

13th PSI Summer School 2014, Zug
Exploring time, energy and length scales in condensed matter

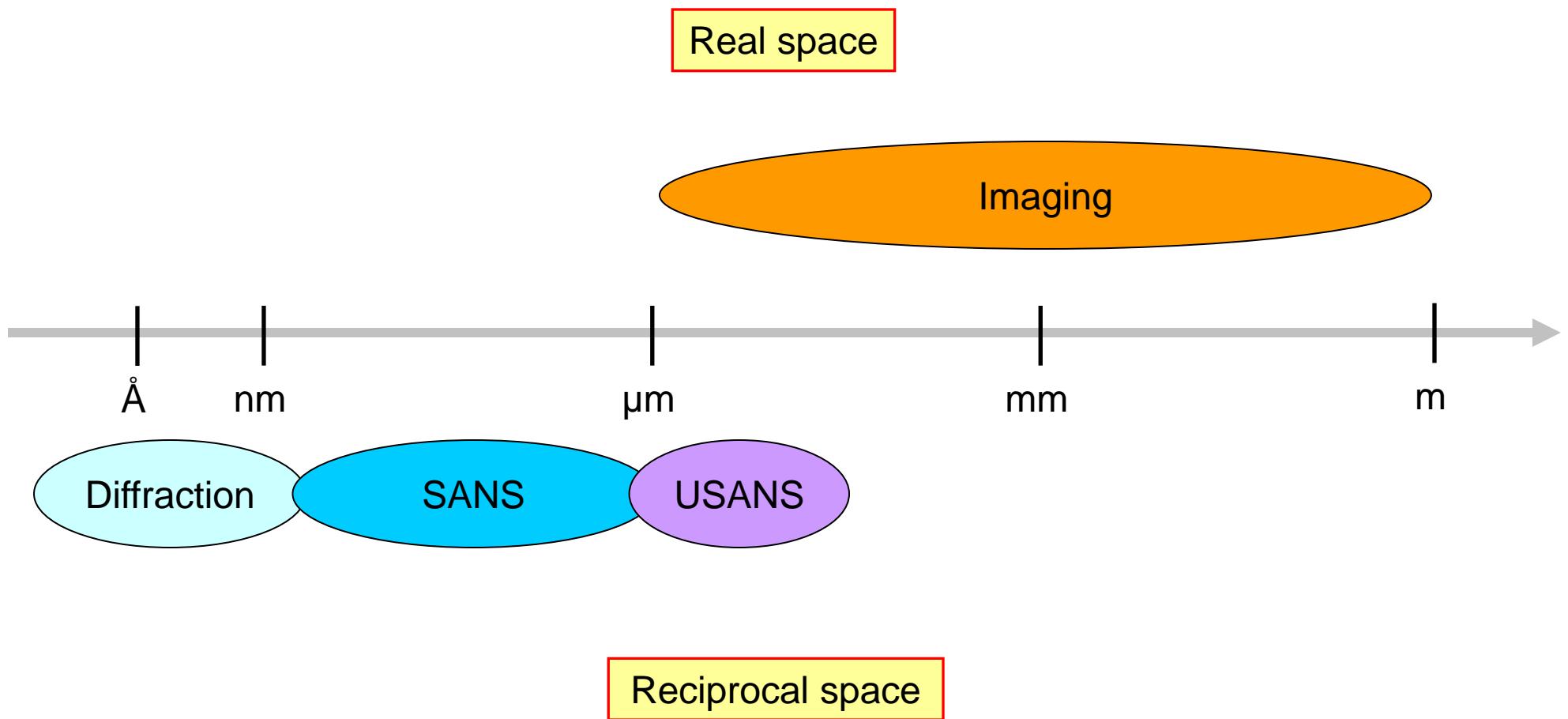


Wir schaffen Wissen – heute für morgen

Christian Grünzweig, et al. (NIAG team)
Paul Scherrer Institut

**How NEUTRON IMAGING explores
time, energy and length scales
in condensed matter**

Length scales and „neutron“ techniques



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)

