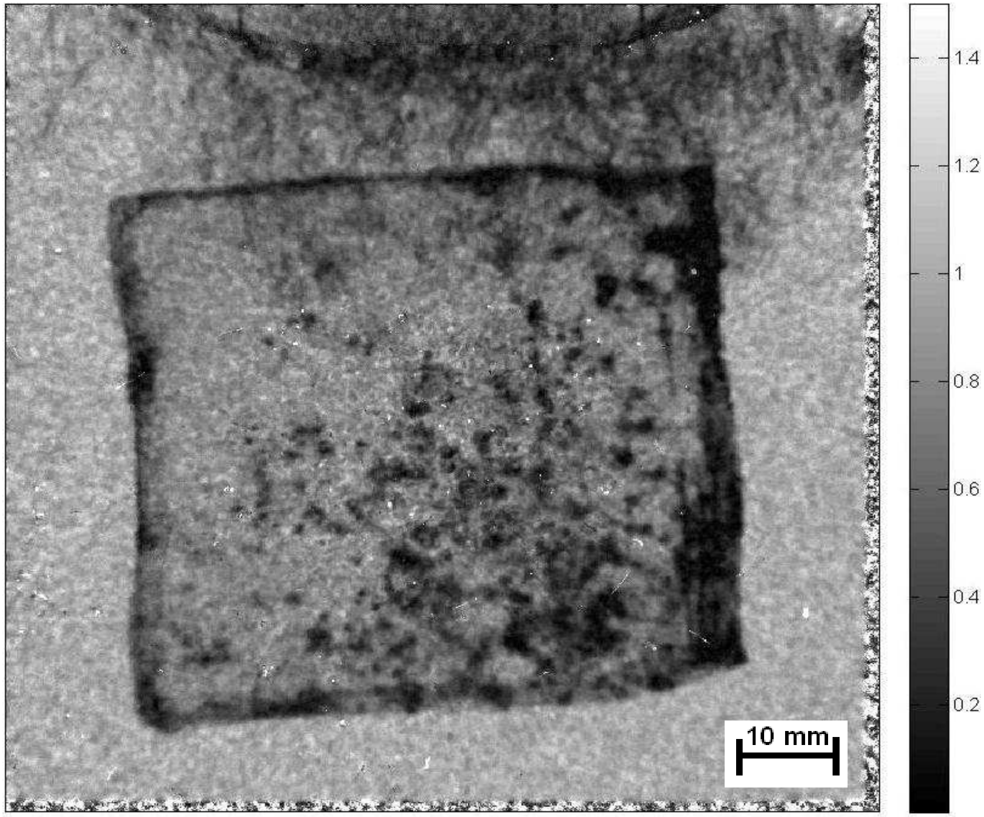
DFI applications:

Part of an ancient mold

Attenuation image



Dark-field image



DFI applications:

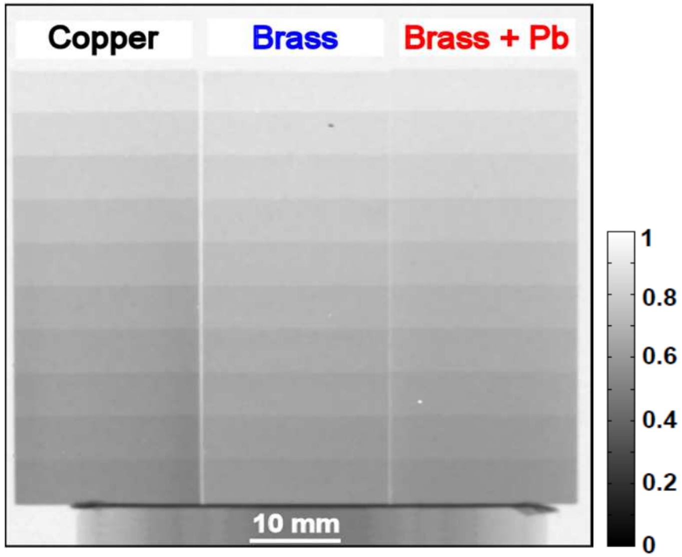
Analogy of
dark-field imaging and transmission imaging

$$\int \Omega(t)dt = -\frac{p_2^2}{2\pi^2 d^2} \ln V(t)$$

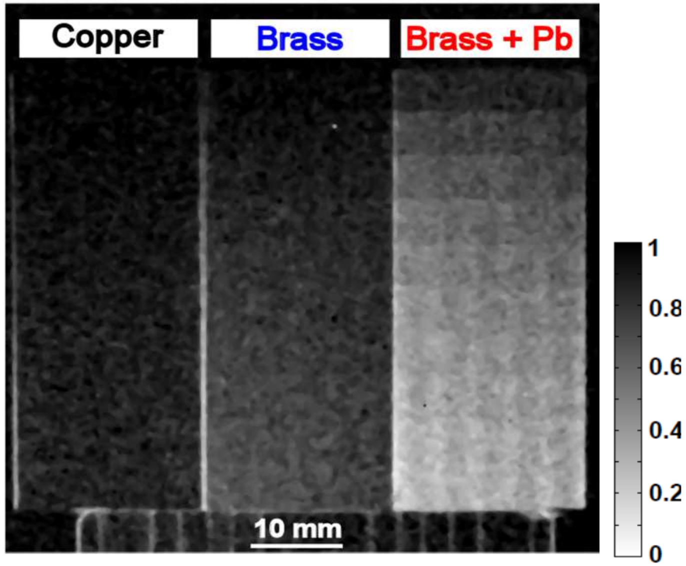
$$\int \Sigma(t)dt = -\ln T(t)$$

DFI applications:

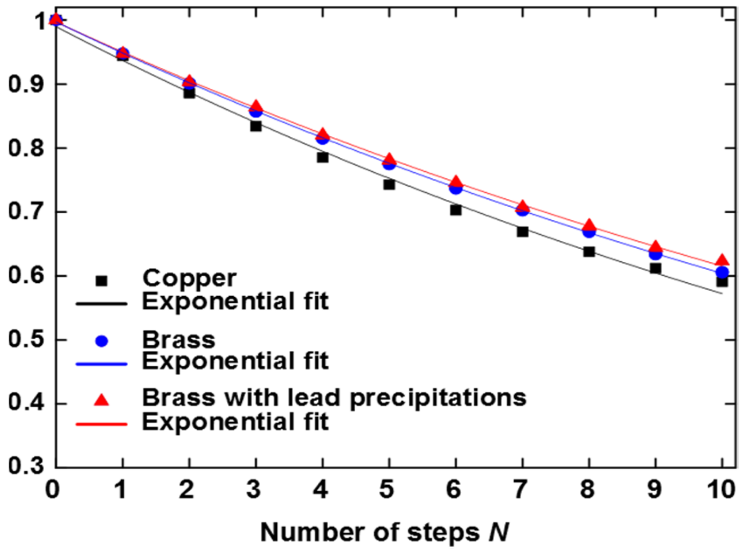
Transmission image (TI)



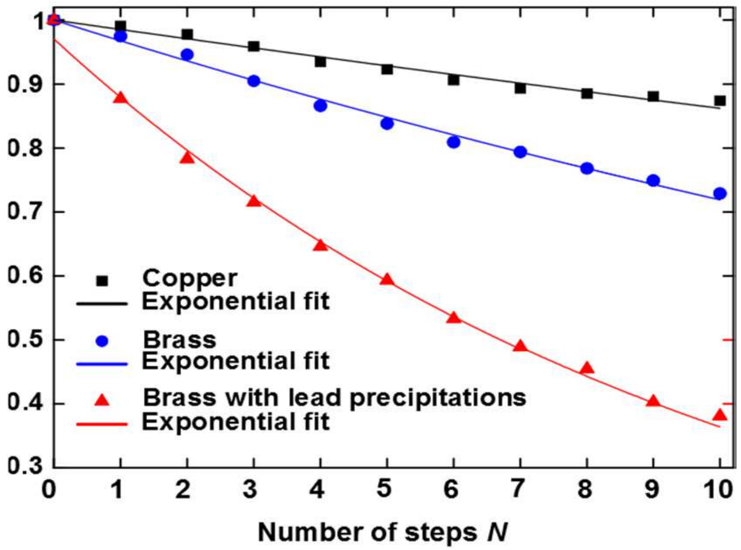
Dark-field image (DFI)



Transmission T(*N*)



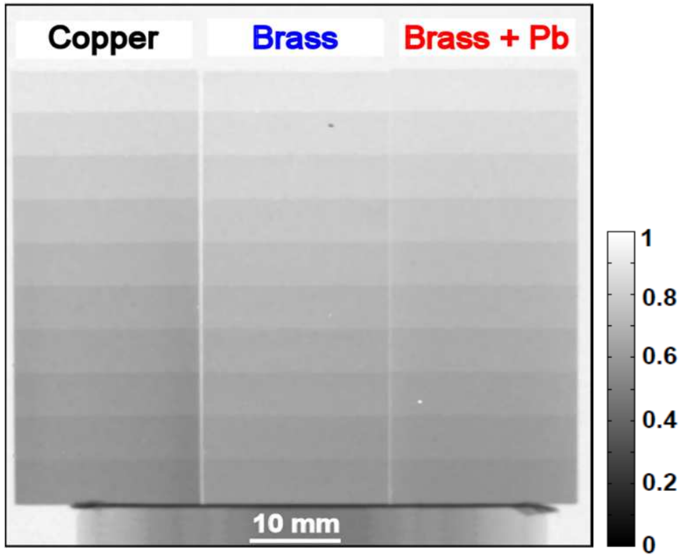
Visibility V(*N*)



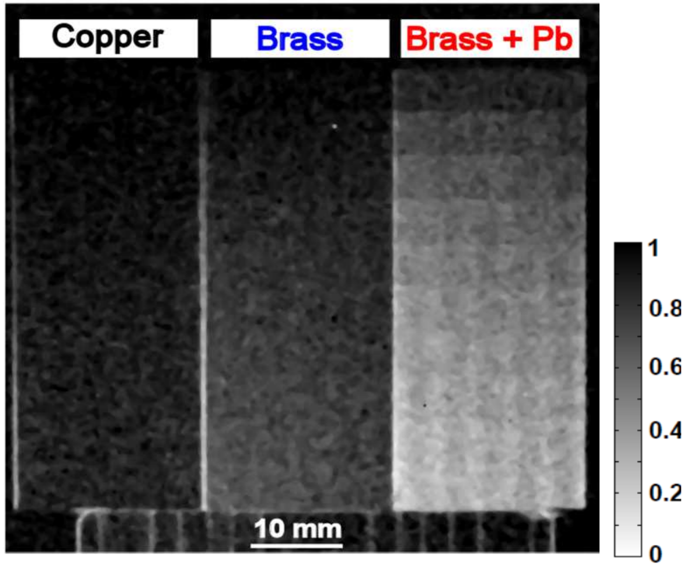
Gruenzweig, Kopecek, Betz, *et al*. PRB **88**, 125104 (2013)

DFI applications:

Transmission image (TI)



Dark-field image (DFI)



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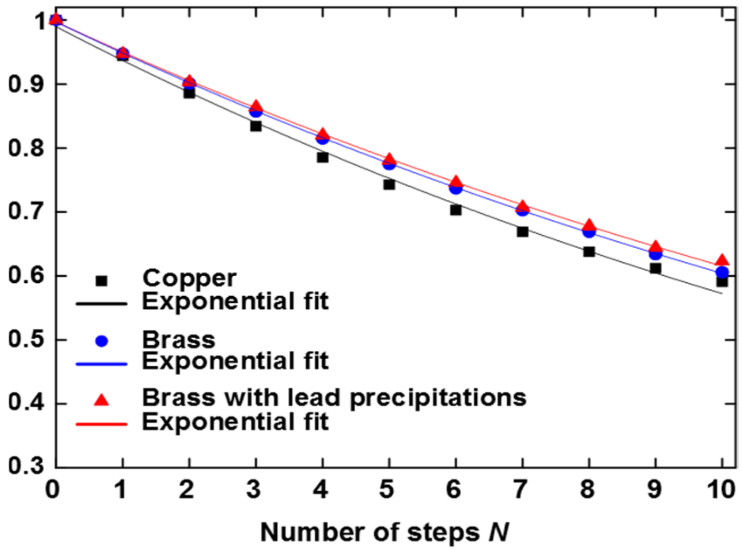
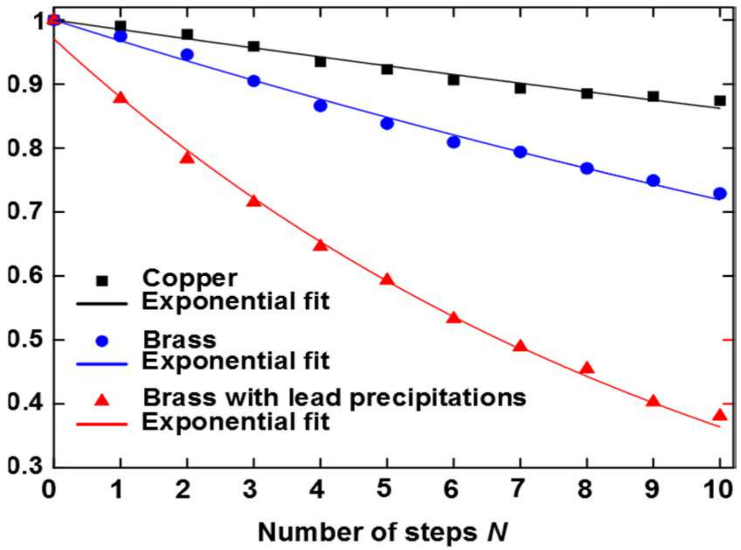
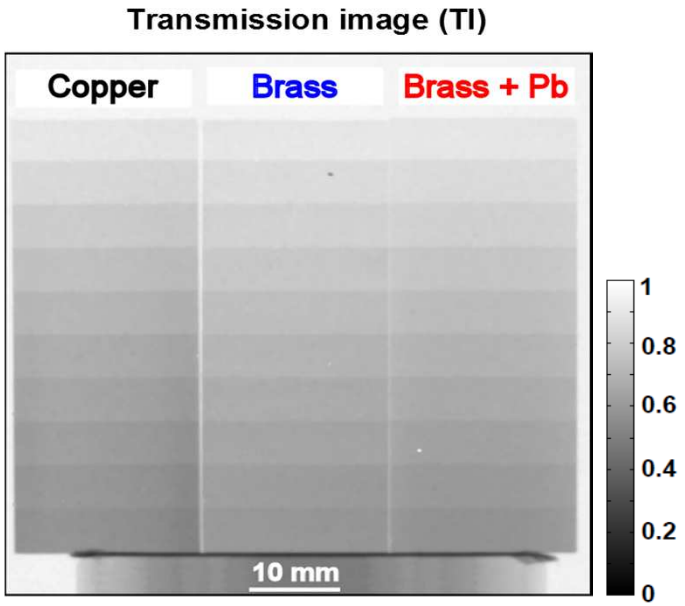


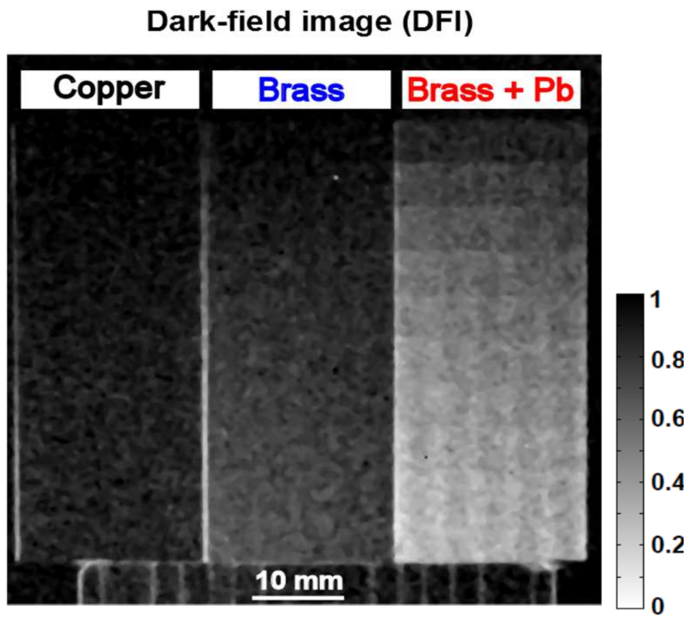
Visibility V(*N*)



Gruenzweig, Kopecek, Betz, *et al*. PRB **88**, 125104 (2013)

DFI applications:





$$\Sigma_{\mathrm{Cu}} = (1.08 \pm 0.02) \quad \mathrm{cm}^{-1}$$

$$\Omega_{\mathrm{Cu}} = (0.62 \pm 0.03) \times 10^{-9}\,\mathrm{cm}^{-1}$$

$$\Sigma_{\mathrm{Brass}} = (1.0 \pm 0.008) \quad \mathrm{cm}^{-1}$$

$$\Omega_{\mathrm{Brass}} = (1.42 \pm 0.03) \times 10^{-9}\,\mathrm{cm}^{-1}$$

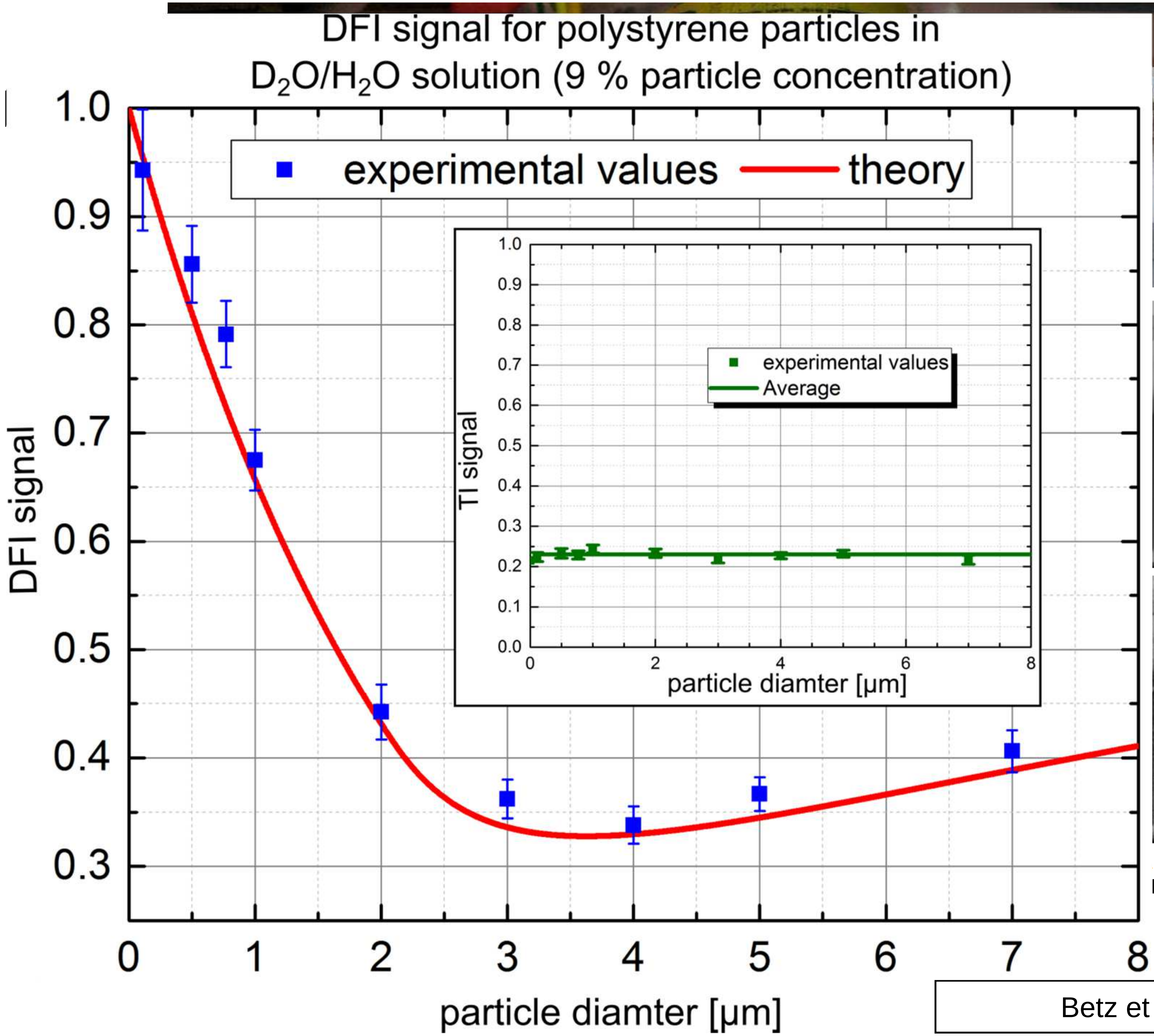
$$\Sigma_{\mathrm{Brass,Pb}} = (0.96 \pm 0.004) \quad \mathrm{cm}^{-1}$$

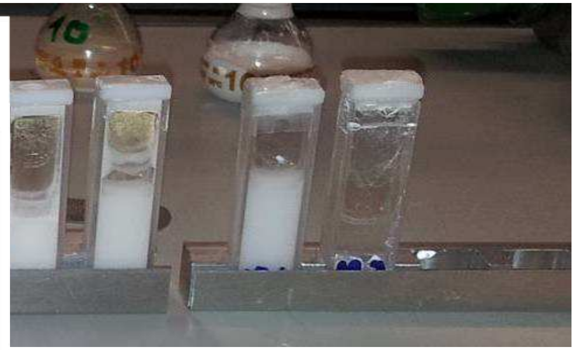
$$\Omega_{\mathrm{Brass,(Pb)}} = (4.21 \pm 0.08) \times 10^{-9}\,\mathrm{cm}^{-1}$$

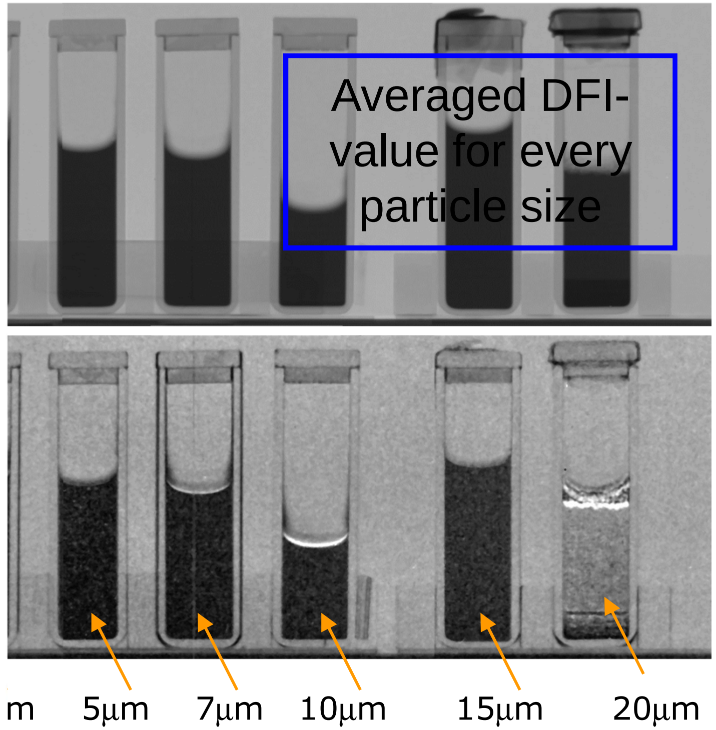
Quantitative DFI

Gruenzweig, Kopecek, Betz, *et al*. PRB **88**, 125104 (2013)

DFI applications:







Averaged DFI-value for every particle size

Betz et al. submitted to Rev. Sci. instr.