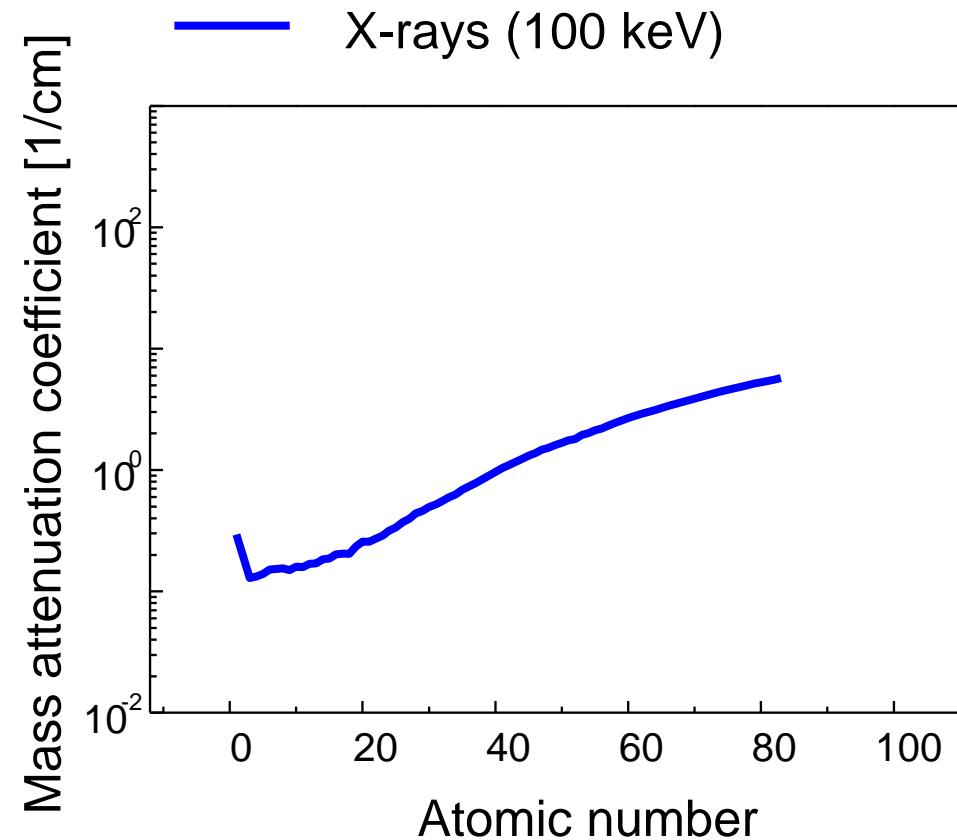
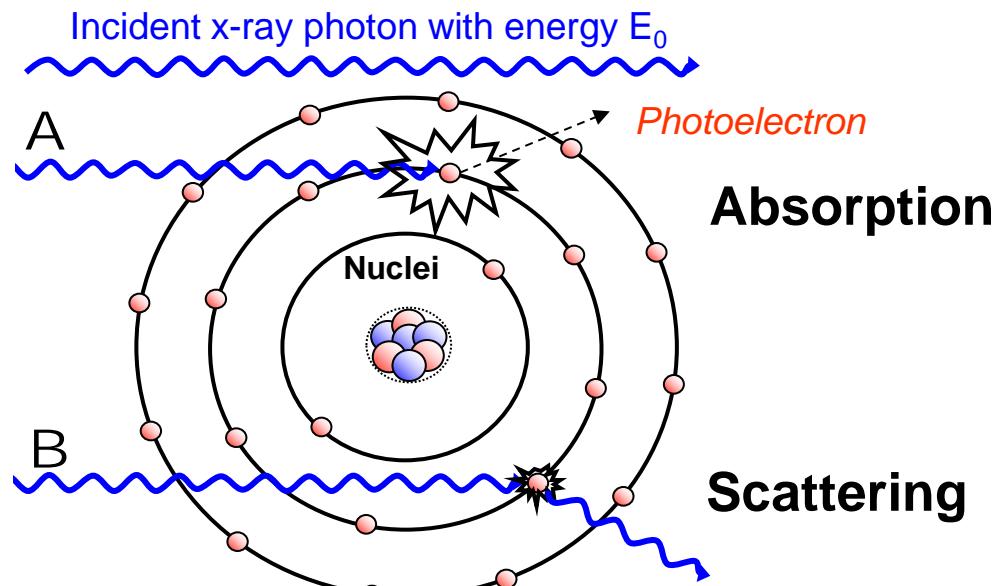
III) DFI results of imaging bulk ferromagnetic samples

- Magnetic domain structures in 2D/3D
- Magnetic domain structures and “saving” energy