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Magnetic interaction of neutrons:

Neutrons' magnetic moment μ_N interacts with magnetic structures

Refractive index for neutrons depends on magnetization

$$n = 1 - (\delta_{nuc} + \delta_{mag}) + i\beta$$

$$\delta_{nuc} = \frac{\lambda^2 N b_c}{2\pi}$$

$$\delta_{mag} = \pm \frac{2\mu_N \cdot Bm\,\lambda^2}{h^2}$$

$$\beta = \frac{\lambda \cdot N \cdot \sigma_r}{4\pi}$$

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$$n = 1 - (\delta_{nuc} + \delta_{mag}) + i\beta$$

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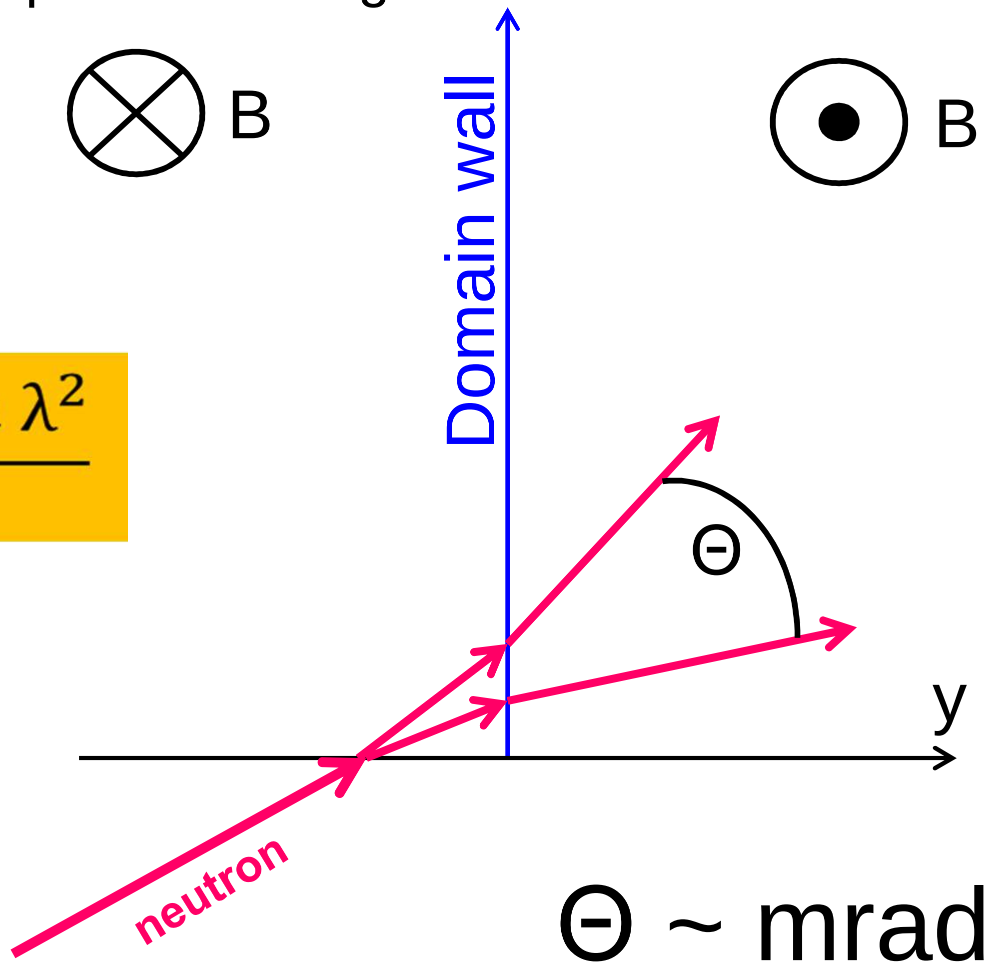
$$\beta = \frac{\lambda \cdot N \cdot \sigma_r}{4\pi}$$

Refraction due to:

- magnetic moment /spin
- magnetization of the sample

Analogy to Snell's law:

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

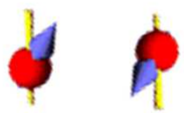
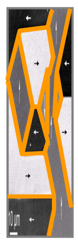
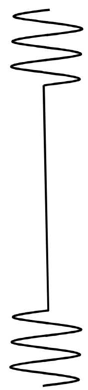


Magnetic structures observed with nGI:

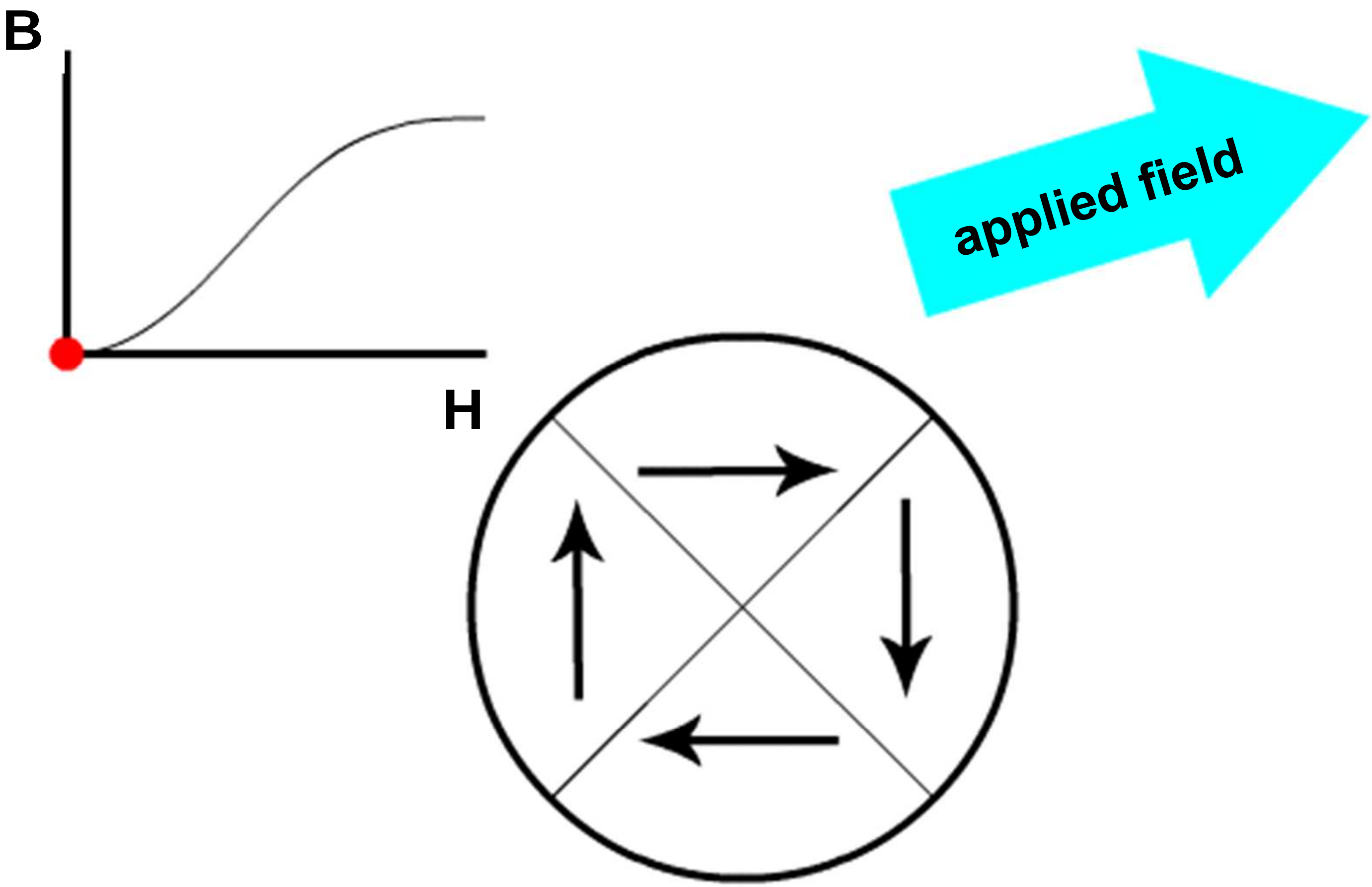
Principle:

Unpolarized neutrons refracted at domain walls

are locally destroying the interference pattern

 +  = 

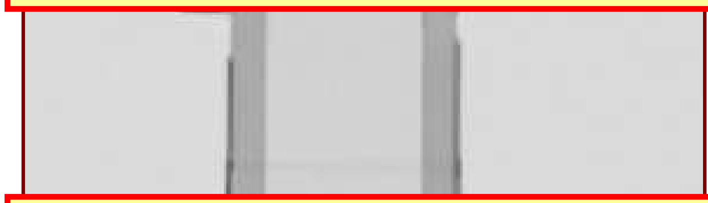
Magnetic structures observed with nGI:



Magnetic structures observed with nGI:

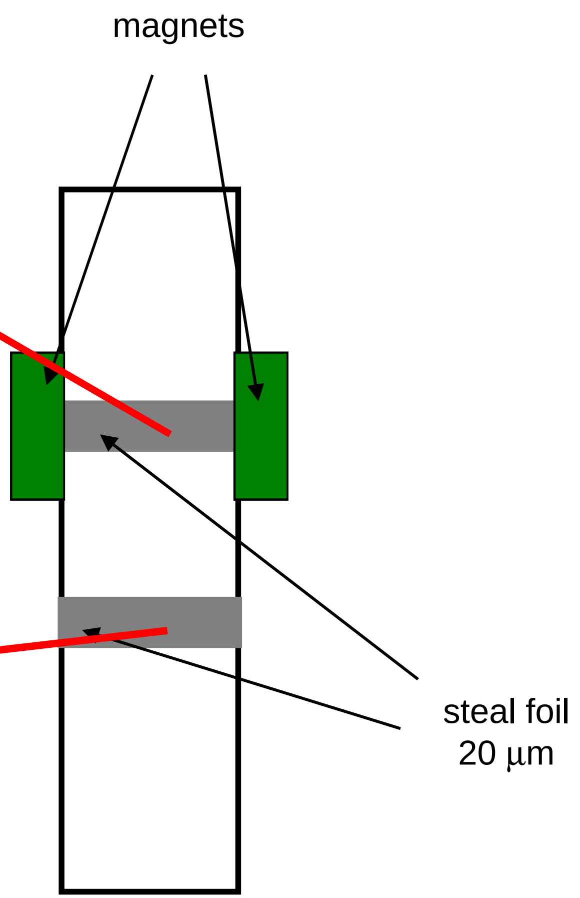
Are this magnetic structures really observable in an experiment ?

Due to the magnetic field, the Domains order.
→ no Domain walls anymore
→ no scattering
→ no Contrast in DFI

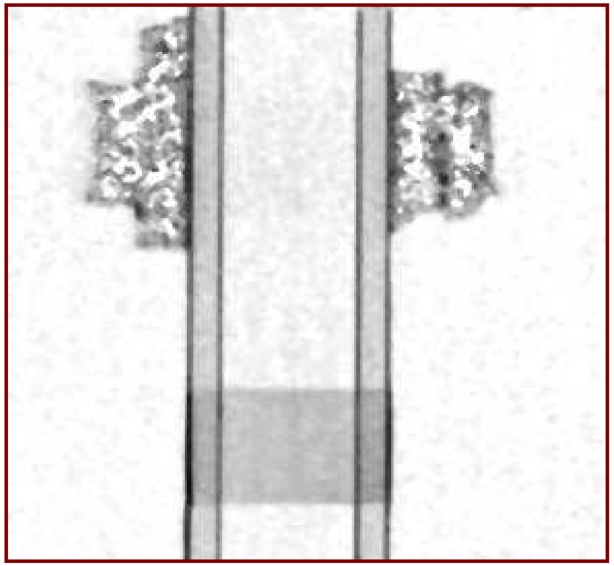


No magnetic field, the Domains are not ordered.
→ many domain walls everywhere
→ scattering
→ Contrast in DFI

without magnets



Dark field image

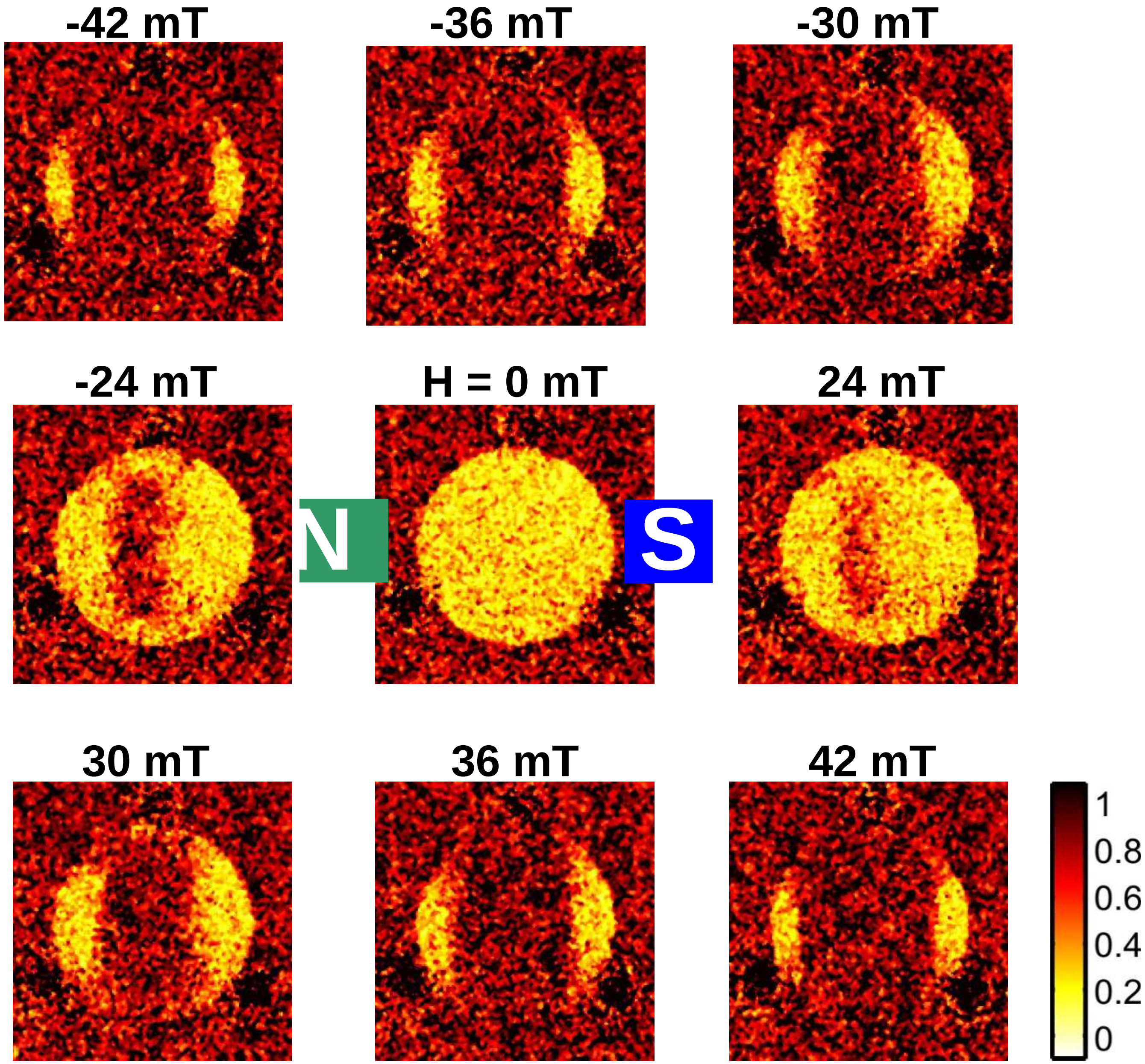


The magnetic ordered foil is invisible, the unordered is clearly visible

Outline

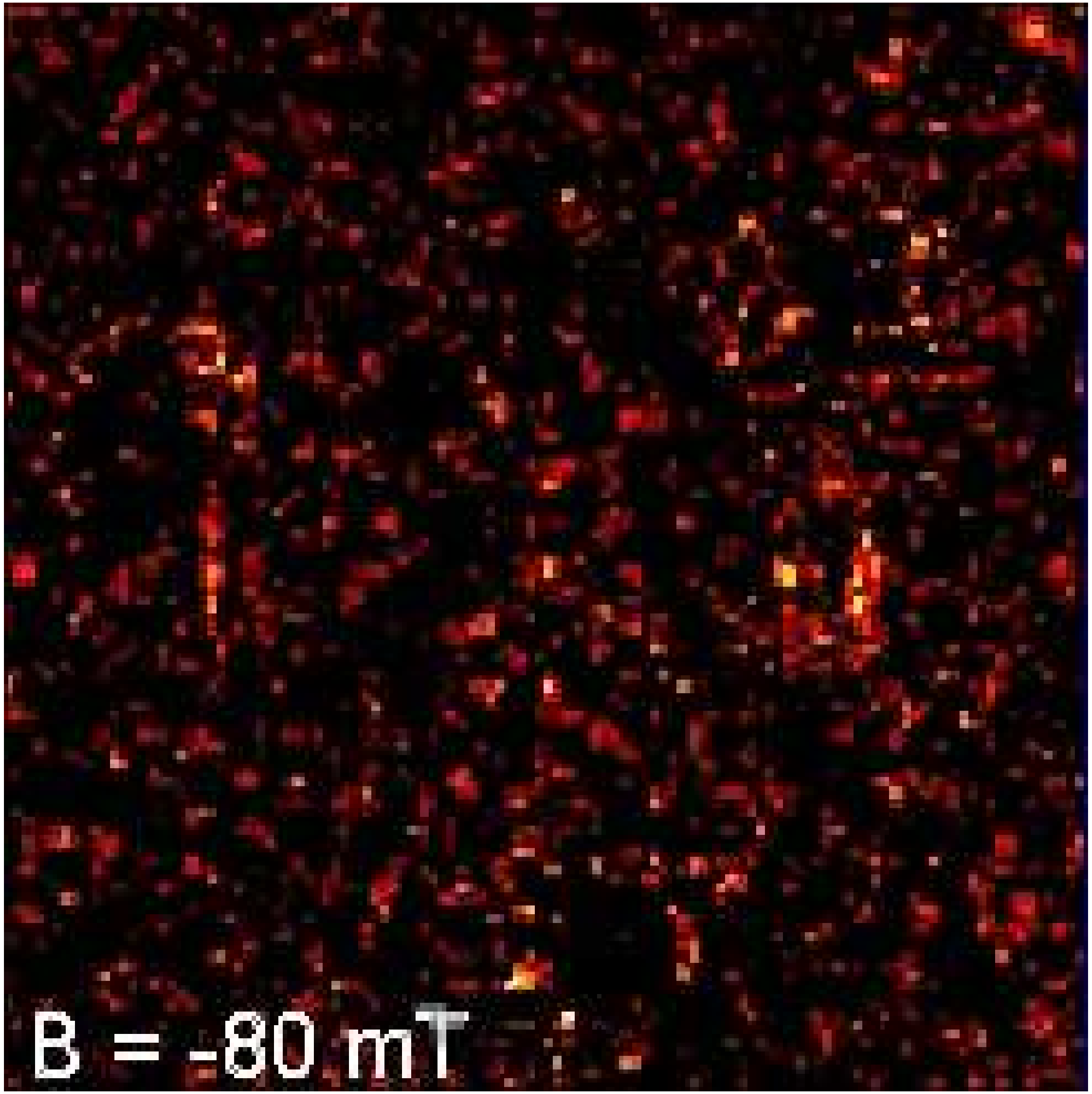
1. Neutron Grating Interferometry:
   a) Setup
   b) Principle
2. Phase contrast and dark-field signals
3. Detection of nuclear scattering properties (applications)
4. Magnetic interaction
5. Magnetic investigations (applications)
6. Summary & Outlook

Magnetic investigations:



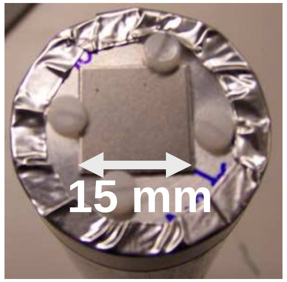
C. Grünzweig et al., Appl. Phys. Lett. **93**, 112504, (2008)

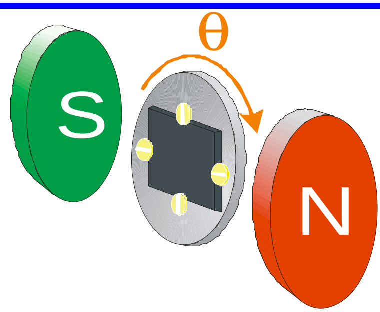
Magnetic investigations:

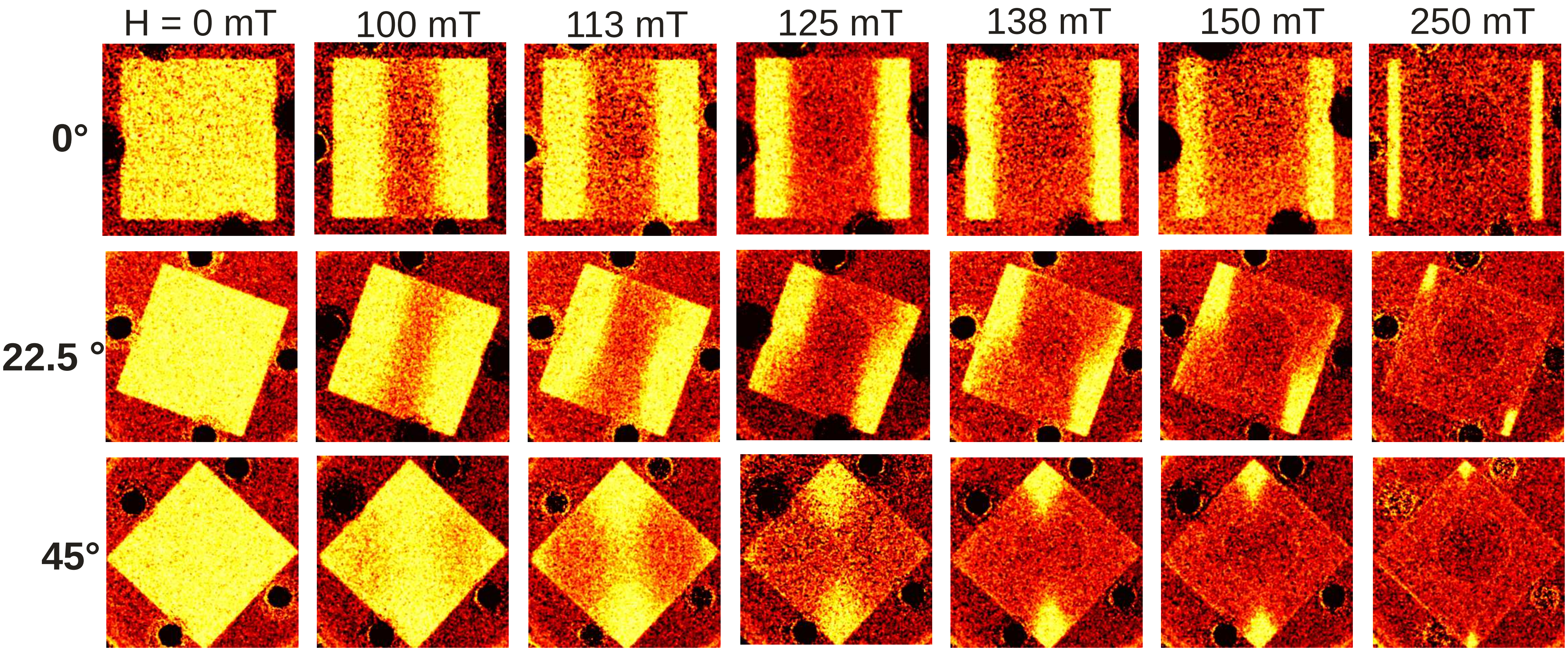


Magnetic investigations:

C. Grünzweig, et al. J. Appl. Phys.
107, 09D308 (2010)







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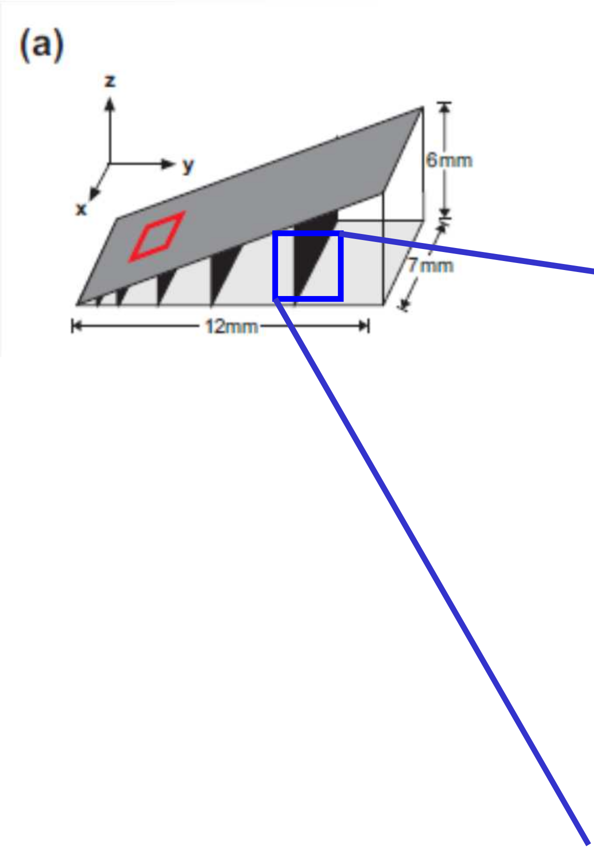
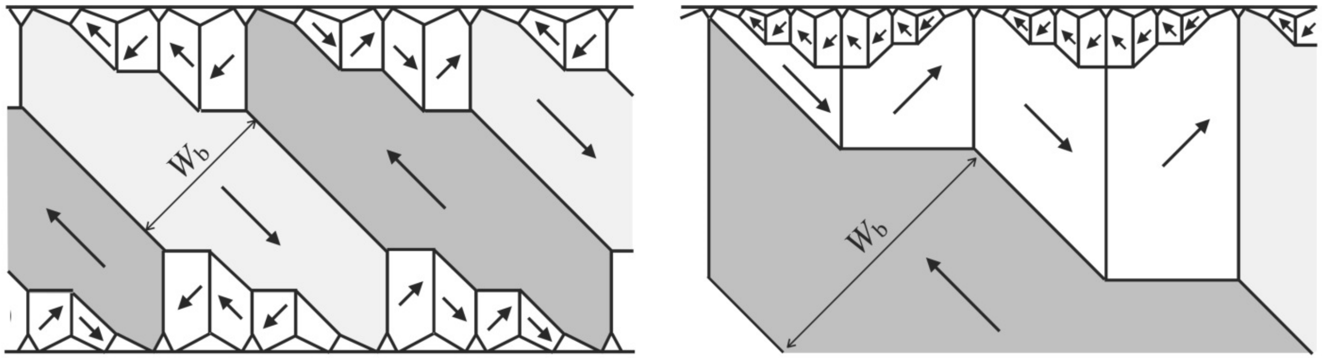
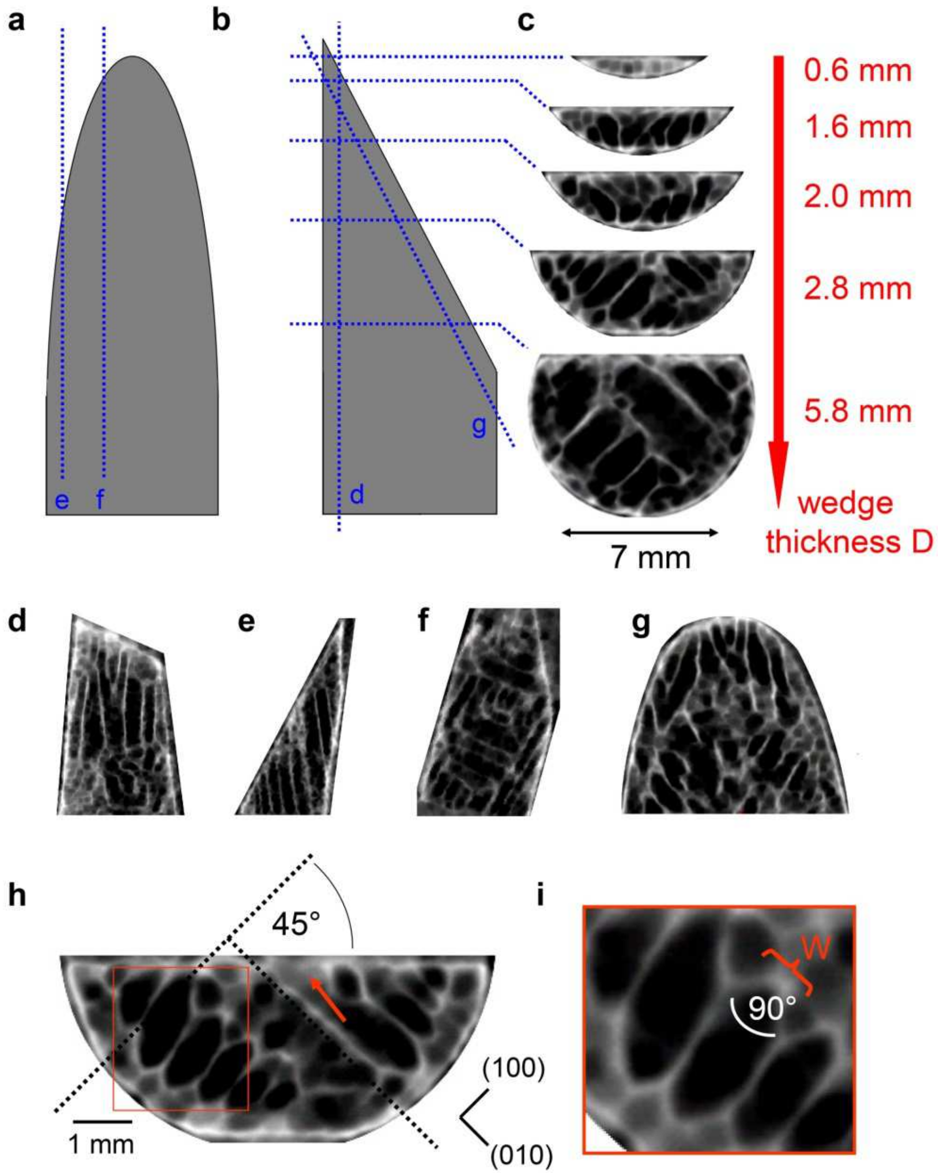


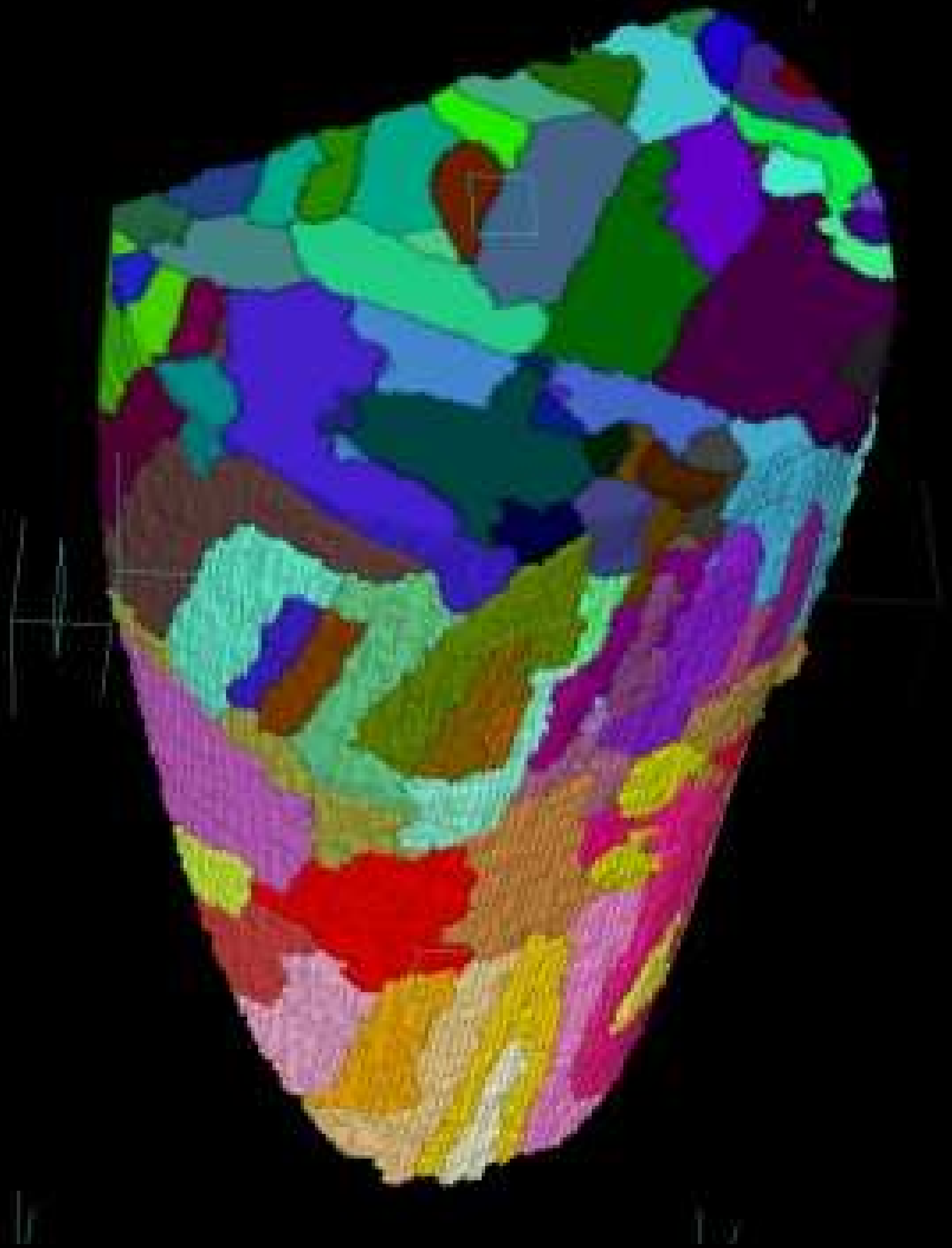


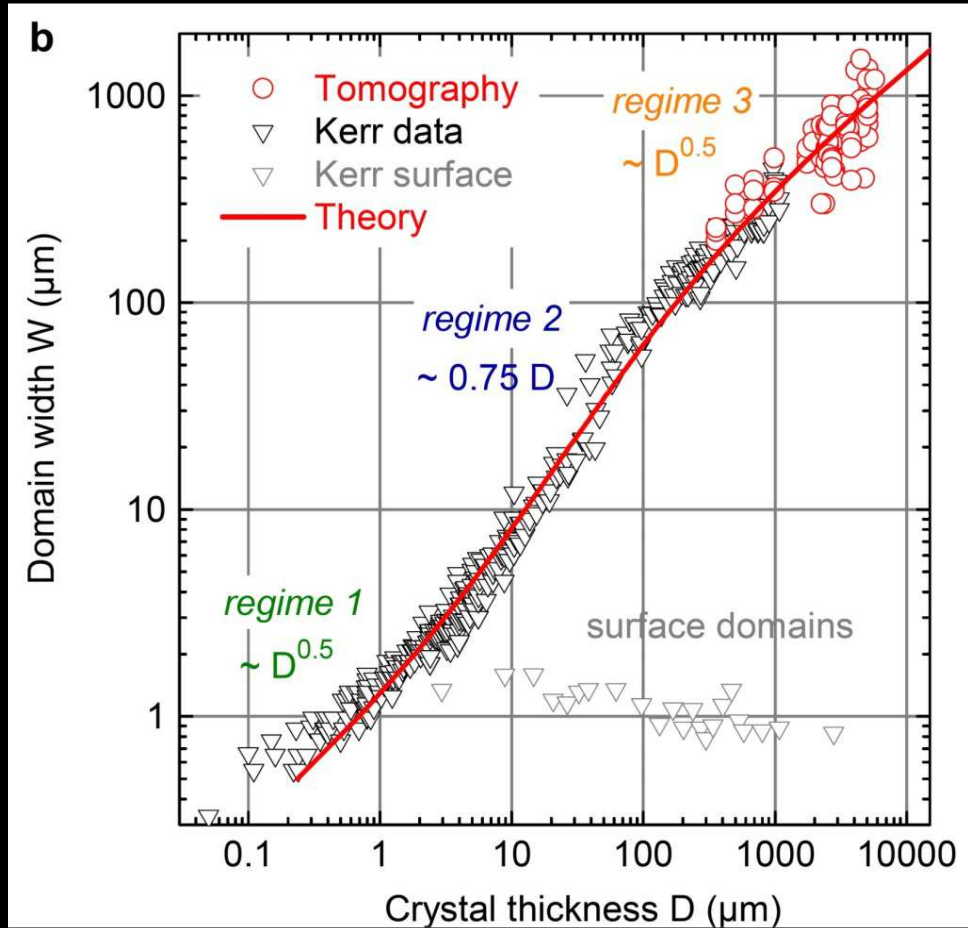
theory predicts: $$W_b \approx \sqrt{D}$$

Magnetic investigations:



I. Manke, et al. Nature Communications 1 (8), p.125 (2010).





I. Manke, N. Kardjilov, R. Schäfer, A. Hilger, M. Strobl, M. Dawson,
C. Grünzweig, G. Behr, M. Hentschel, C. David, A. Kupsch, A. Lange, J. Banhart.
Three-dimensional imaging of magnetic domains.
Nature Communications 1 (8), p.125 (2010).

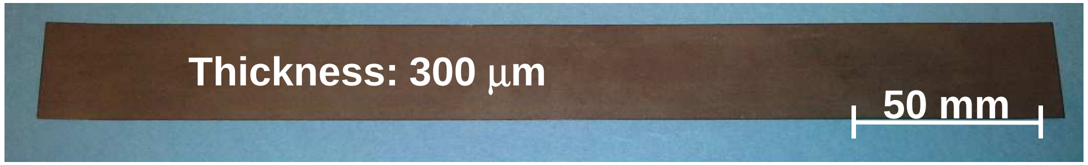
Magnetic investigations:

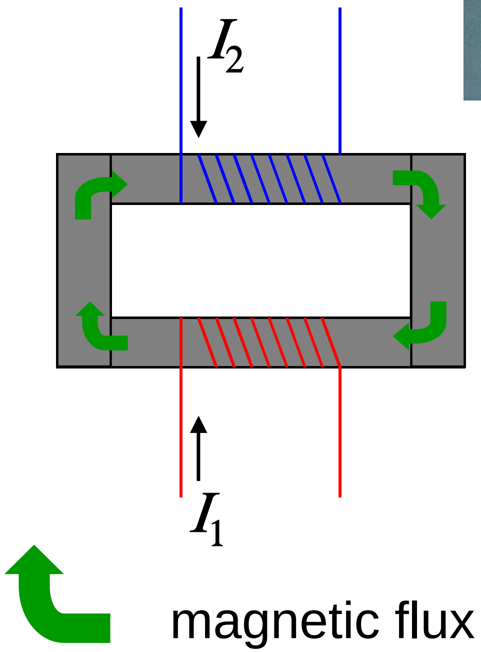
Grain-oriented (GO) electrical steel :

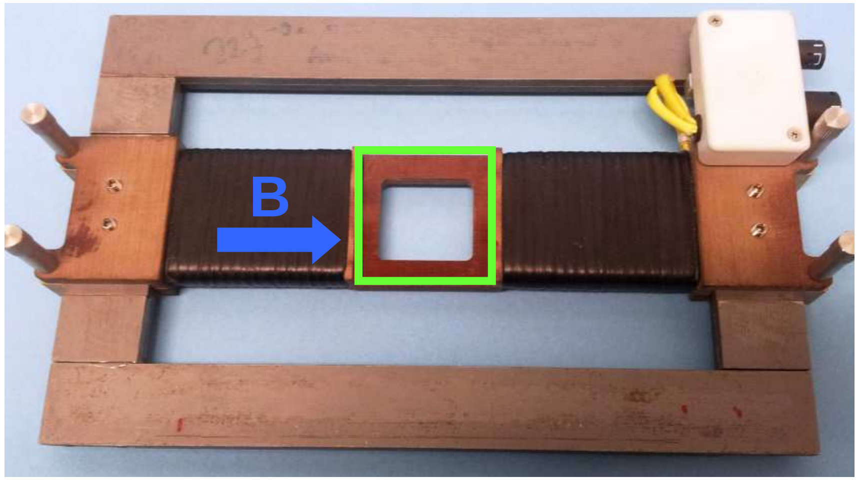
- anisotropic
- domain size up to mm
- used in industrial transformers

www.moeller.net

GO electrical steel lamination:



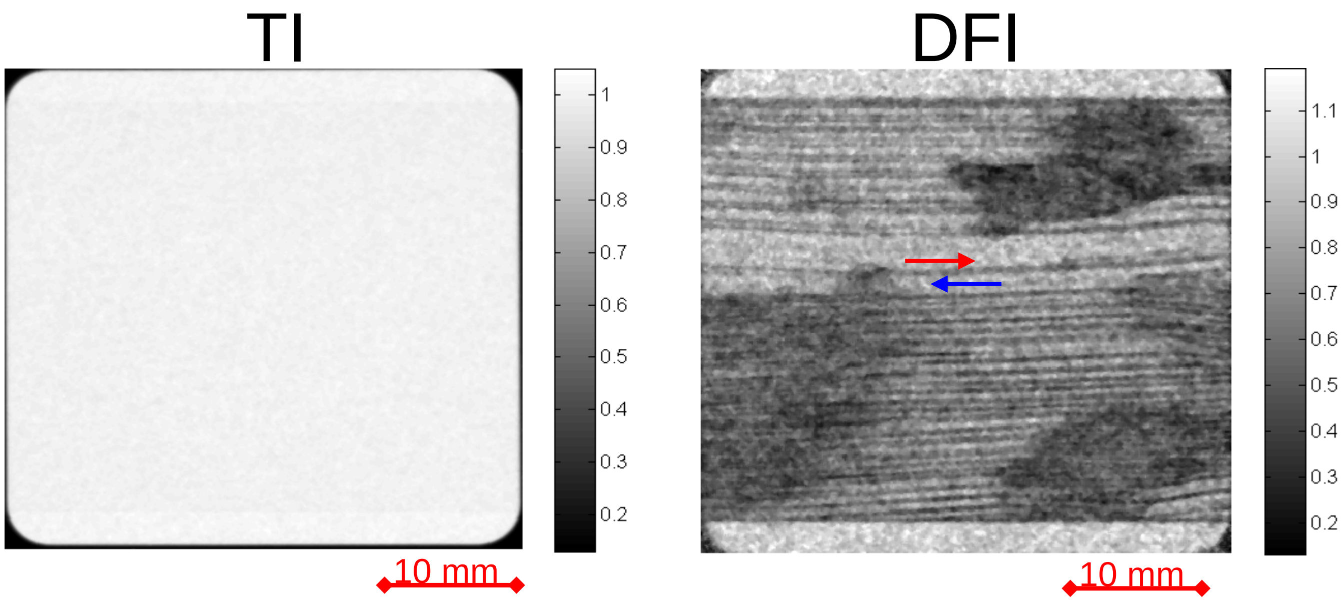




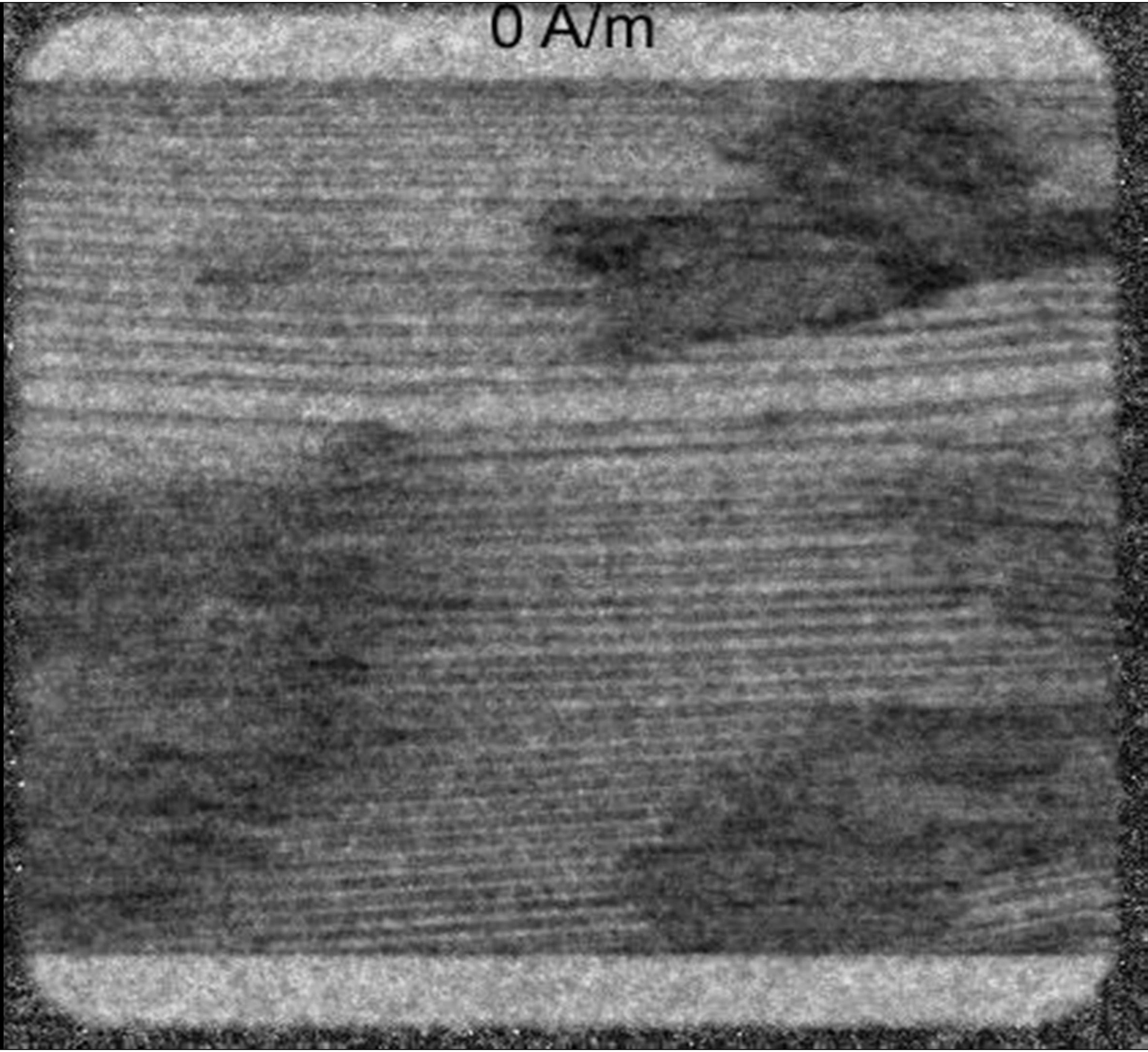
Magnetic test-frame:

- Up to 4 A (≙ 6000 A/m)
- FoV: 35 mm x 35 mm
- In-situ global magnetic characterization

Magnetic investigations:



- Dark lines represent domain walls
- Arrows mark the magnetization
- Dark areas are slightly misoriented grains with small surface domains

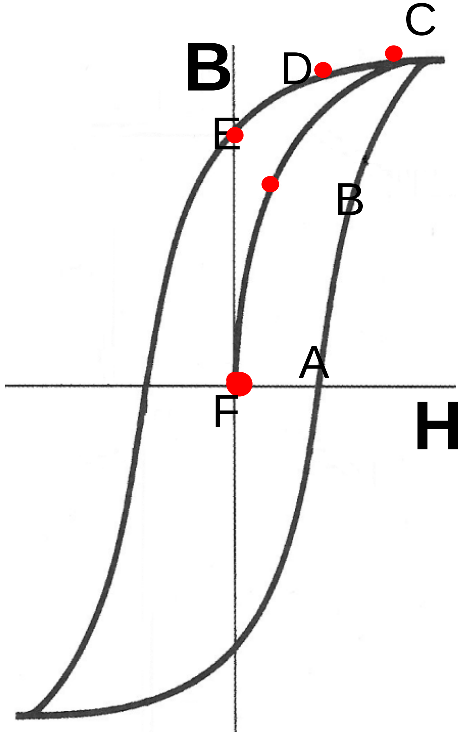

0 A/m

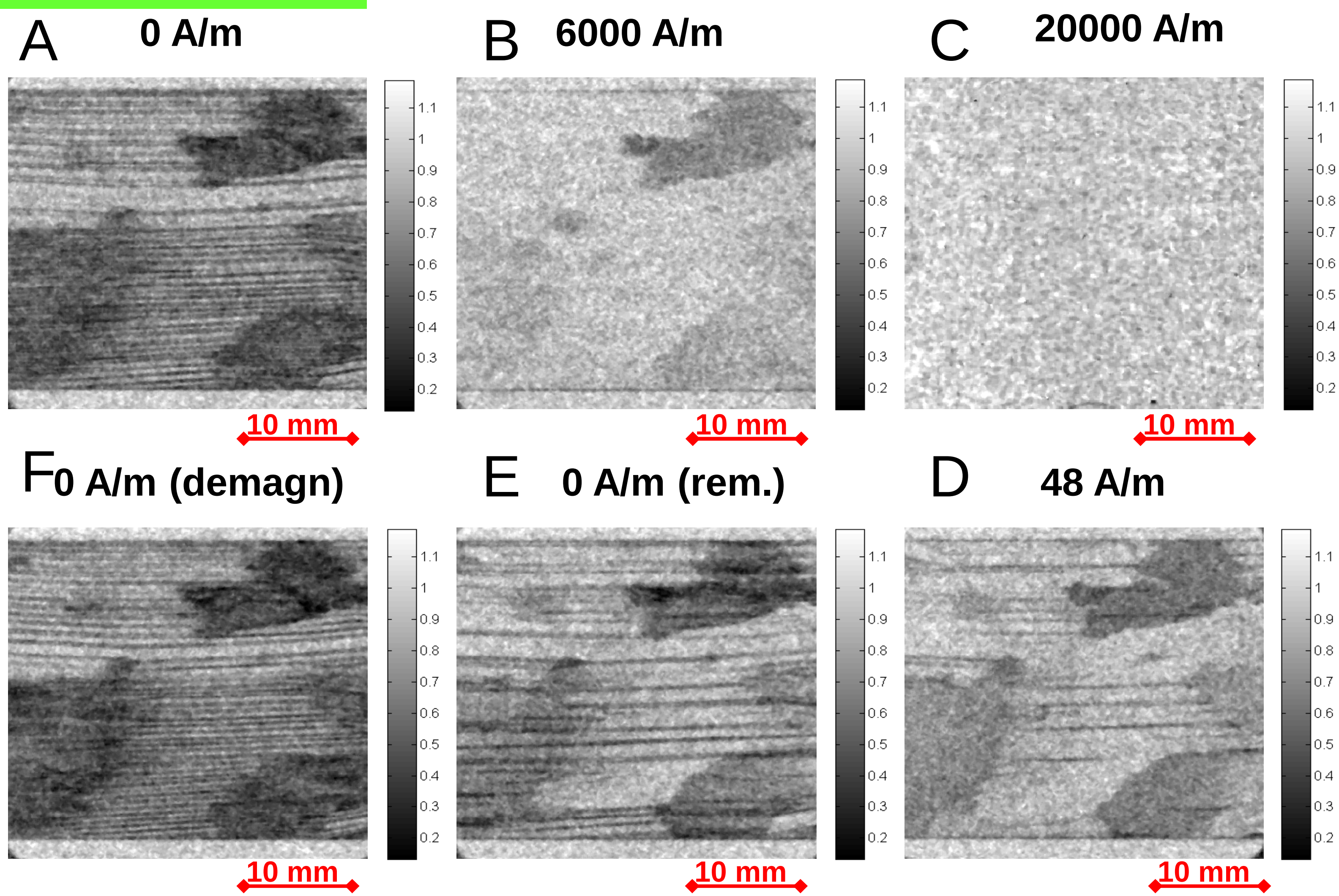
Magnetic investigations:

Magnetic domains in Grain-oriented sheets:

- In transmission (Volume information)
- Large field of view
- Spatially resolved

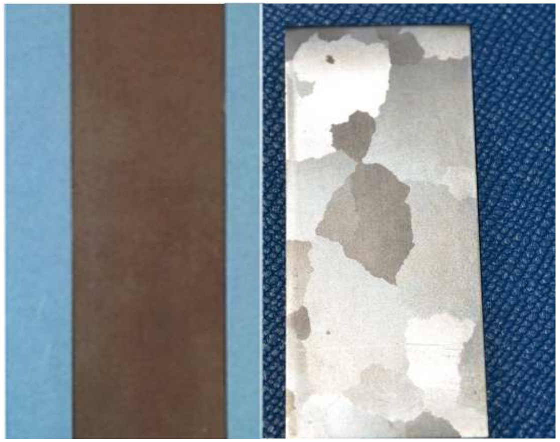
To be published….

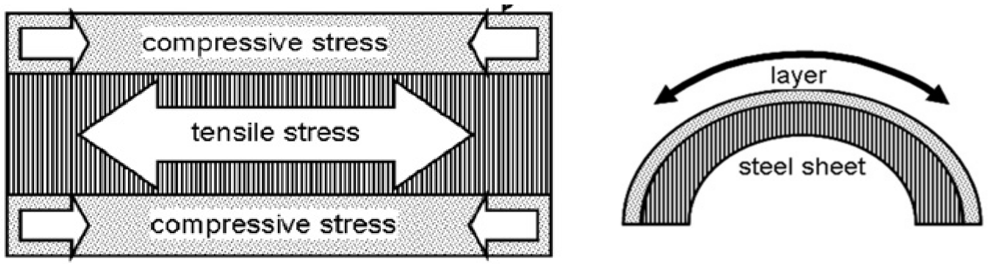




Magnetic investigations:

Protective, insulating coating used in applications applies tensile stress to the laminations

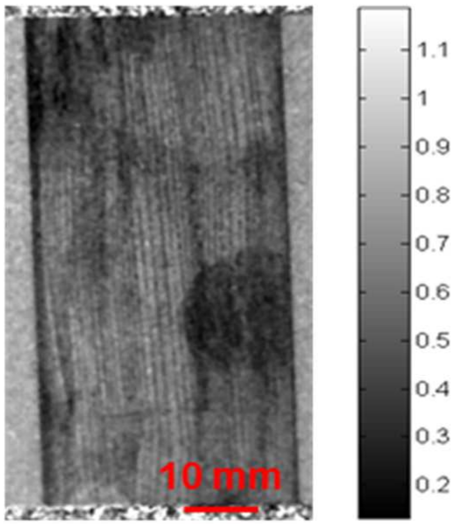




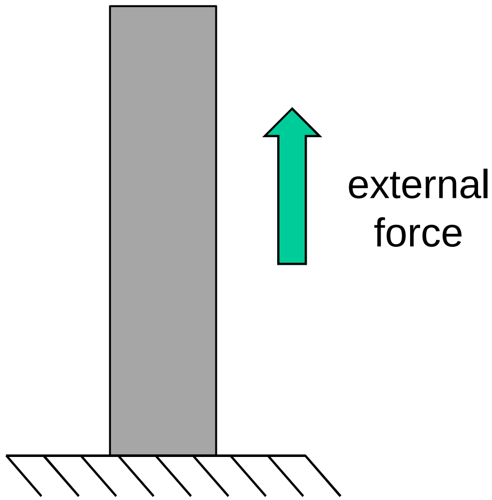
E.Bayer et *al*. Journal of magnetism and magnetic materials, **323**, 1985-1991 (2011)

clear influence to the magnetic domain structure

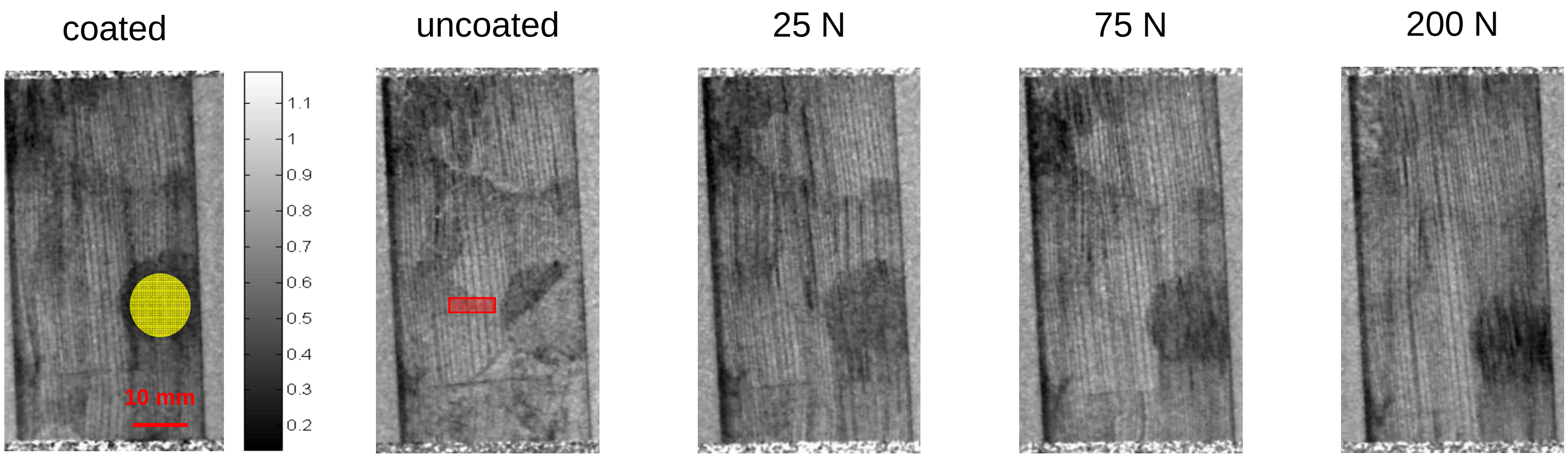
with coating



Add an external force, to reproduce the stress state



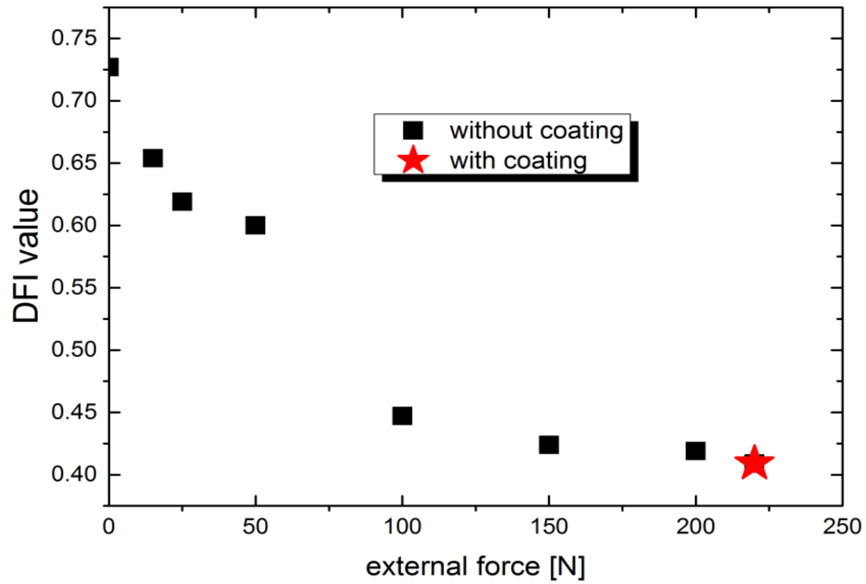
Magnetic investigations:



To be published….

Domain structure is predicted to refine due to tensile stresses

Mean:				
coated	0 N	25 N	75 N	200 N
0.410	0.763	0.623	0.578	0.440



Outline

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   a) Setup
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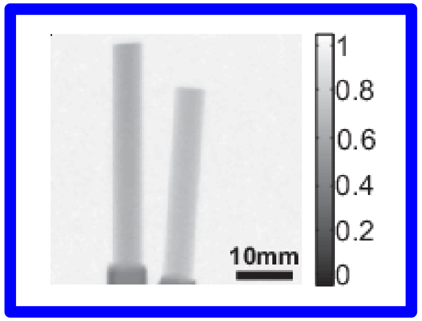
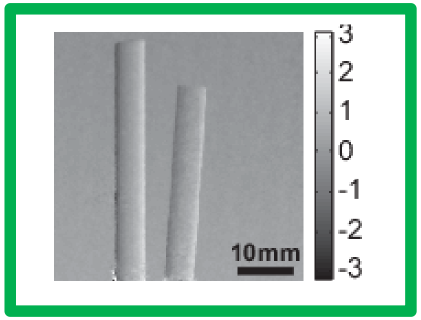
Summary & Outlook:

Neutron grating interferometry delivers simultaneously:

- **Transmission image**
  → **Attenuation behavior**

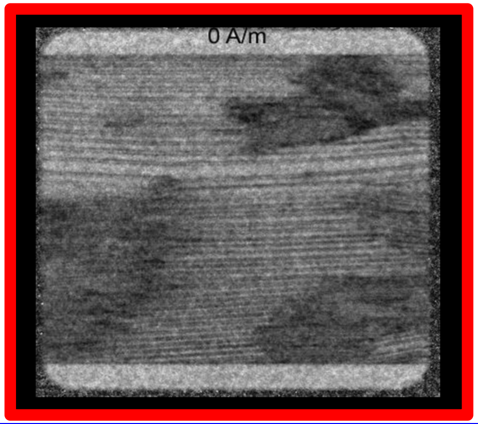


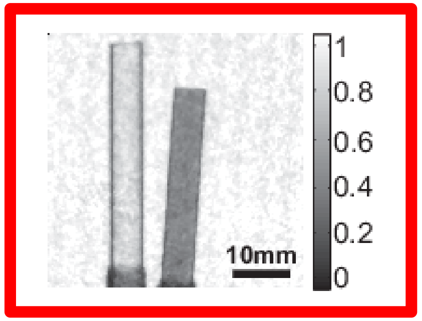
- **Differential phase image**
  → **Phase information**



- **Dark-field image**
  → **Scattering information**

Magnetic structure visible in the dark-field image





Summary & Outlook:

Dynamic magnetization processes

Magnetic transitions

Open for new ideas…

Localized detection of scattering

Porous media studies

Ordering processes

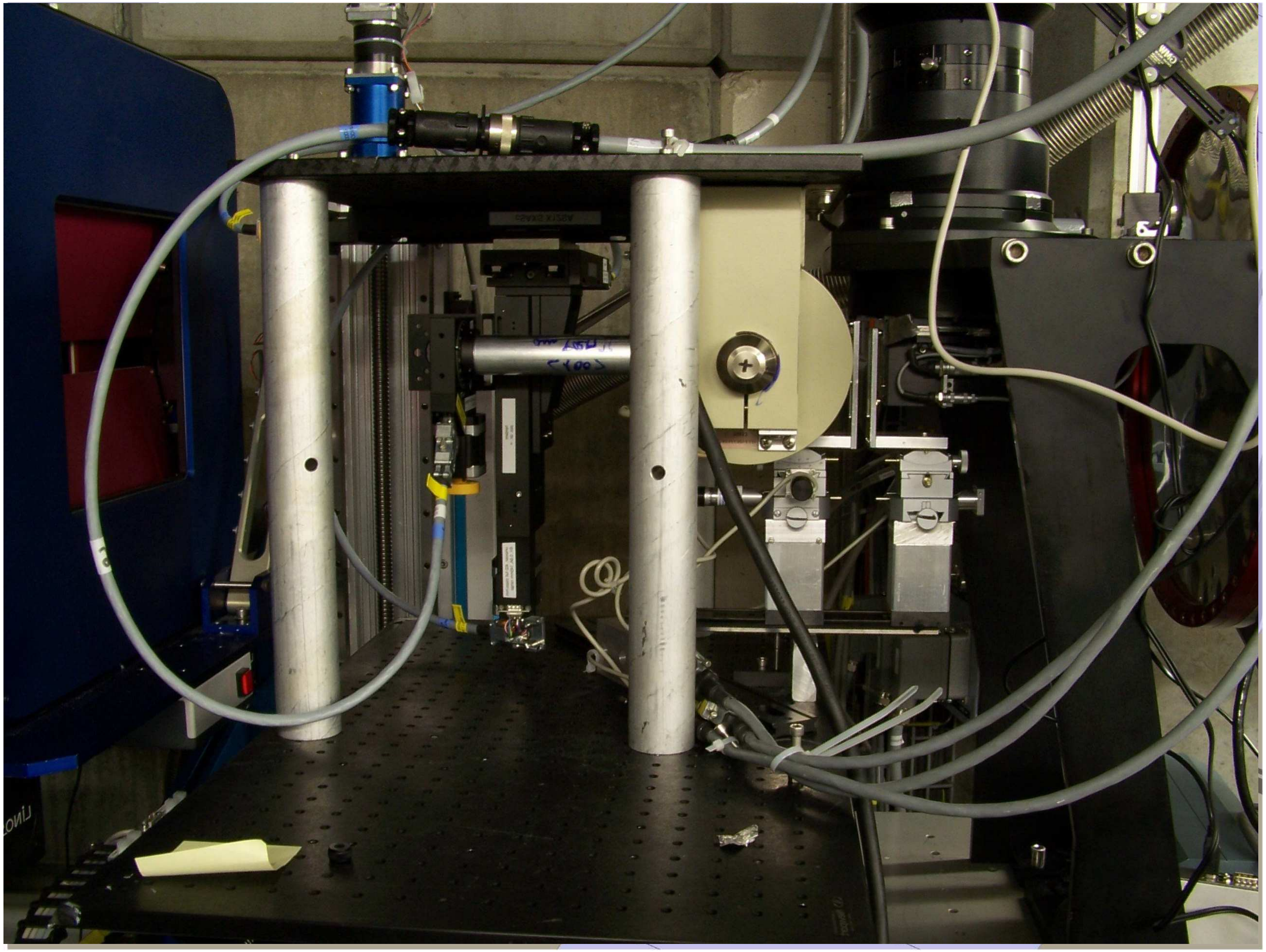
Phase imaging for additional contrasts

Investigations of fibers

Thanks for your attention.

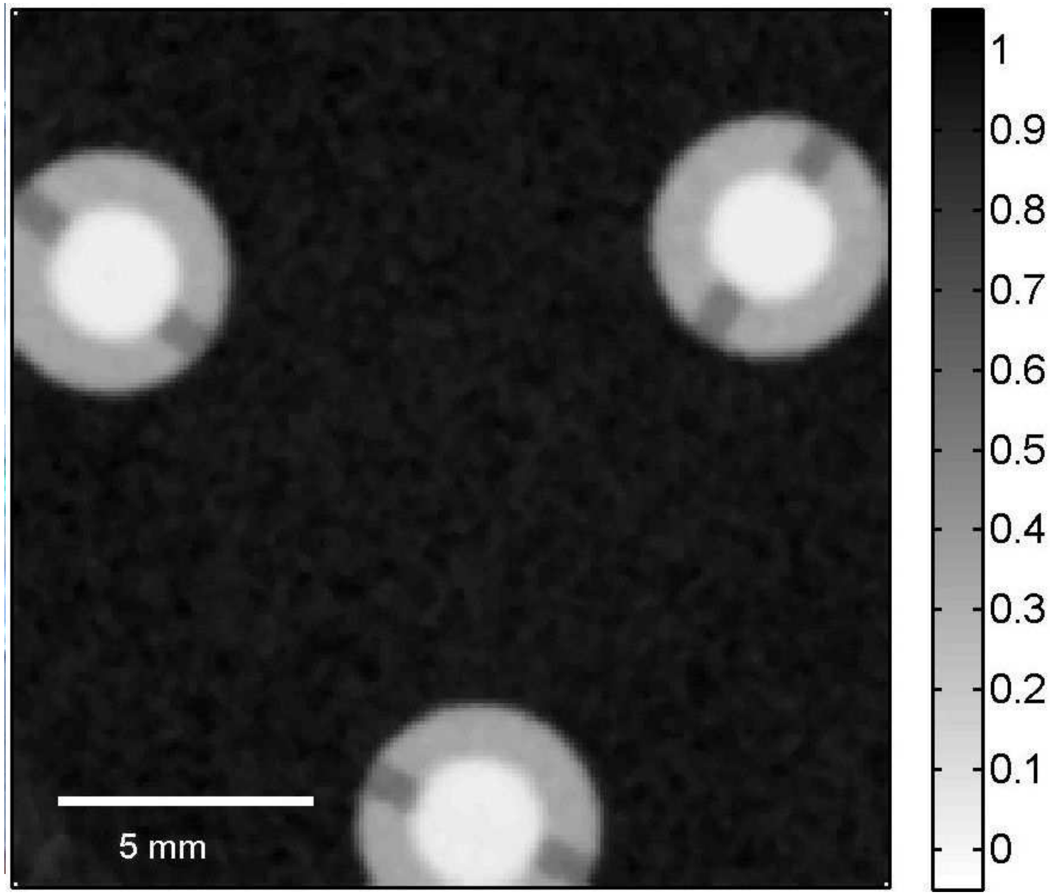
Questions?

Neutron grating interferometry: the setup

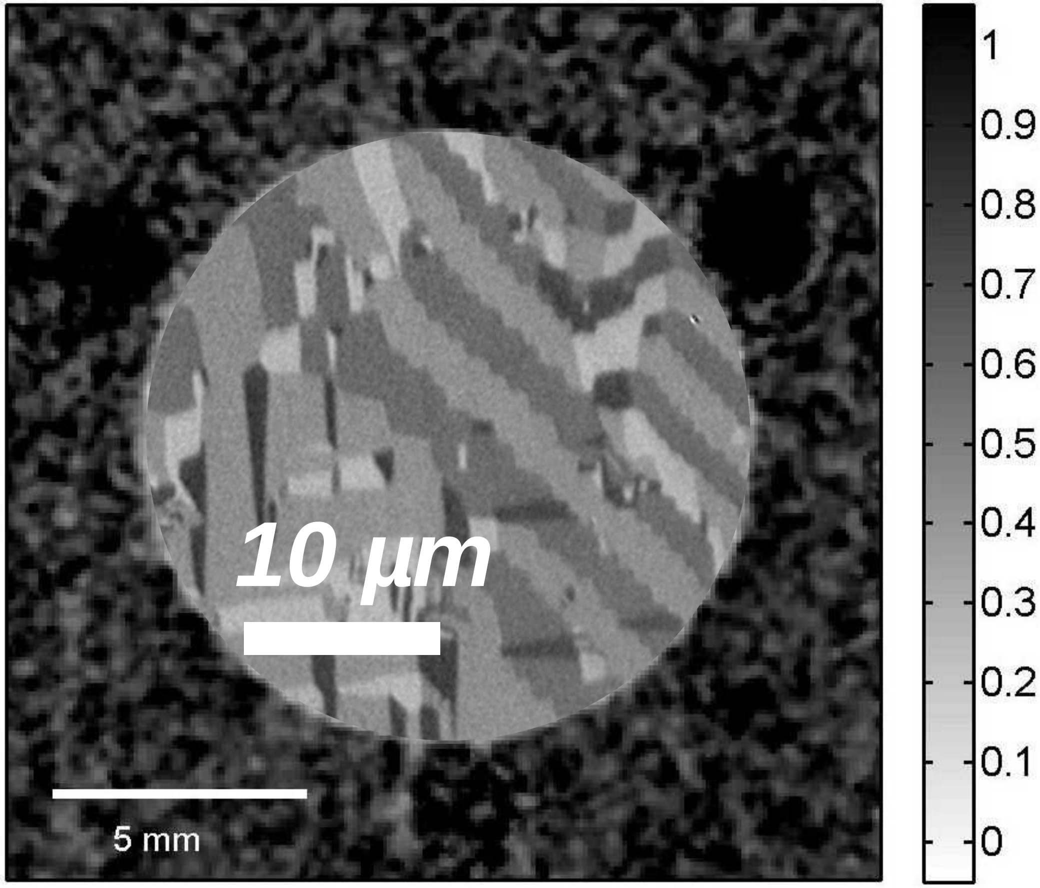


Experimental results: <100> FeSi(3%), 400 µm thick

transmission



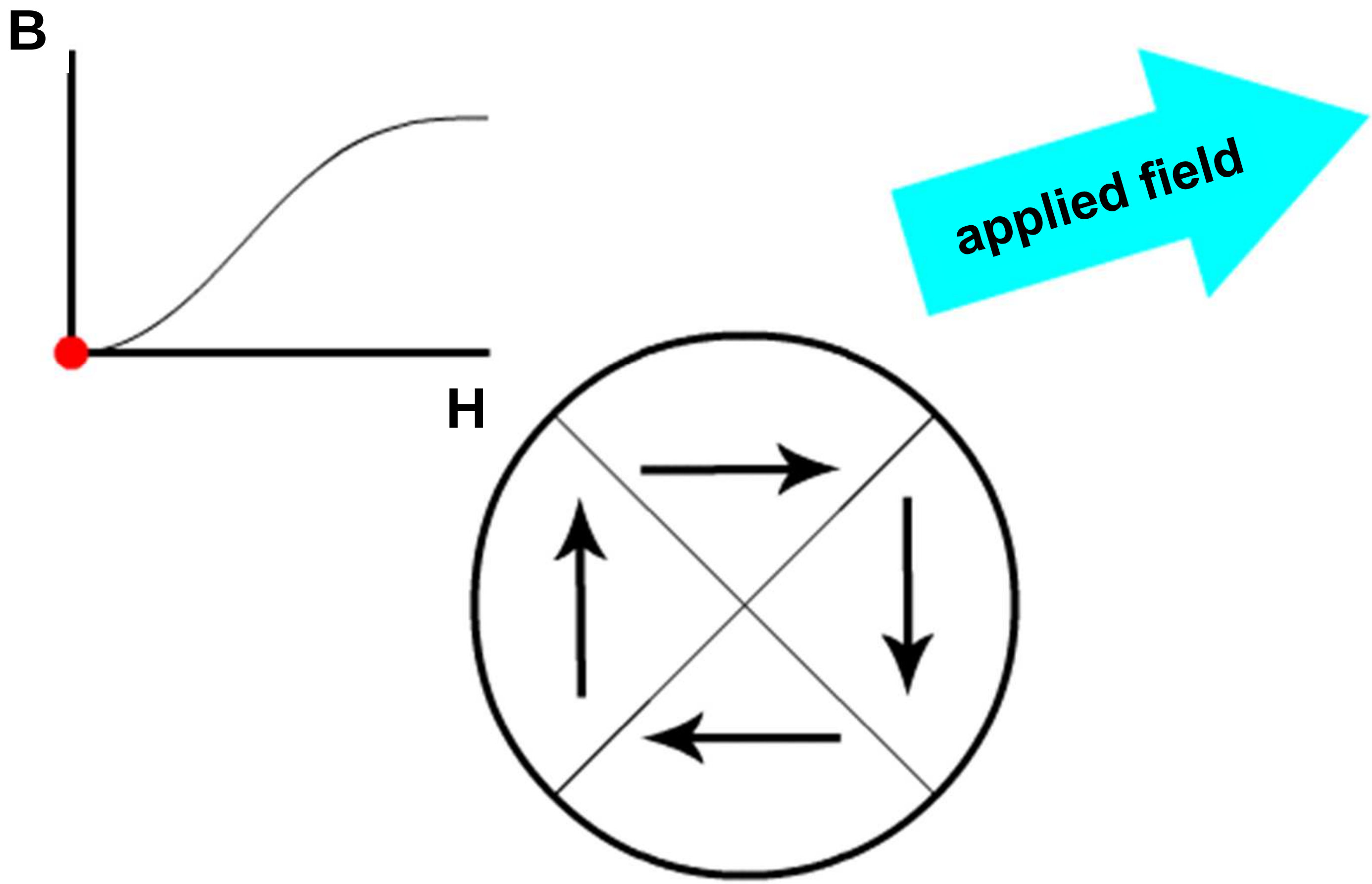
DFI



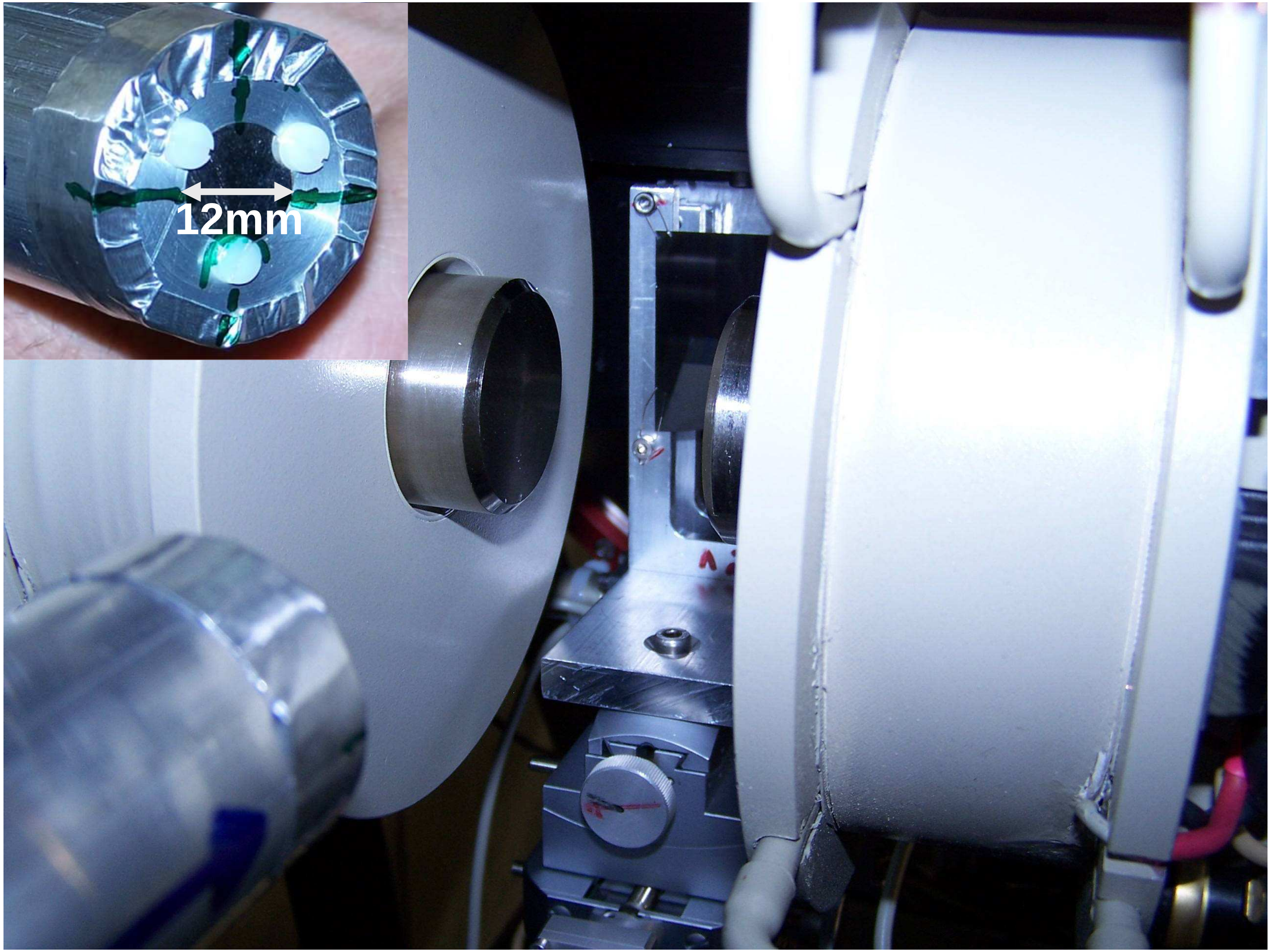
magnetic field ≠ 0 ?

C. Grünzweig, C. David, O. Bunk, M. Dierolf, G. Frei, G. Kühne, J. Kohlbrecher, R. Schäfer, P. Lejcek, H. Rønnow, and F. Pfeiffer. *Neutron decoherence imaging for visualizing bulk magnetic domain structures.* Phys. Rev. Lett. **101**, 025504 (2008).

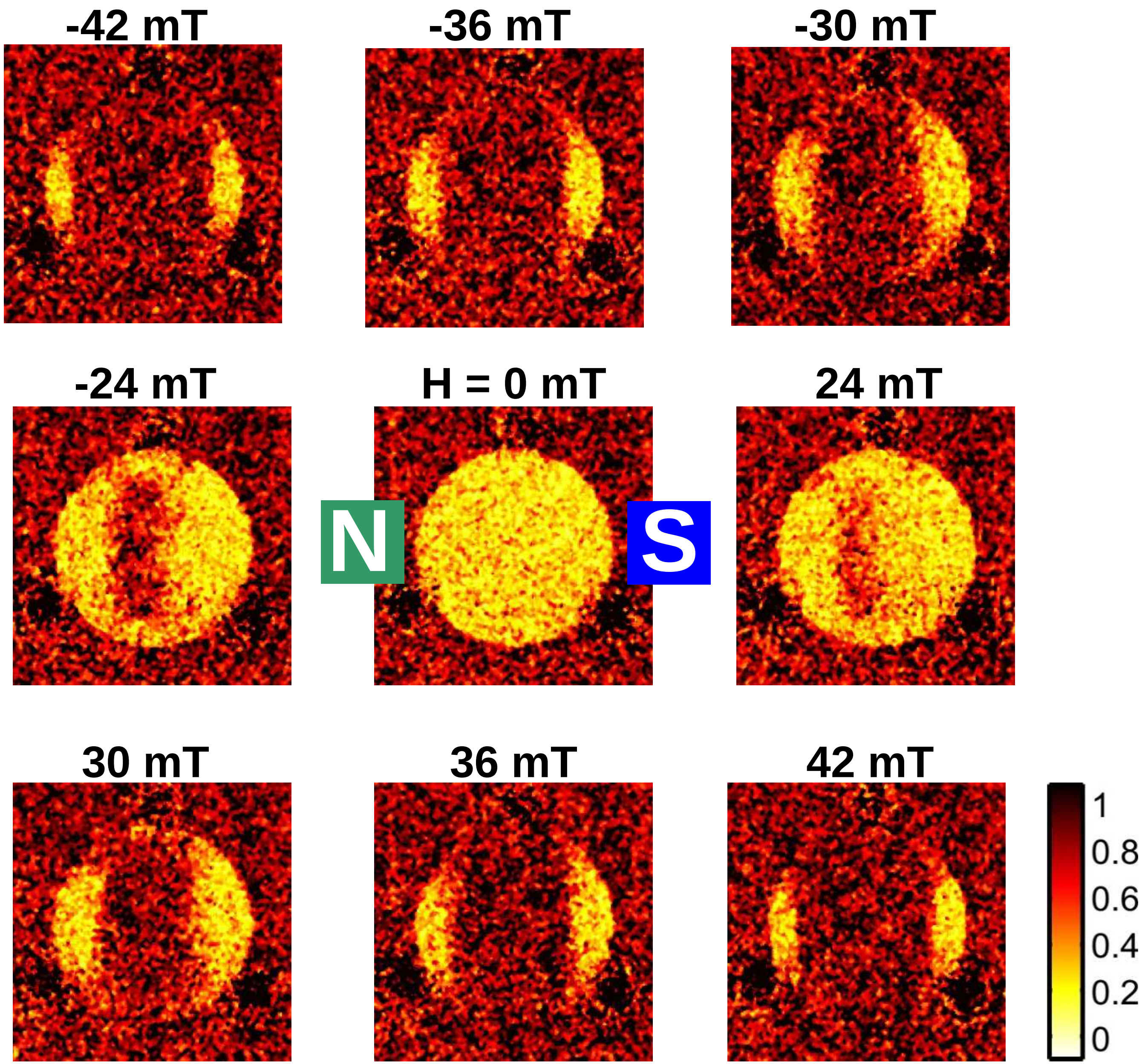
Magnetization process



Ramping of magnetic field



Magnetization process

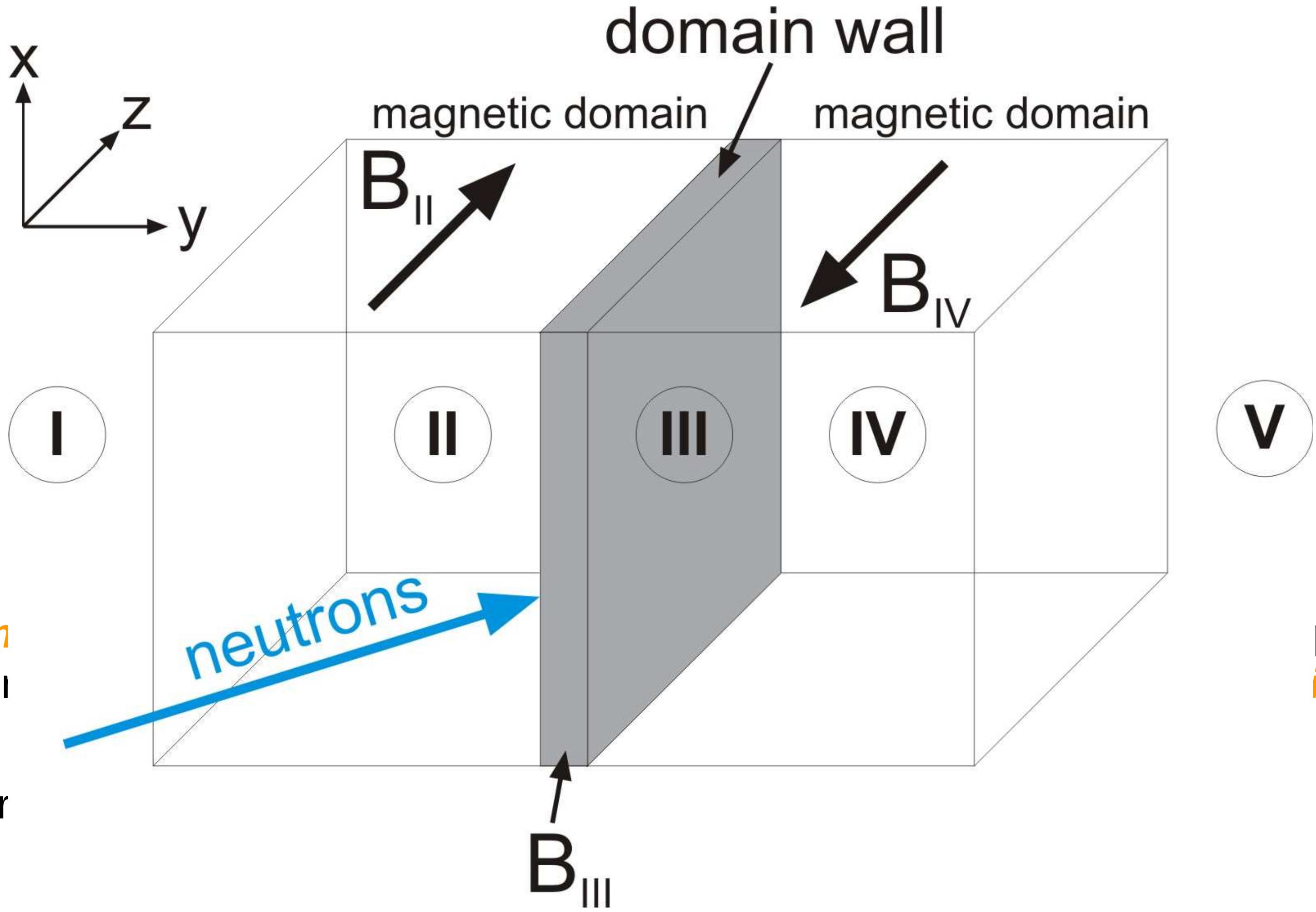


Magnetism: Why using neutrons?

<u>**Some properties of the neutron**</u>:

- Magnetic moment: → makes it sensitive to magnetic fields
→ interaction with magnetic moment of unpaired electrons of the atomic shell (same order as nuclear interaction)

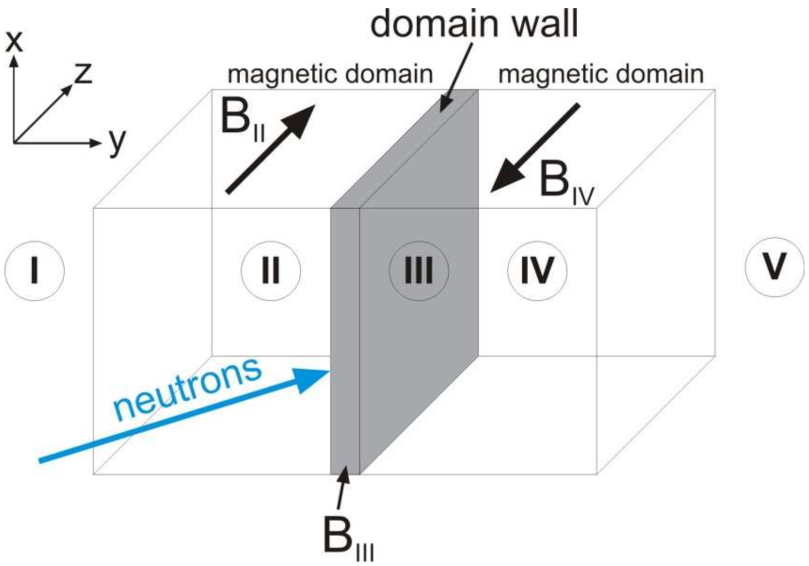
Refraction of unpolarized neutrons at domain walls



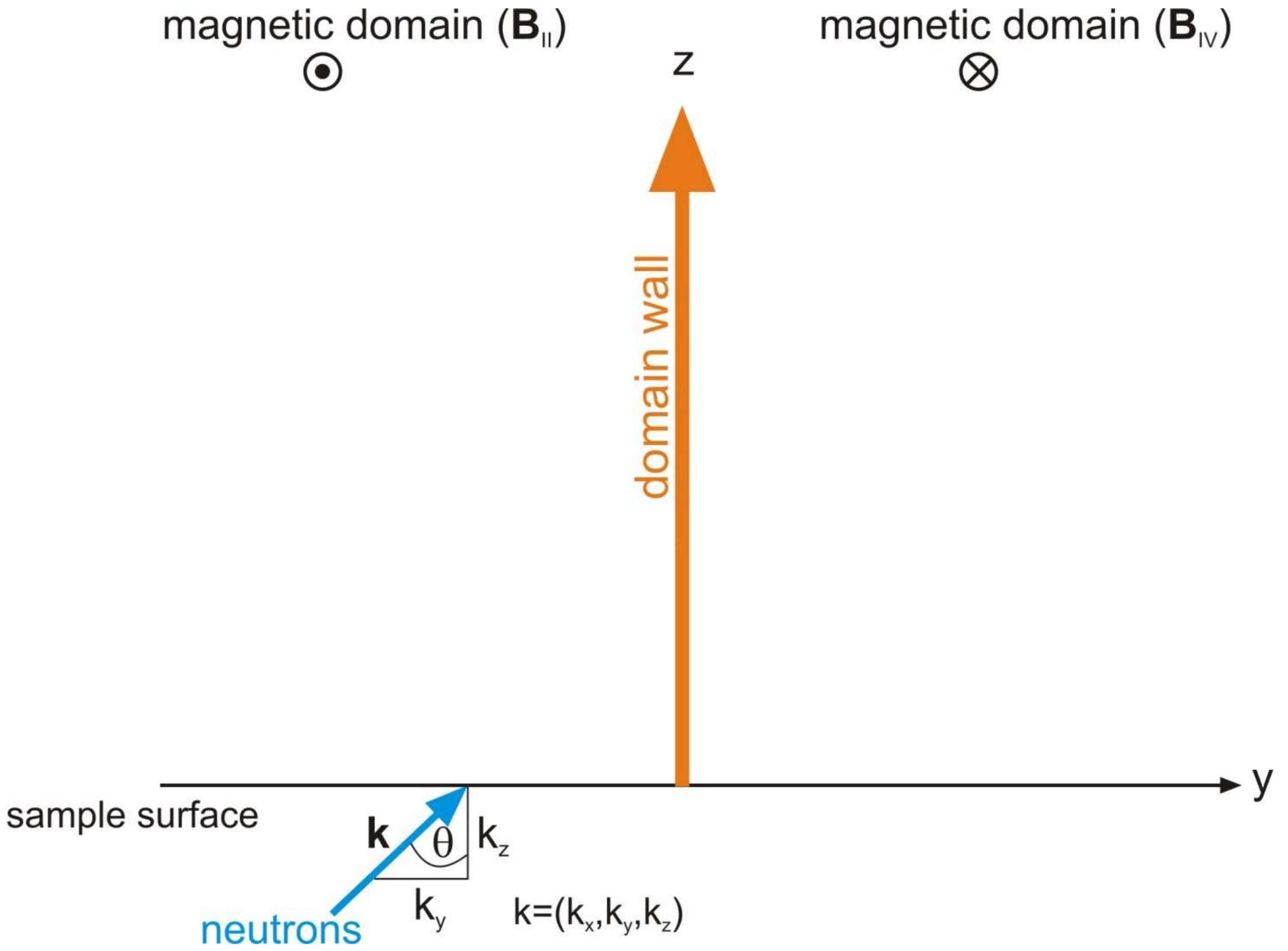
• Refraction of ***un*** … pin-
dependent pote… ***ion B***

• Domain walls ar…

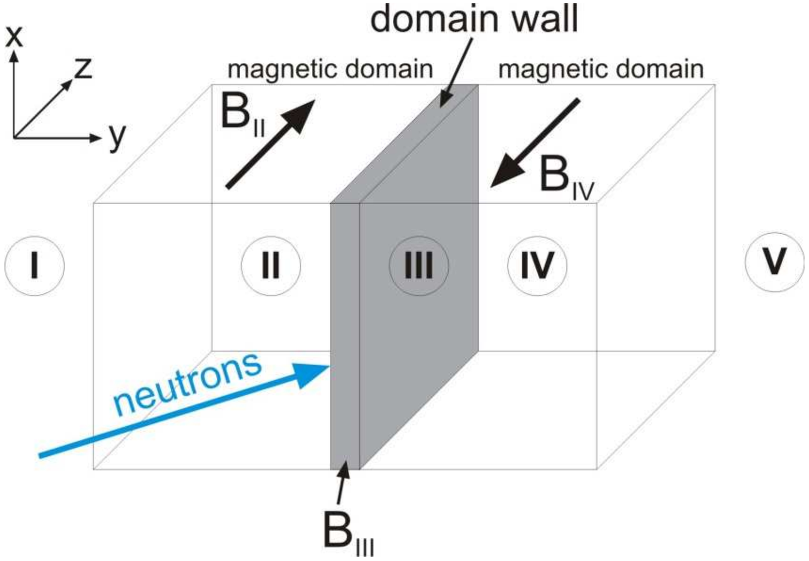
Refraction of unpolarized neutrons at domain walls



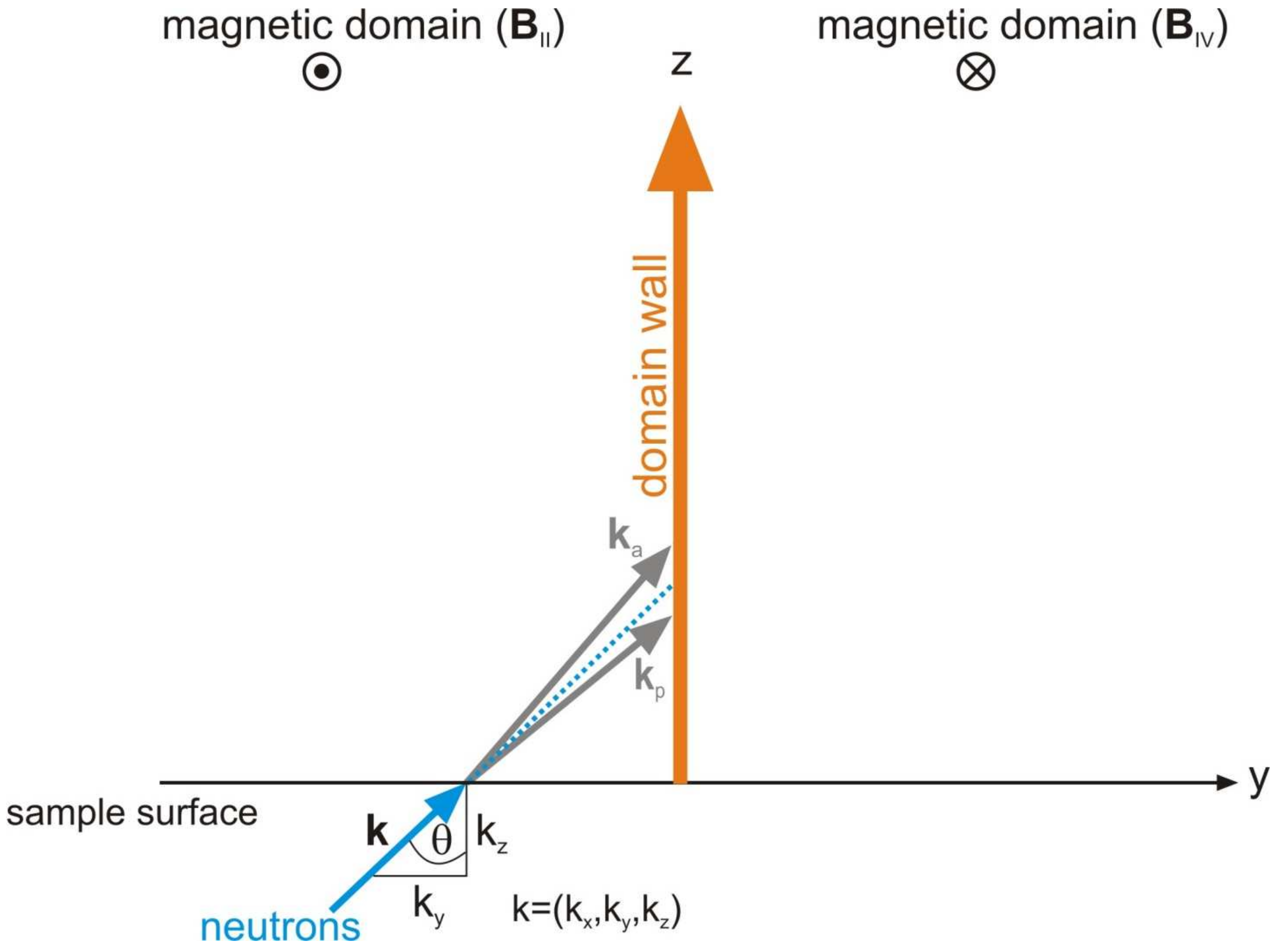
$$n = 1 - \delta_{mag} = 1 \pm \frac{2\boldsymbol{\mu}_N \cdot \boldsymbol{B} m \lambda^2}{h^2}$$



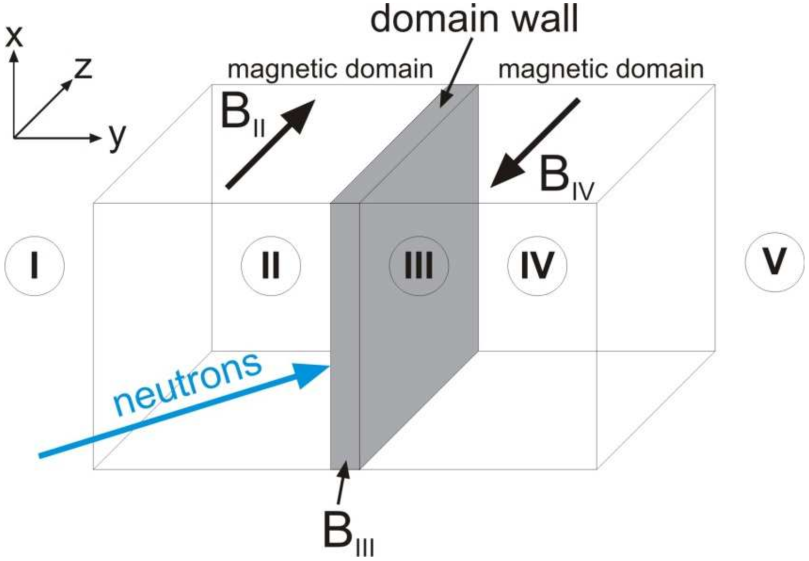
Refraction of unpolarized neutrons at domain walls



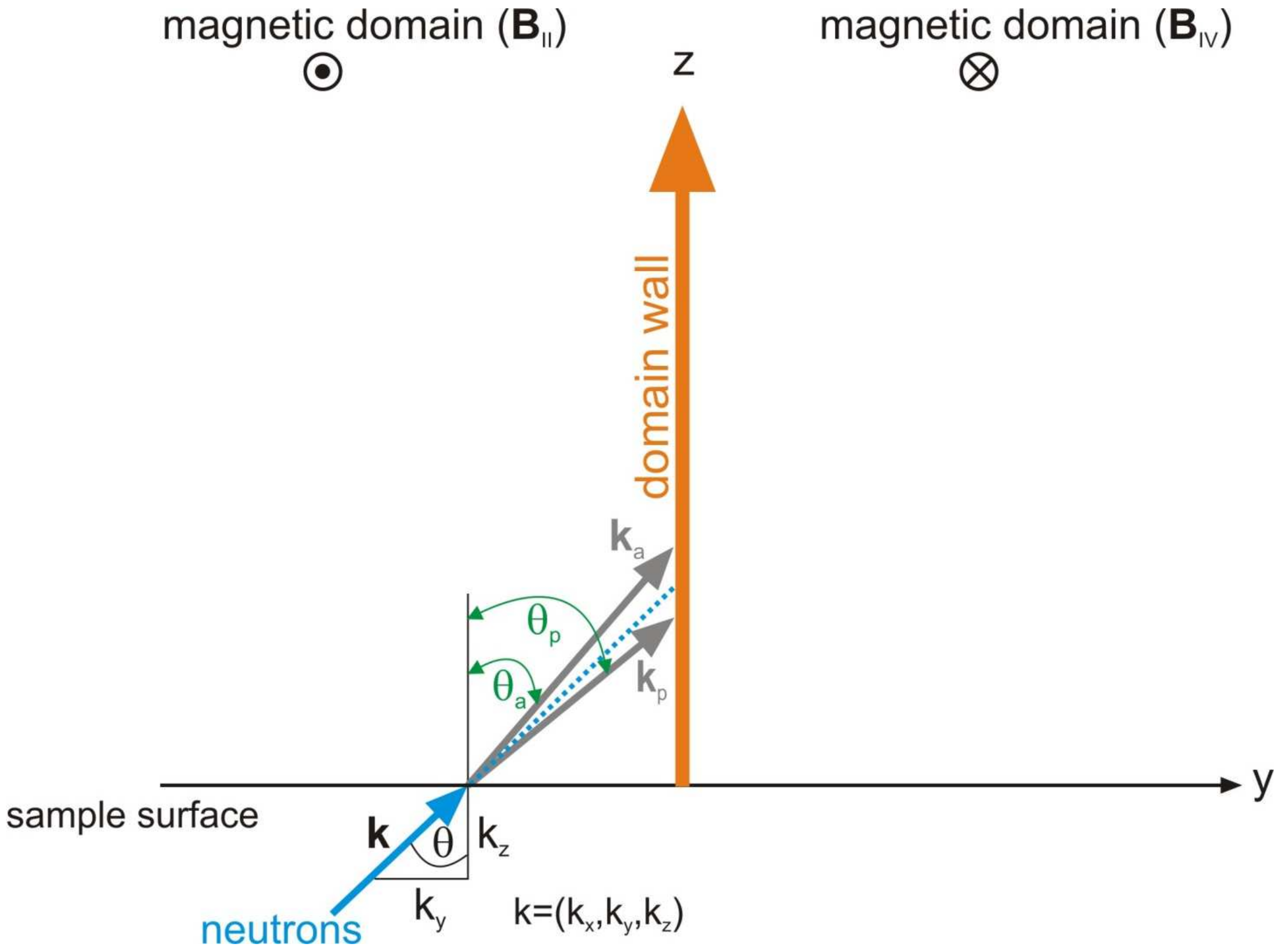
$$n = 1 - \delta_{mag} = 1 \pm \frac{2\boldsymbol{\mu}_N \cdot \boldsymbol{B} m \lambda^2}{h^2}$$



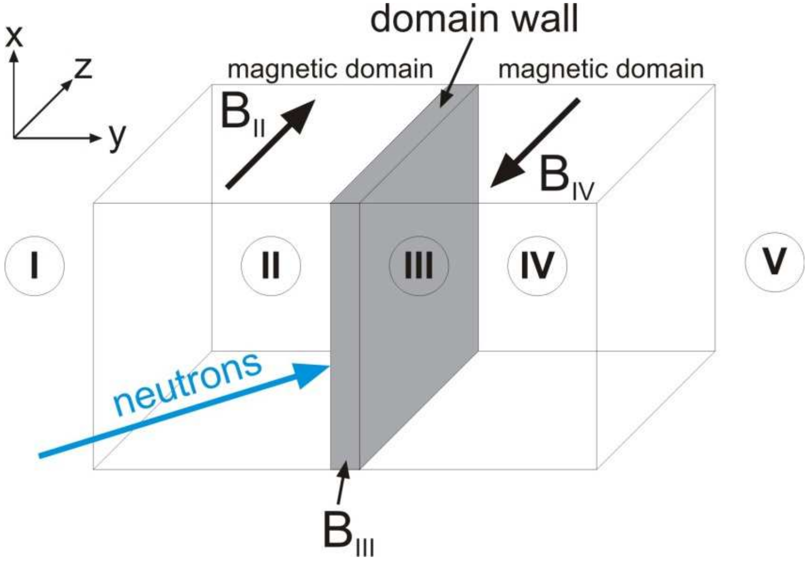
Refraction of unpolarized neutrons at domain walls



$$n = 1 - \delta_{mag} = 1 \pm \frac{2\boldsymbol{\mu}_N \cdot \boldsymbol{B} m \lambda^2}{h^2}$$



Refraction of unpolarized neutrons at domain walls



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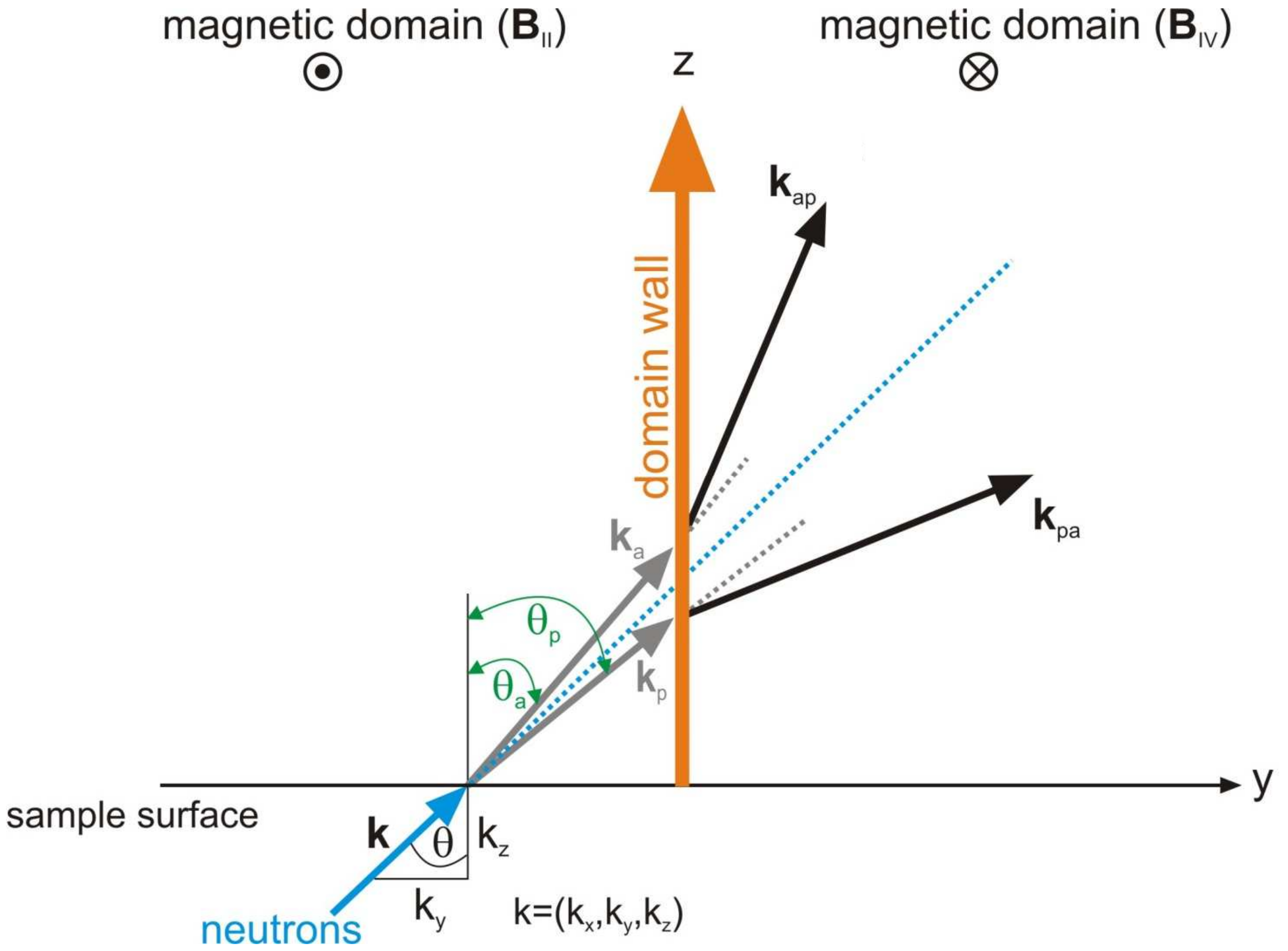
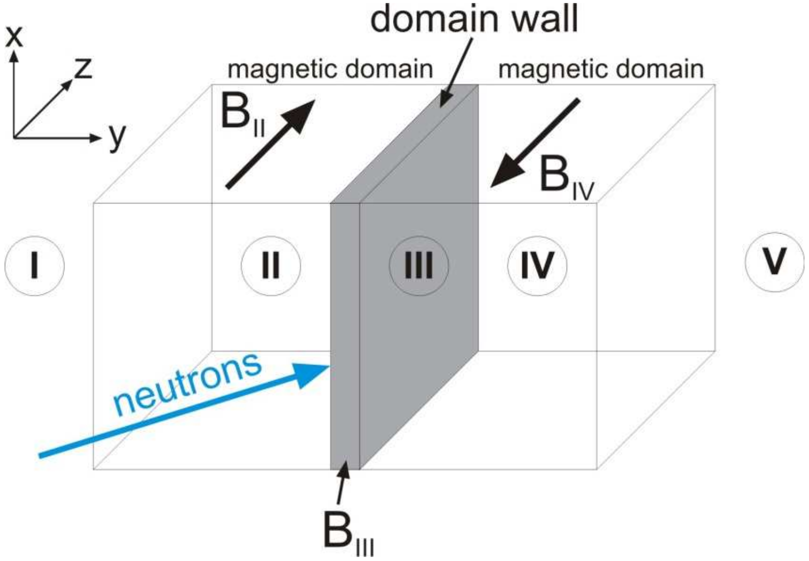
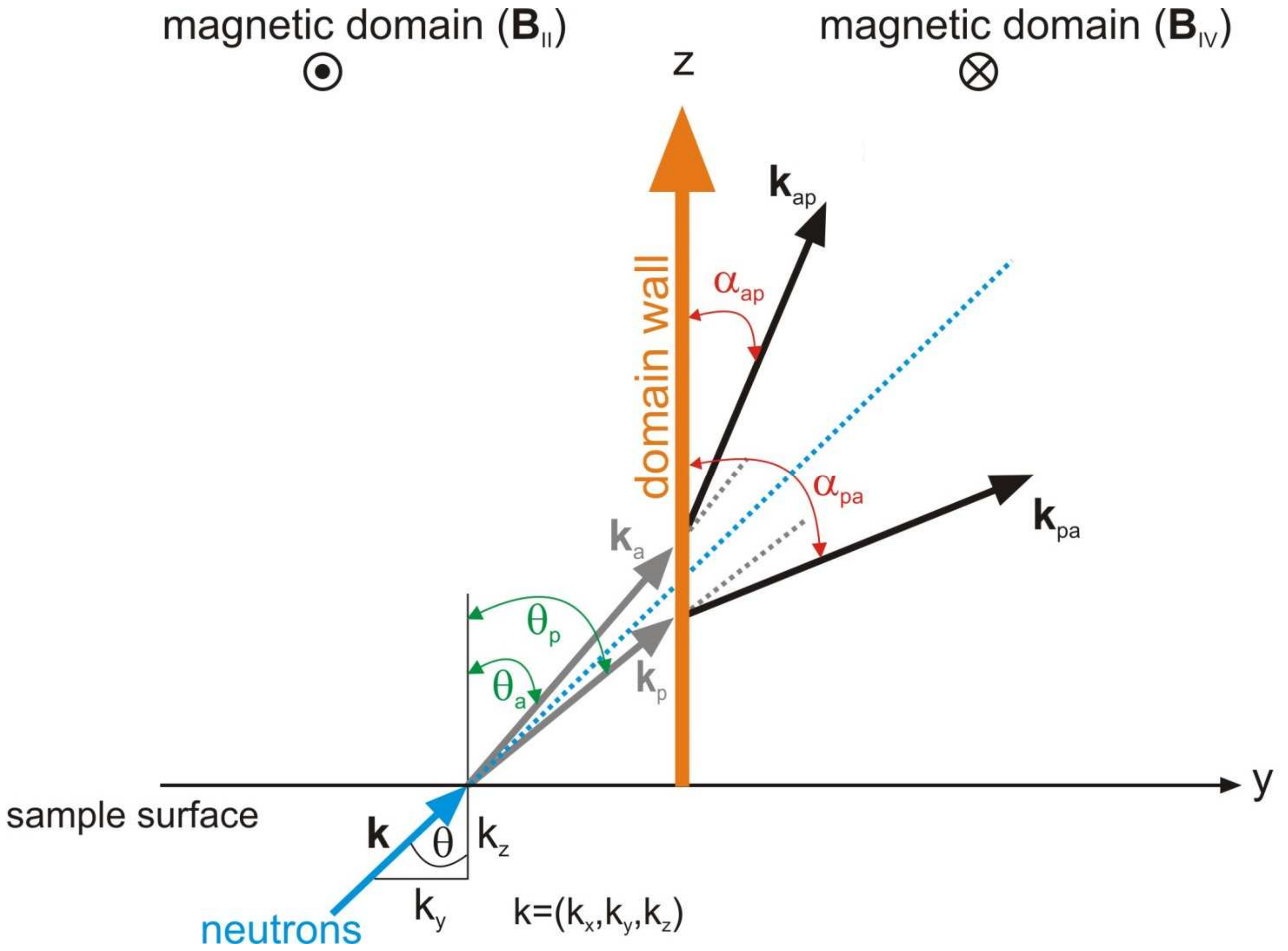


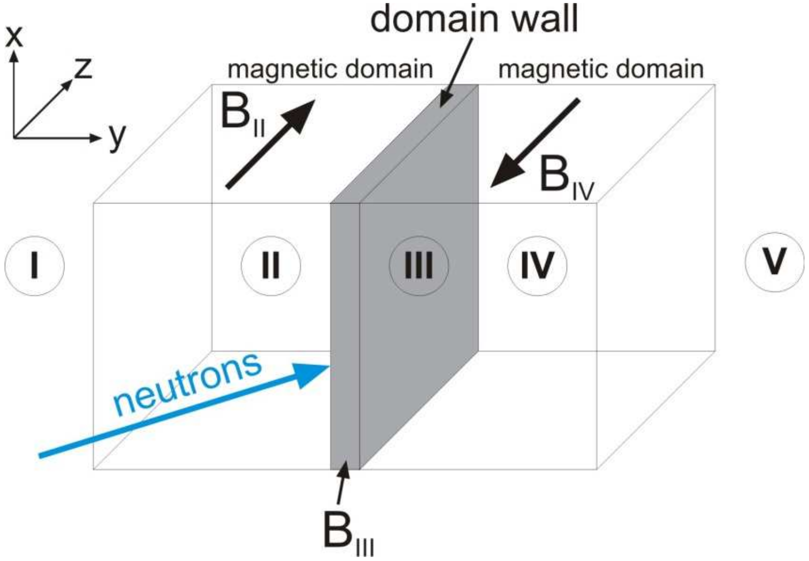
Refraction of unpolarized neutrons at domain walls



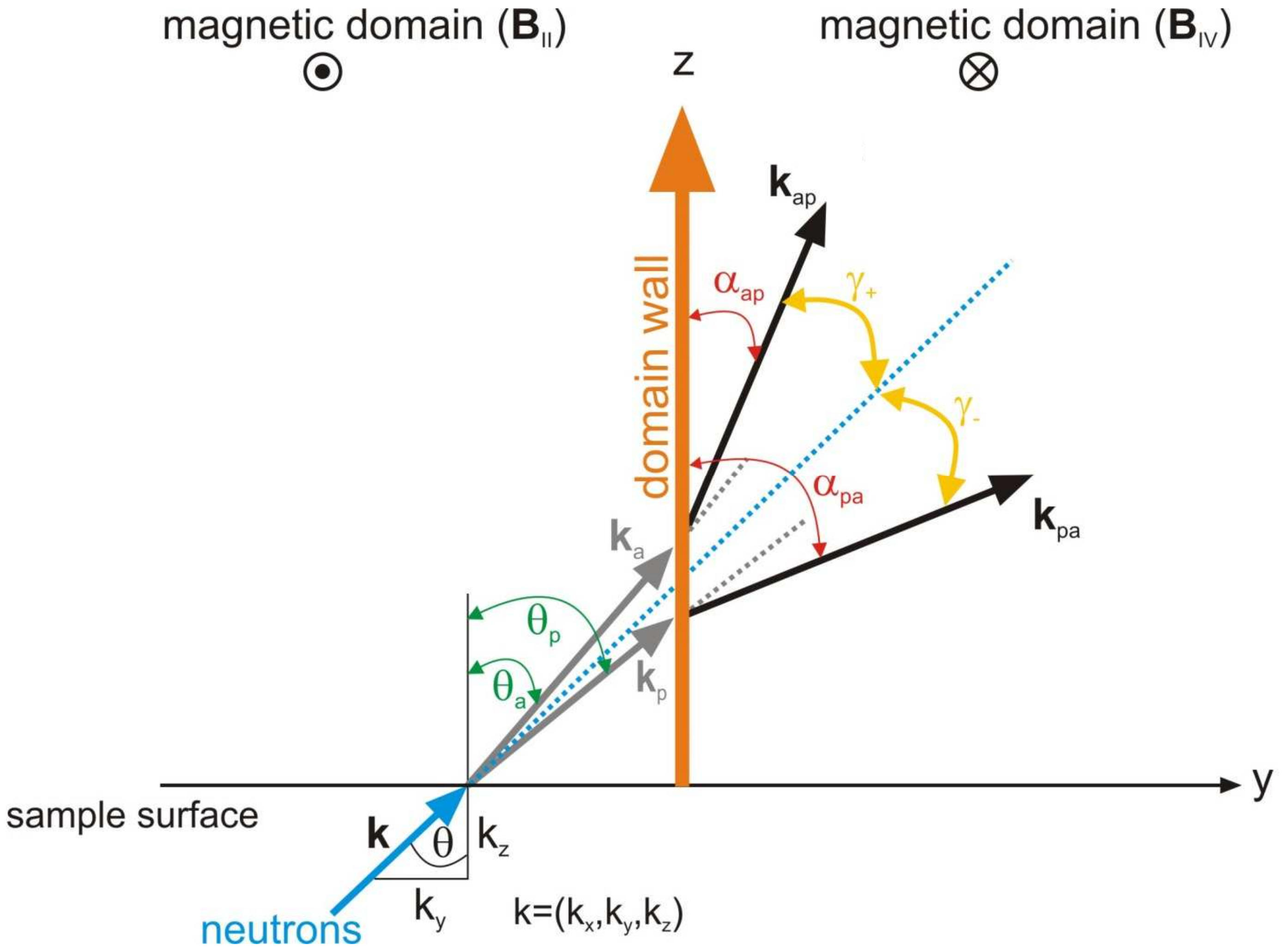
$$n = 1 - \delta_{mag} = 1 \pm \frac{2\boldsymbol{\mu}_N \cdot \boldsymbol{B} m \lambda^2}{h^2}$$



Refraction of unpolarized neutrons at domain walls



$$n = 1 - \delta_{mag} = 1 \pm \frac{2\mu_N \cdot B m \lambda^2}{h^2}$$



≈ mrad

Outline

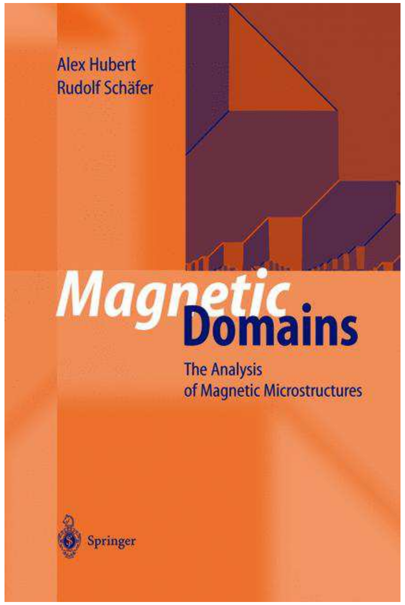
I) Classical Neutron Imaging
- Comparison of X-ray and neutron interaction with matter
- Length scales: Field of view and image resolution
- Exploring time and energy

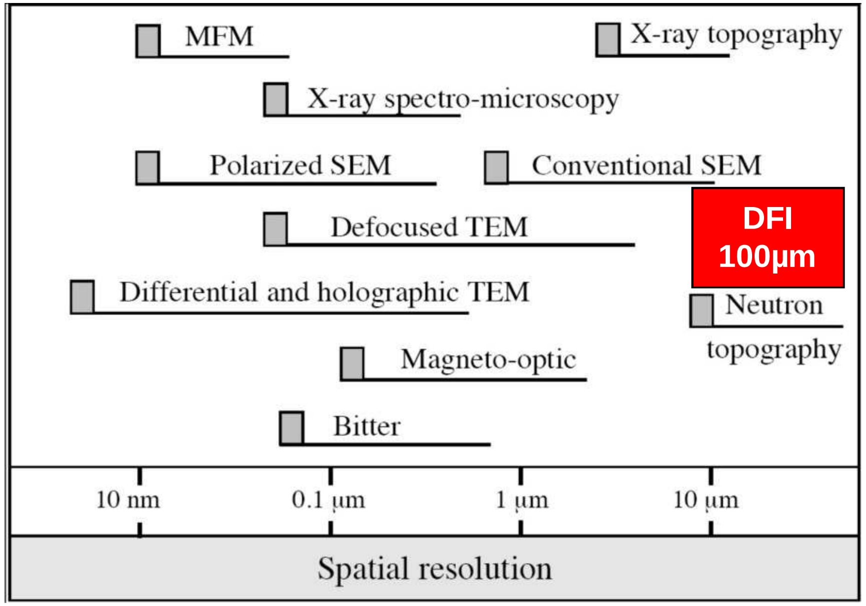
II) Neutron grating interferometry (nGI)
- The setup and working principle
- Refraction of unpolarized neutrons at magnetic domain walls
- Magnetic contrast: Dark-field image (DFI)

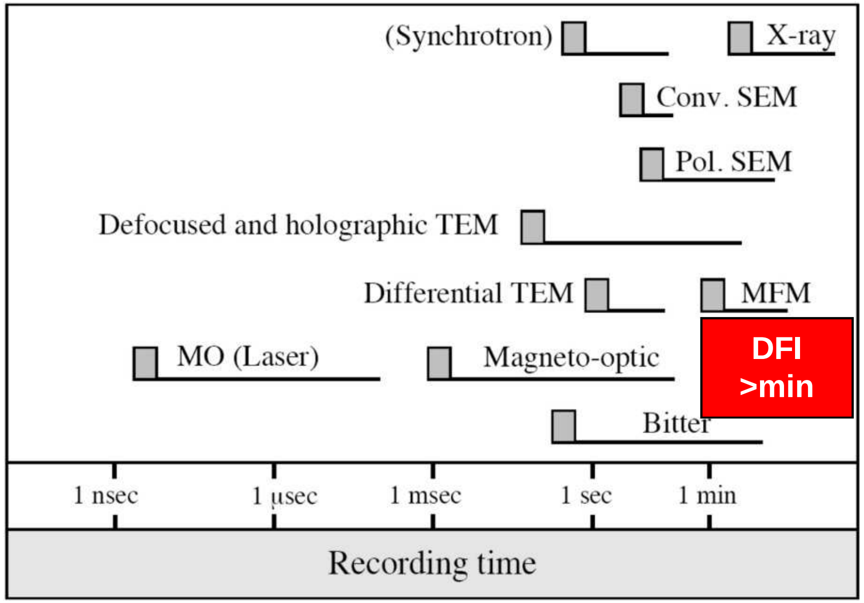
III) DFI results of imaging bulk ferromagnetic samples
- **Magnetic domain structures in 2D/3D**
- **Magnetic domain structures and “saving” energy**

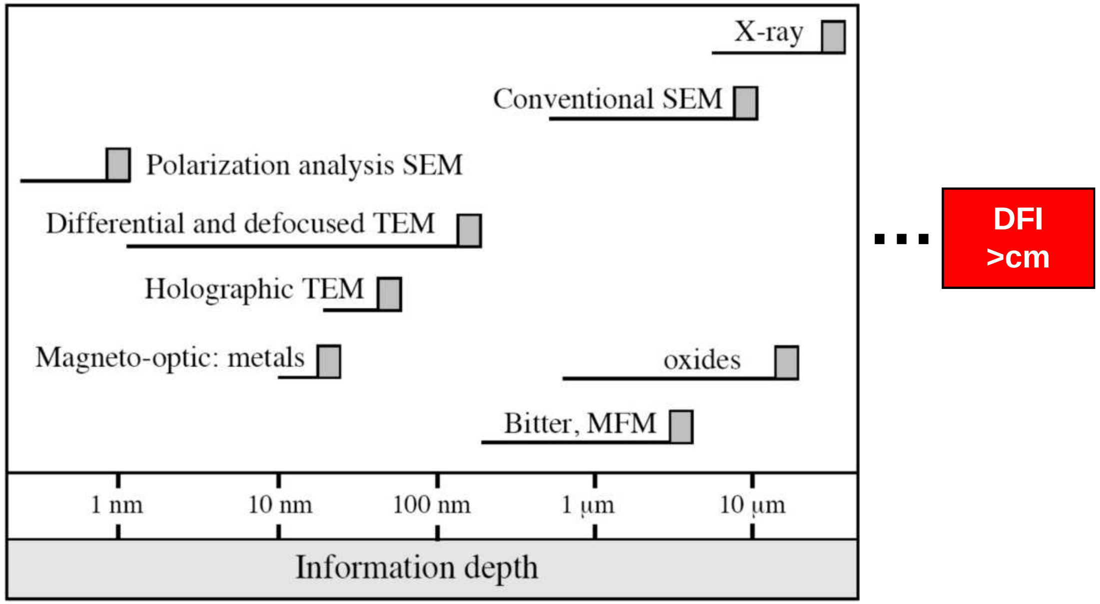
V) Summary

Existing observation techniques for magnetic structures



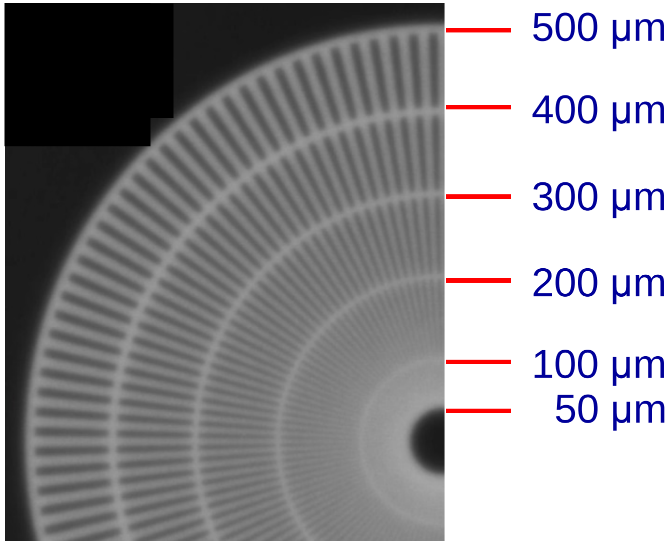


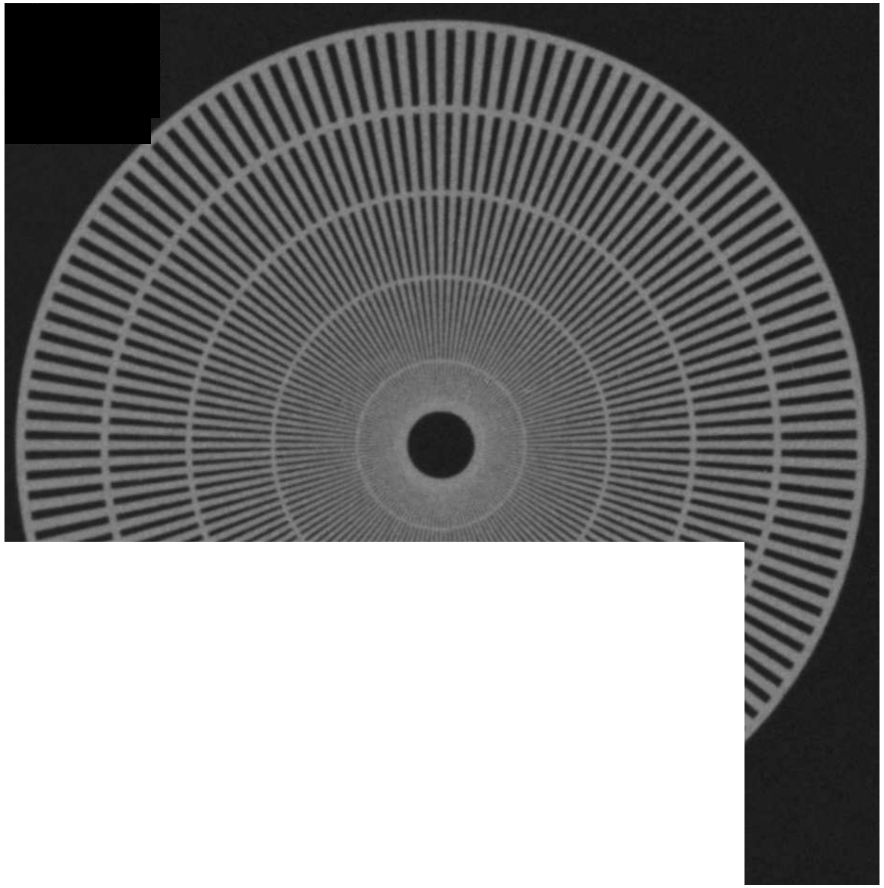




Magnetic domain structures: The resolution problem

300 µm thick	25 µm thick

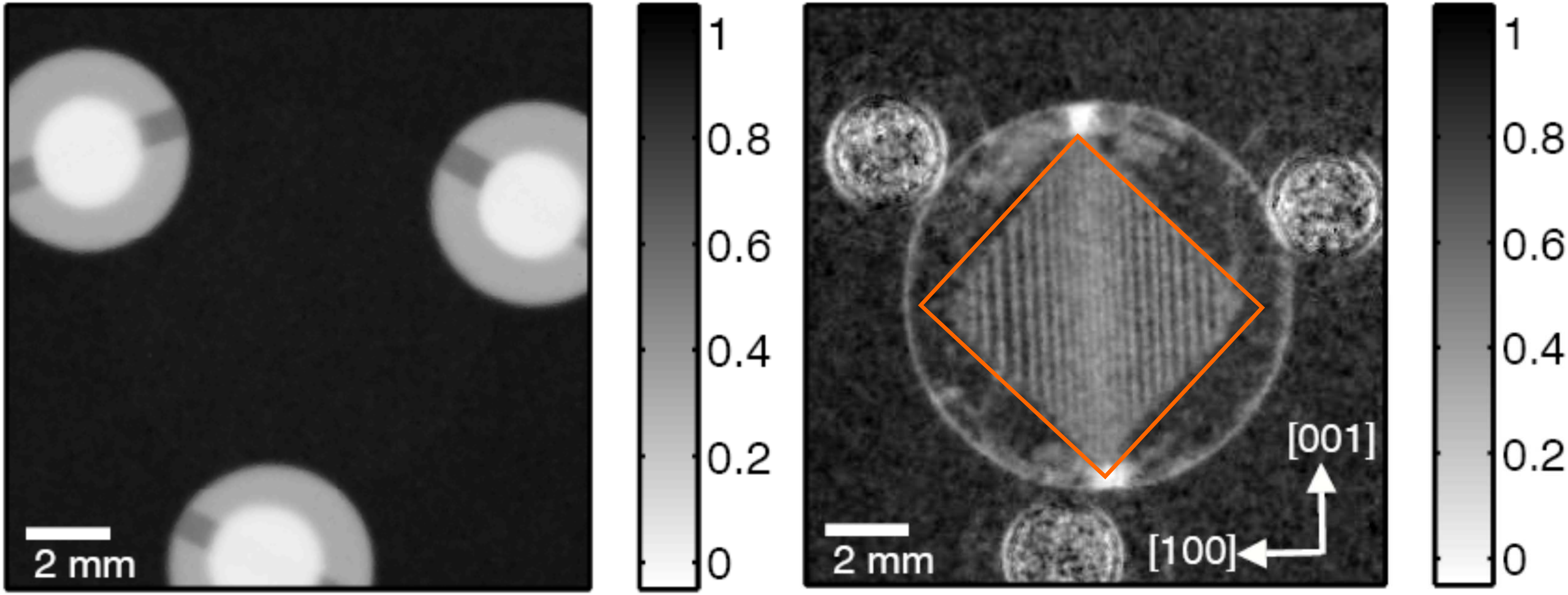




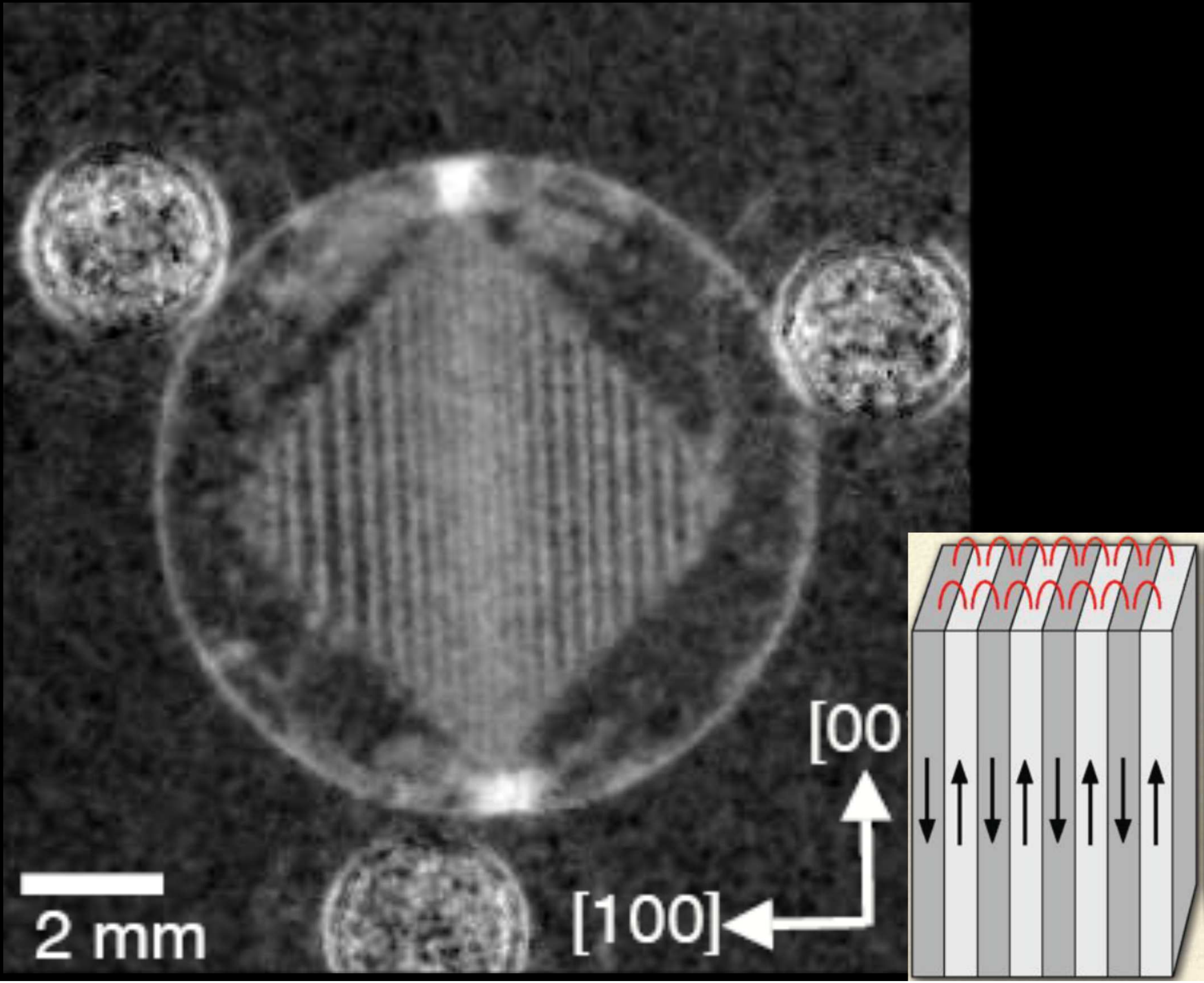
r systems.

Magnetic domain structures
<110> FeSi(3%), 300 µm thick

transmission **DFI**

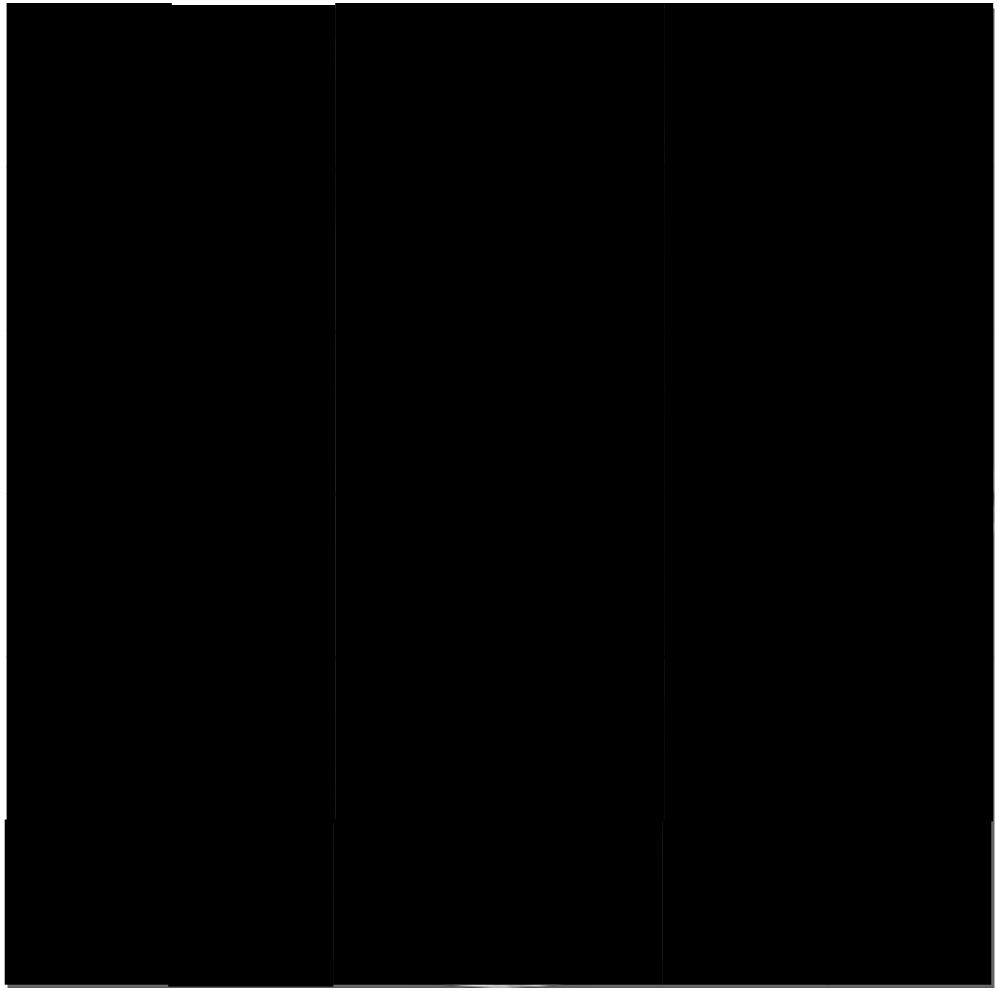


C. Grünzweig, C. David, O. Bunk, M. Dierolf, G. Frei, G. Kühne, R. Schäfer, S. Pofahl, H. Rønnow, and F. Pfeiffer.
Bulk magnetic domain structures visualized by neutron dark-field imaging.
Appl. Phys. Lett. **93**, 112504 (2008).

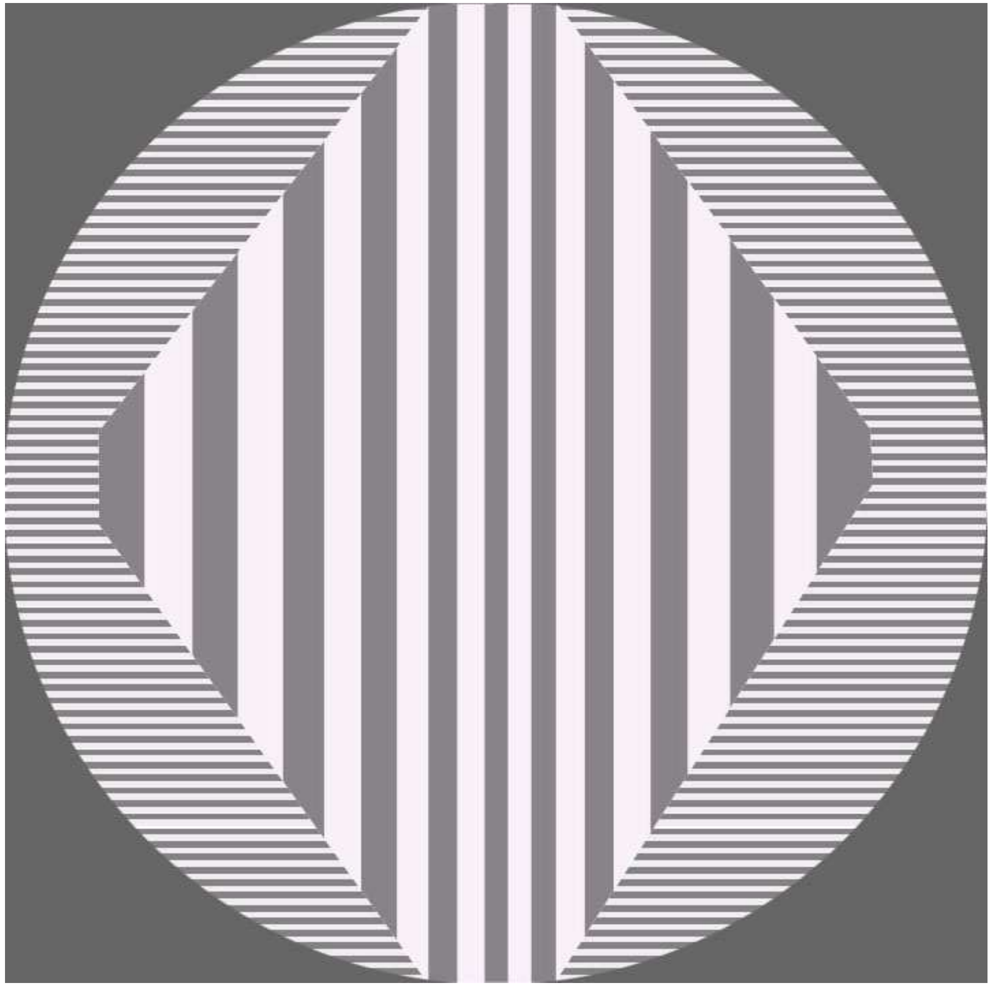

2 mm
[100]
[00

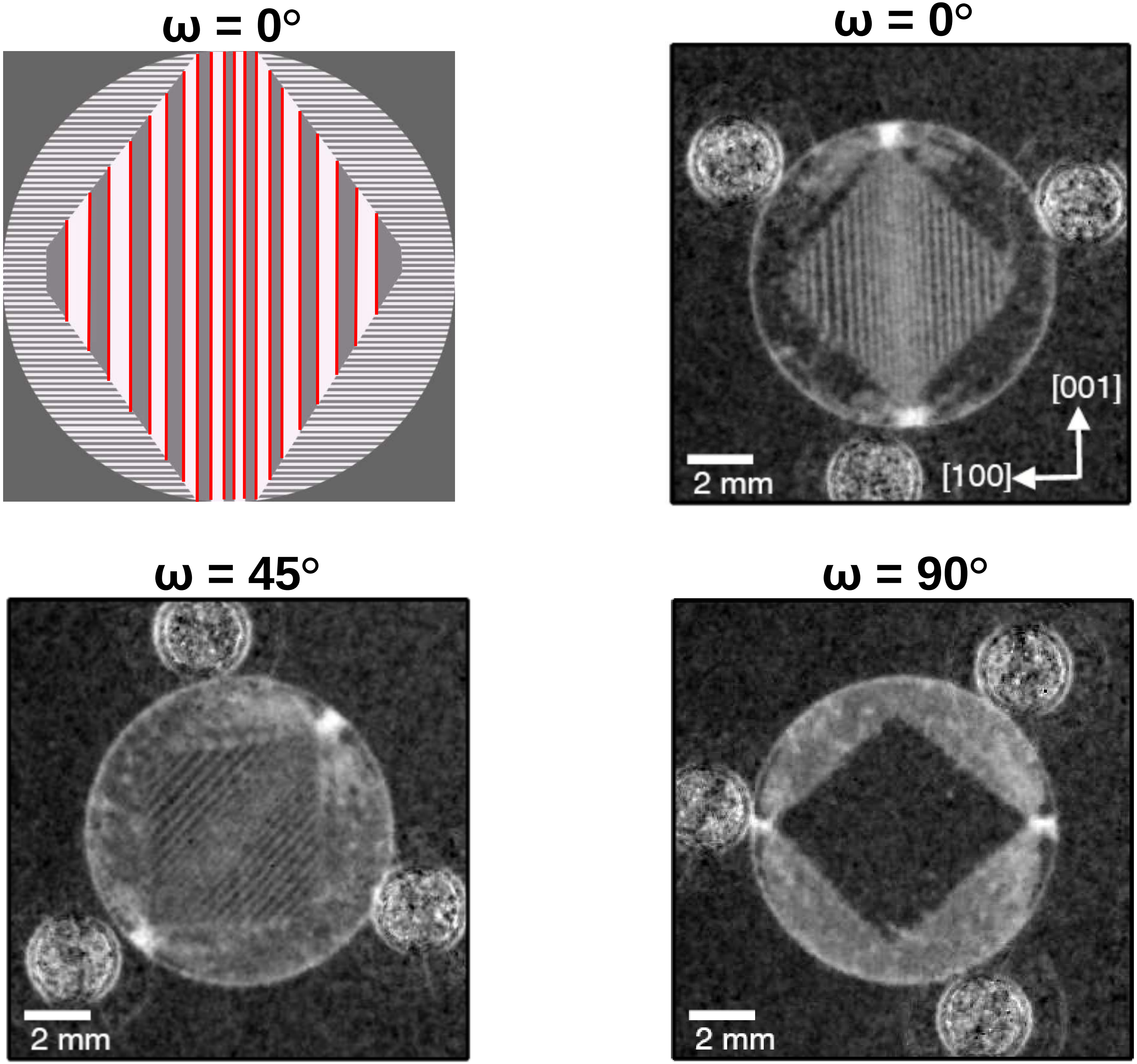
MOKE measurements: Verification of the DFI

MOKE

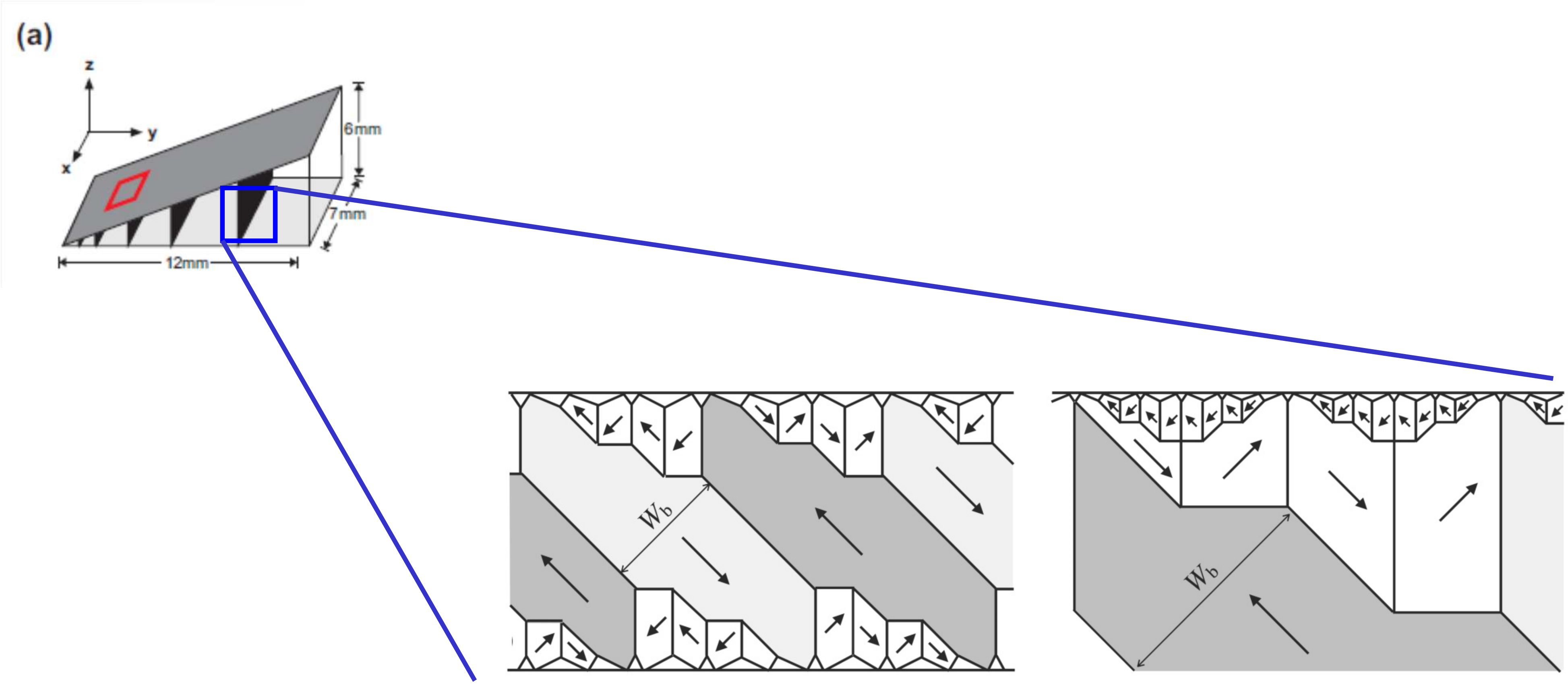


schematical map



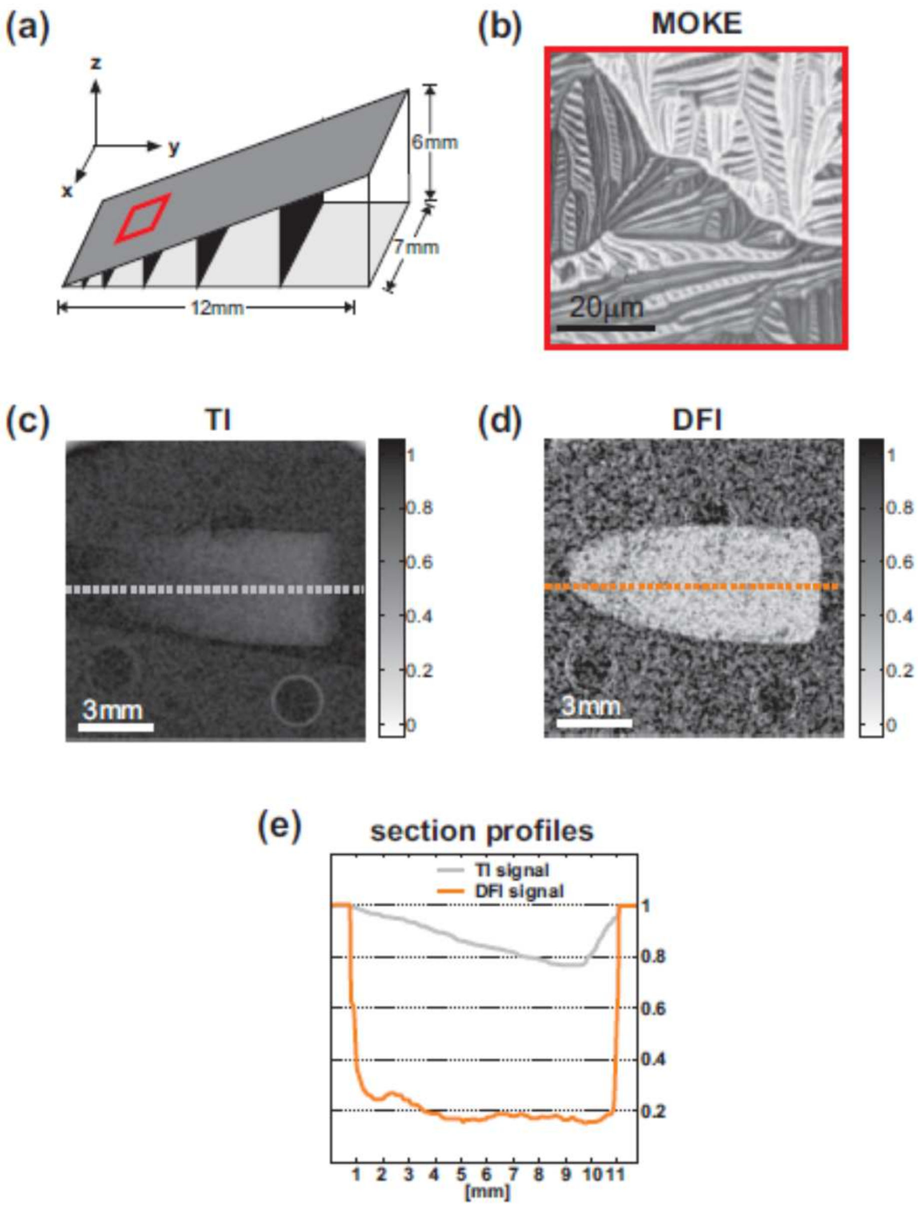

ω = 0°
ω = 0°
[001]
[100]
2 mm
ω = 45°
2 mm
ω = 90°
2 mm

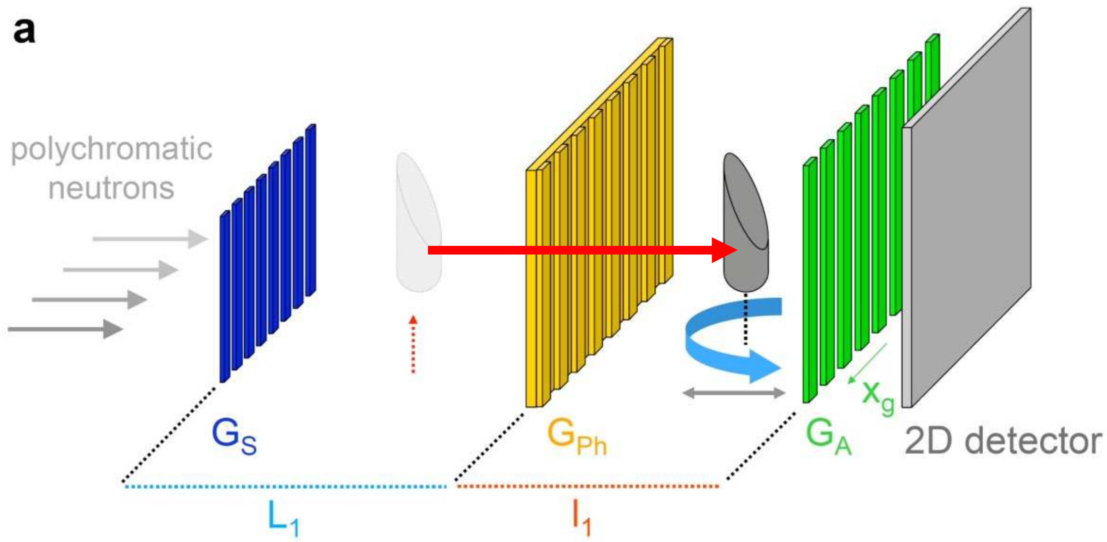
Tomography of magnetic domains

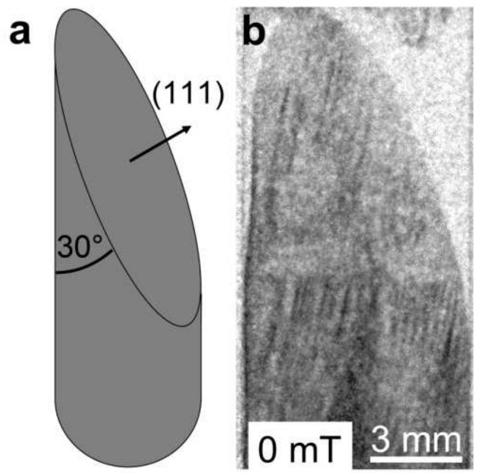


theory predicts: $$W_b \approx \sqrt{D}$$

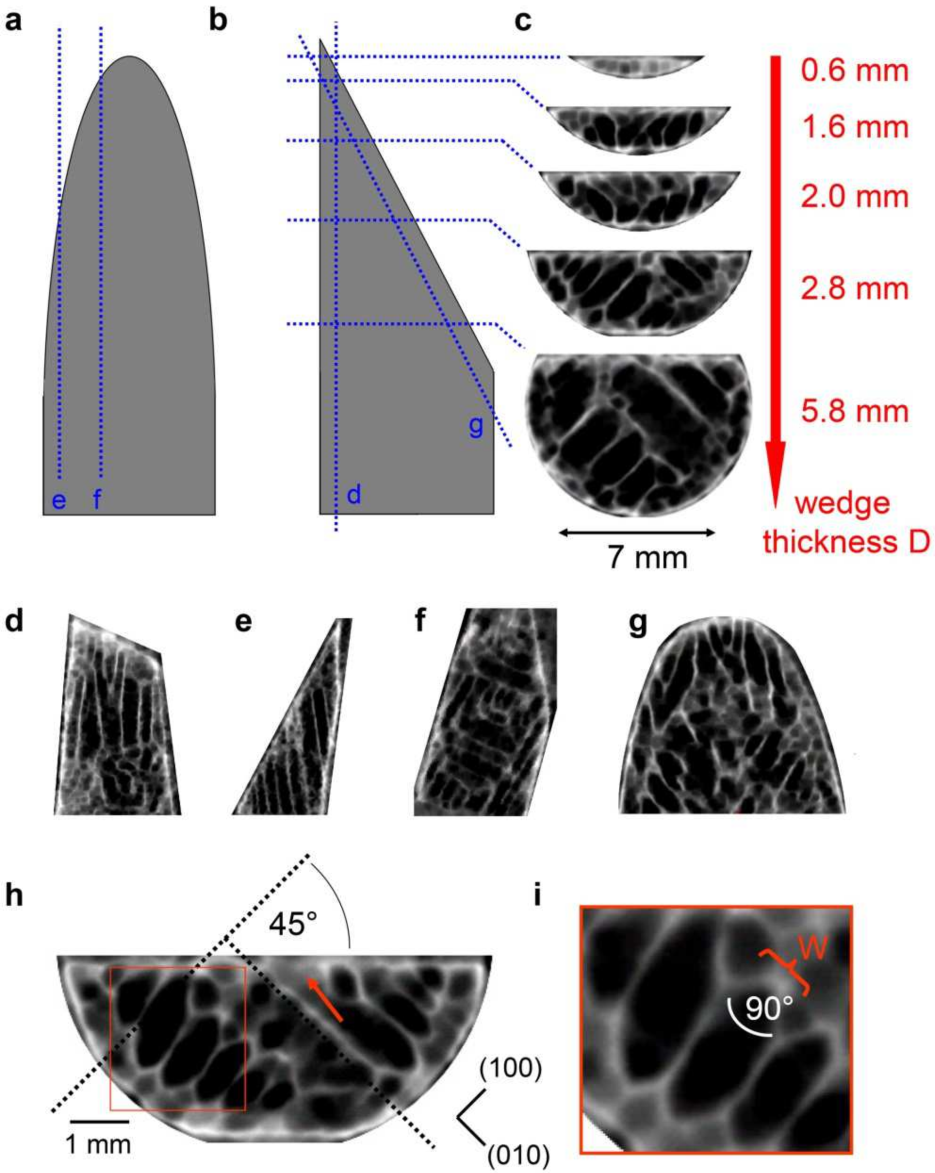
Tomography of magnetic domains

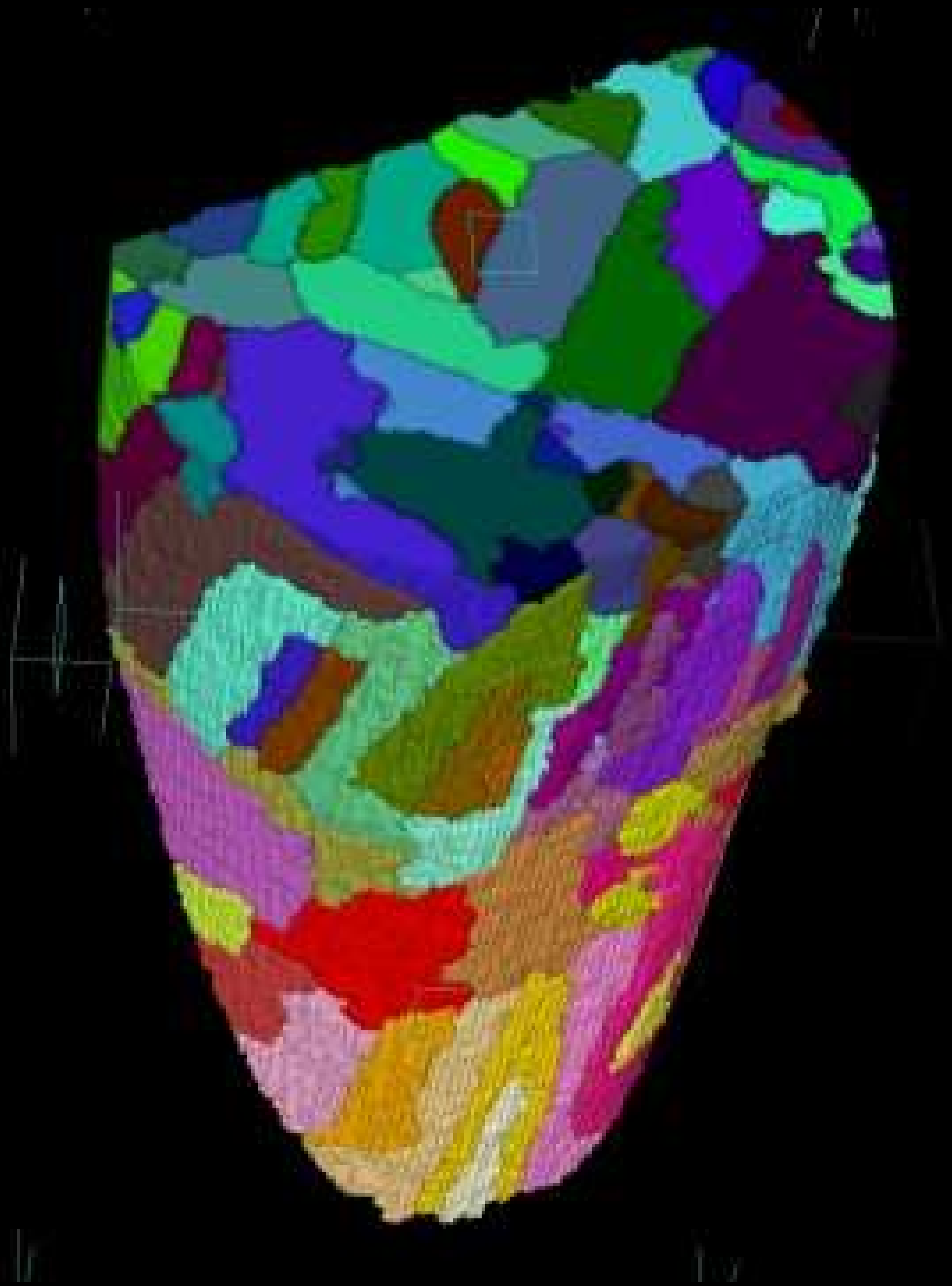


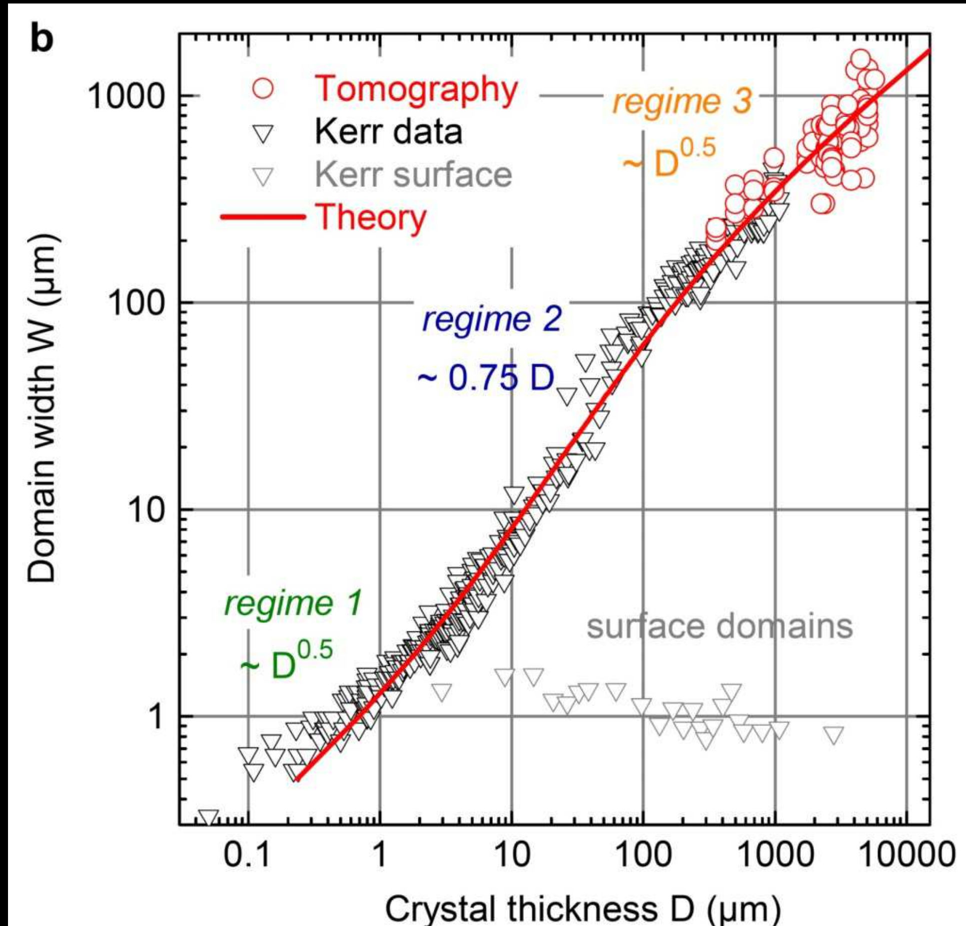




Tomography of magnetic domains





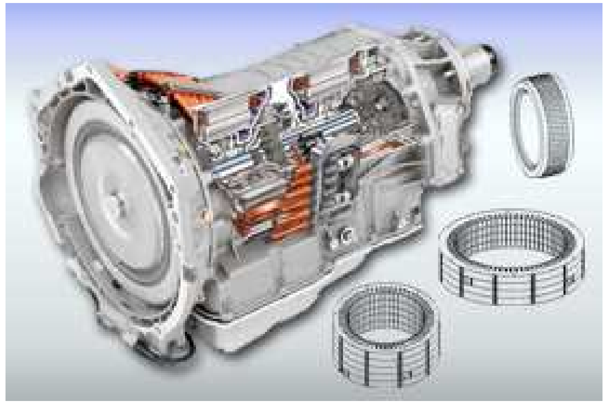


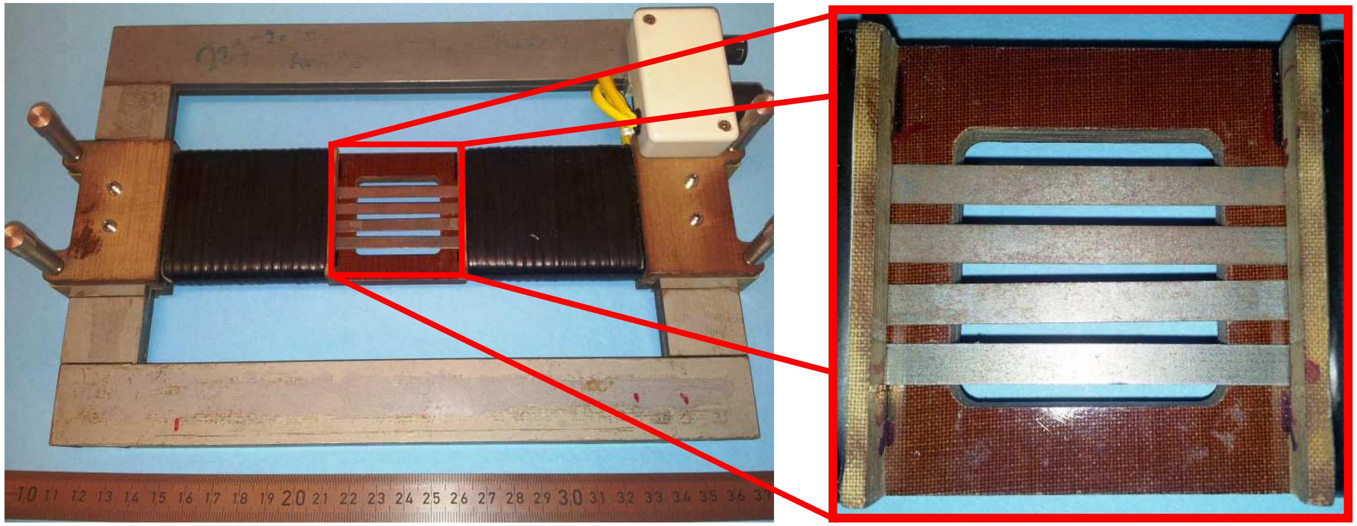
I. Manke, N. Kardjilov, R. Schäfer, A. Hilger, M. Strobl, M. Dawson,
C. Grünzweig, G. Behr, M. Hentschel, C. David, A. Kupsch, A. Lange, J. Banhart.
Three-dimensional imaging of magnetic domains.
Nature Communications 1 (8), p.125 (2010).

DFI helps to "save" energy

Deterioration effects in NO steel laminations

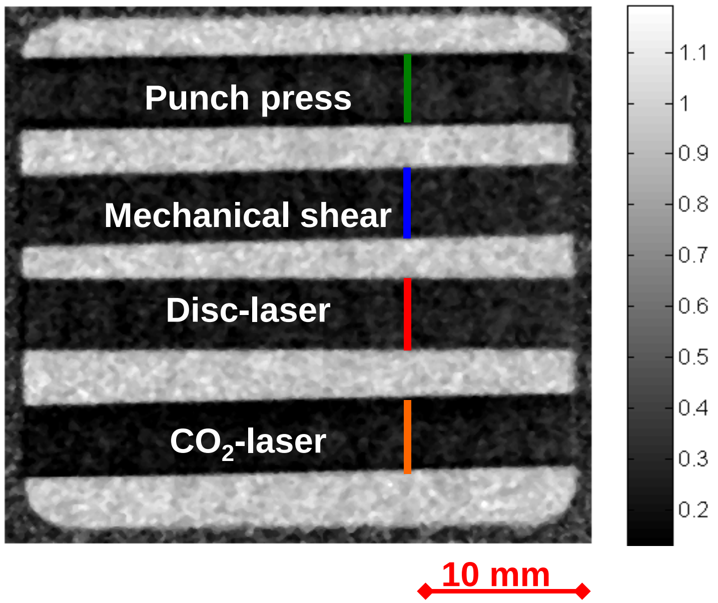
and used e.g. in electrical motors/generators

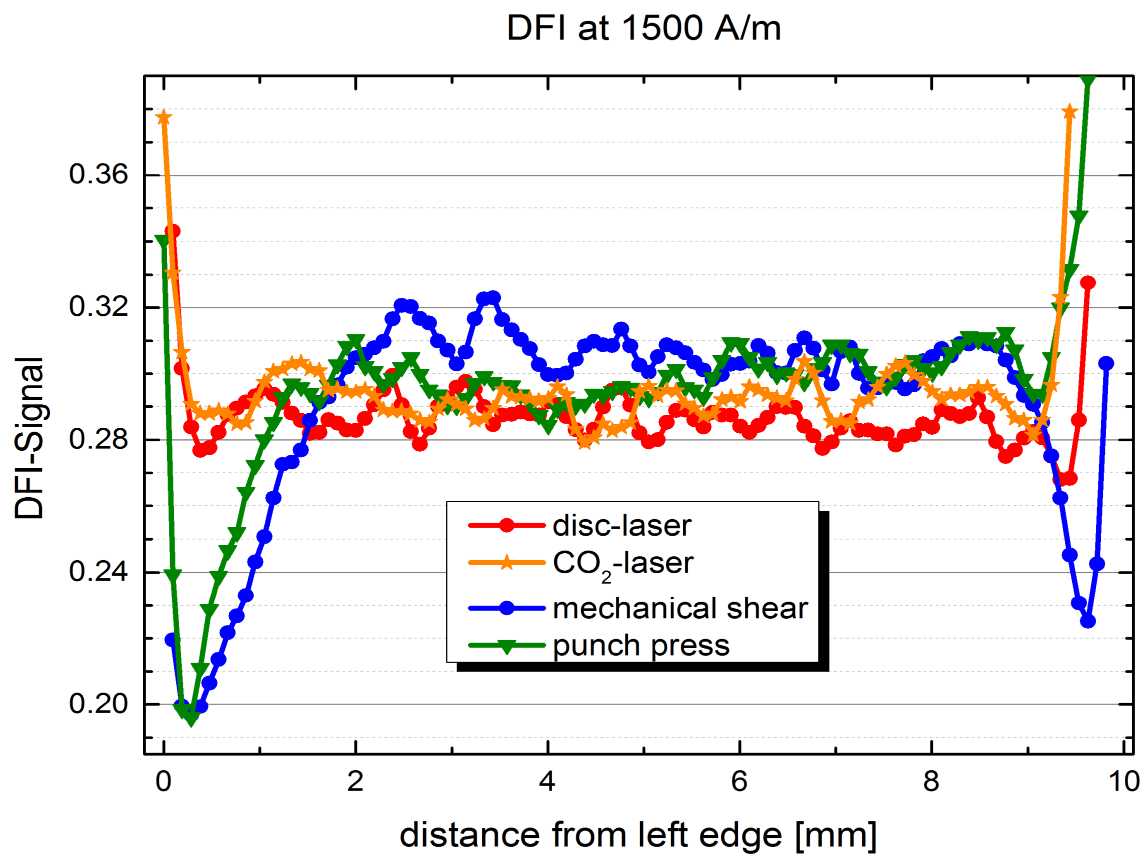




Deterioration effects in NO steel laminations

DFI at 1500 A/m





4 different types of cutting:

- **punch press (one side)**
- **mechanical shear**
- **Disc-laser**
- **CO_2-laser**

Due to the cutting process,
magnetic properties are influenced !

-> Increasing the efficiency of electical maschines

Outline

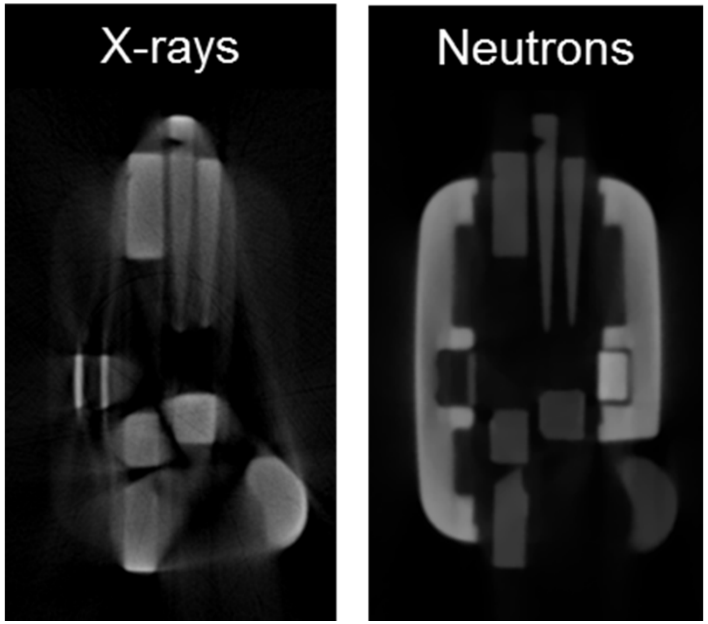
I) Classical Neutron Imaging
- Comparison of X-ray and neutron interaction with matter
- Length scales: Field of view and image resolution
- Exploring time and energy

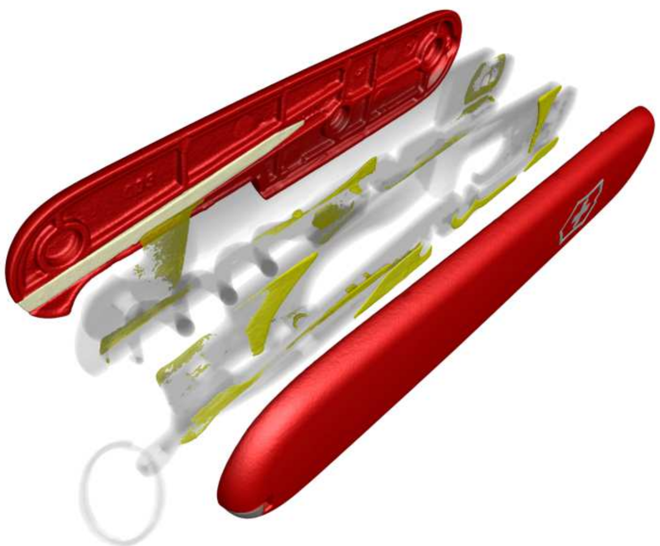
II) Neutron grating interferometry (nGI)
- The setup and working principle
- Refraction of unpolarized neutrons at magnetic domain walls
- Magnetic contrast: Dark-field image (DFI)

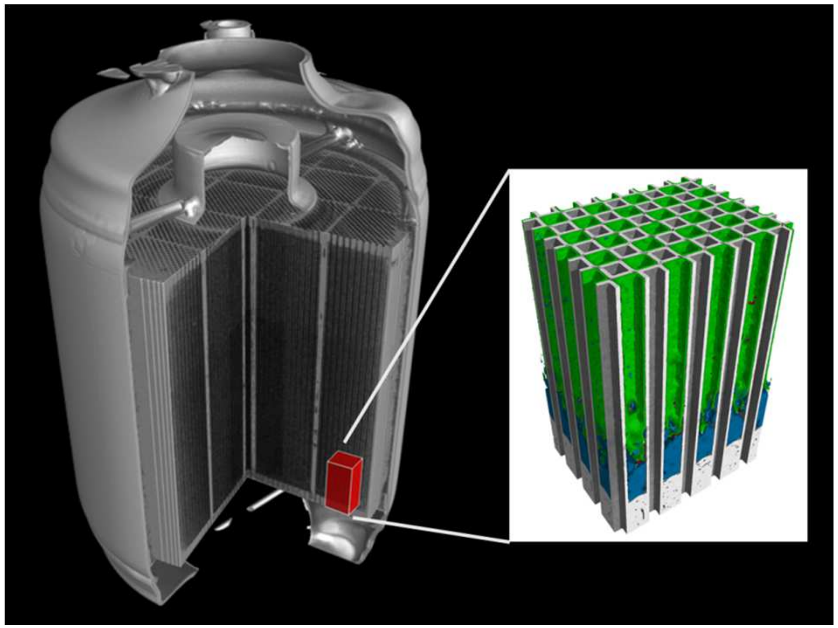
III) DFI results of imaging bulk ferromagnetic samples
- Magnetic domain structures in 2D/3D
- Magnetic domain structures and “saving” energy

V) Summary

Summary I: classical neutron imaging

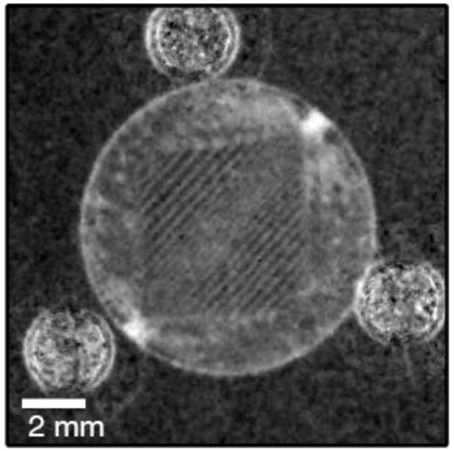


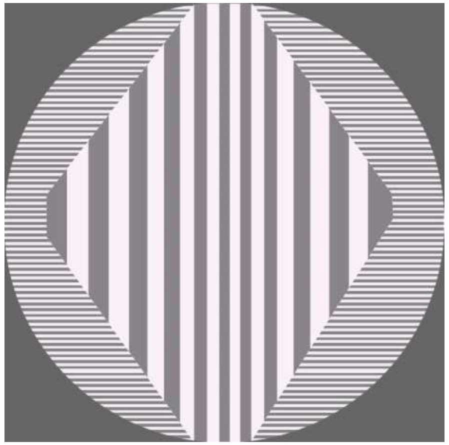


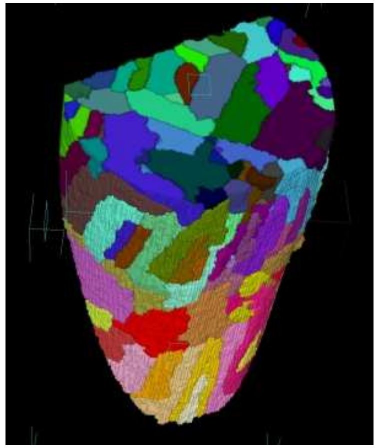


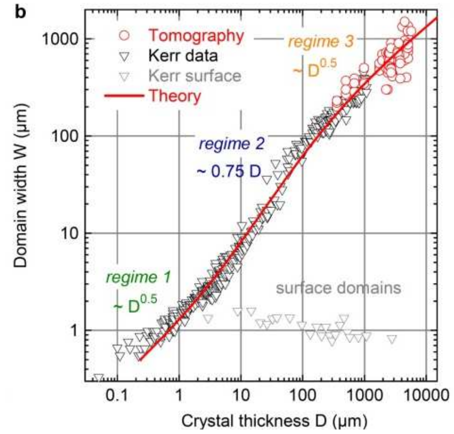
Summary II: neutron grating interferometry

Imaging bulk magnetic domain structures

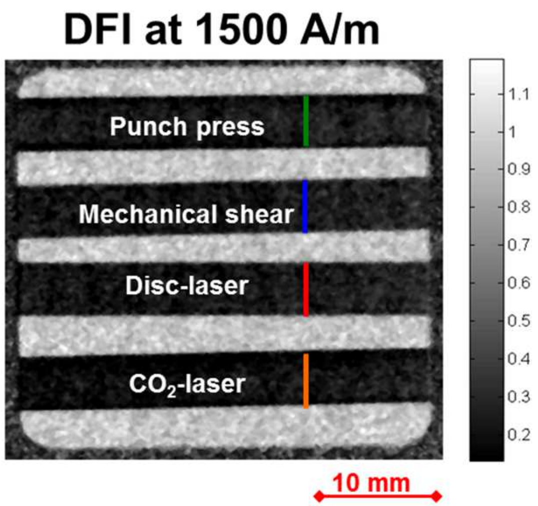


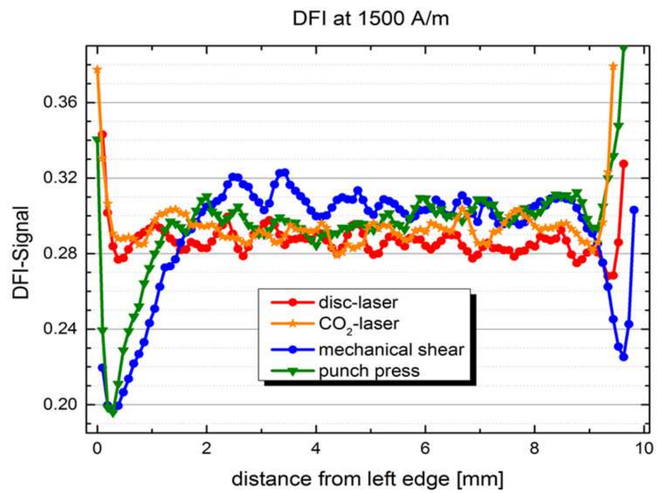






Improving electrical machines





Announcement: open PhD position

PAUL SCHERRER INSTITUT

The Paul Scherrer Institute, PSI, is with 1500 employees the largest research centre for natural and engineering sciences within Switzerland. We perform world-class research in three main subject areas: Matter and Material; Energy and the Environment; and Human Health. By conducting fundamental and applied research, we work on long-term solutions for major challenges facing society, industry and science.

The Laboratory for Neutron Scattering and Imaging (LNS) at the Paul Scherrer Institute operates the neutron scattering and imaging instruments at the Swiss Spallation Neutron Source SINQ. The members of the LNS conduct a strong in-house research program with special emphases on strongly correlated electron systems, magnetism, superconductivity, material science and soft condensed matter.

For the Neutron Imaging and Activation Group (NIAG) at the LNS we are looking for a

PhD Student

in Neutron Grating Interferometry

Research Project on superconducting domains and porous media

Neutron grating interferometry (nGI) was developed over the past years at PSI and is now an important neutron imaging technique. Especially the dark-field image (DFI) provides spatially resolved 2D scattering information with correlation lengths ranging from the nm to the µm scale. The DFI is therefore an excellent experimental tool delivering real-space insights into bulk magnetic and superconducting domain structures.

The goal of the PhD project is to extend the DFI towards a *quantitative* 2D scattering technique for the study of superconducting domains and porous media. You will perform nGI experiments at SINQ and at other institutes in Europe, and develop high-precision experimental equipment. You will use cryo-magnetic and pressure sample environment and learn how to analyse complex imaging data.

Your tasks

- Adapting the grating interferometer setup for quantitative DFI
- Study and quantify the coherence lengths in superconducting domain systems
- Quantification of porosities in porous media

Announcement: open Master project

STARTSEITE
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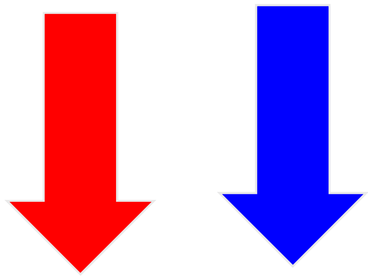
Positions for Master's theses

Investigation of domain systems in type-II superconductors by neutron dark-field imaging

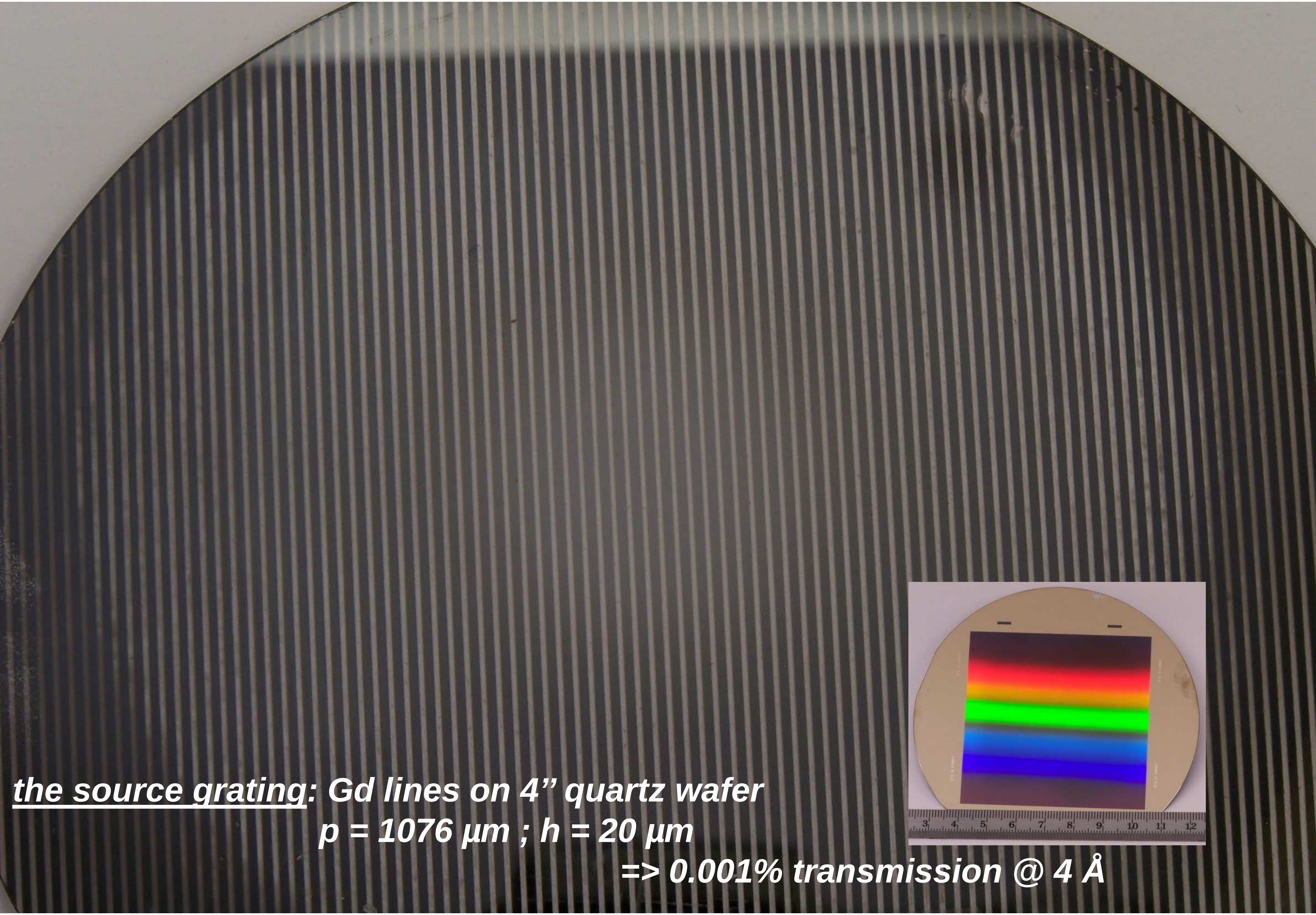
The neutron grating interferometer (nGI) technique developed over the past years at PSI gained rapidly in interest in the neutron imaging and scattering community. In particular the dark-field image (DFI) contrast providing spatially 2D resolved scattering images with correlation lengths ranging from the nm to the µm regime. The DFI moved into the focus of current ongoing research activities delivering so far insight into bulk magnetic and superconducting domain structures. For your project you will perform nGI experiments at PSI and at other institutes in Europe. You will learn to work with grating interferometer setups and performing experiments using cryo-magnetic sample environments. This master project can be continued with a follow-up PhD work.

Contact Persons:
Dr. Christian Grünzweig (christian.gruenzweig@psi.ch), 056 310 4662
Prof. Dr. Christian Rüegg (christian.rueegg@psi.ch), 056 310 4778

Thank your for the attention !



http://www.psi.ch/niag/


the source grating: Gd lines on 4” quartz wafer
p = 1076 µm ; h = 20 µm
=> 0.001% transmission @ 4 Å