V) Summary

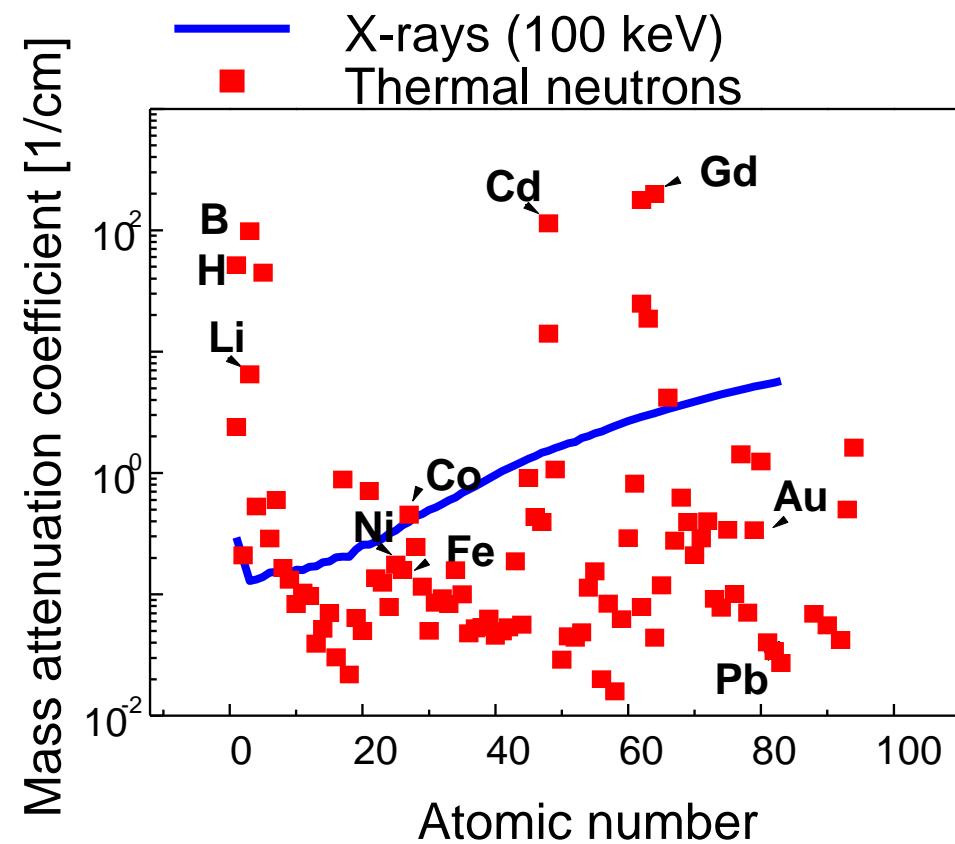
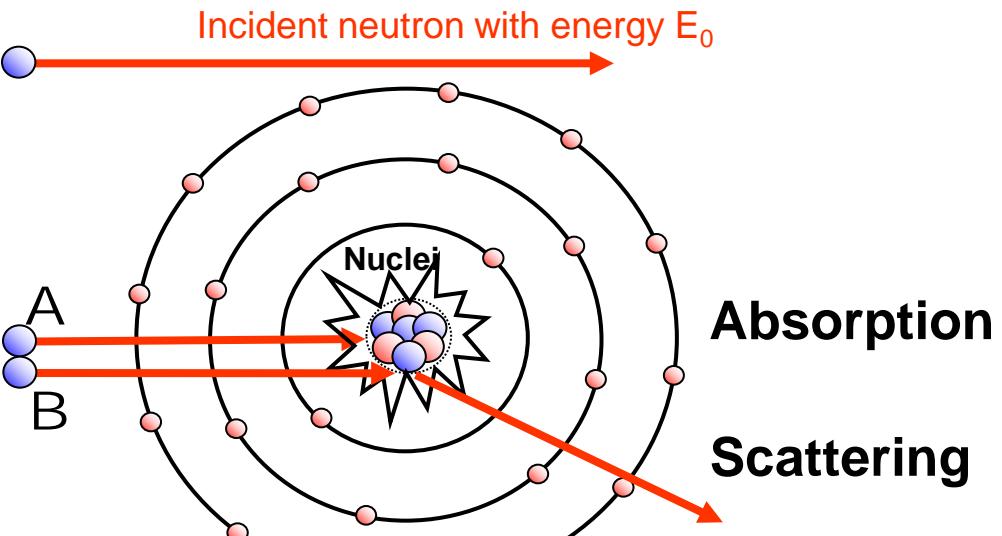
X-rays vs. neutrons

X-Rays



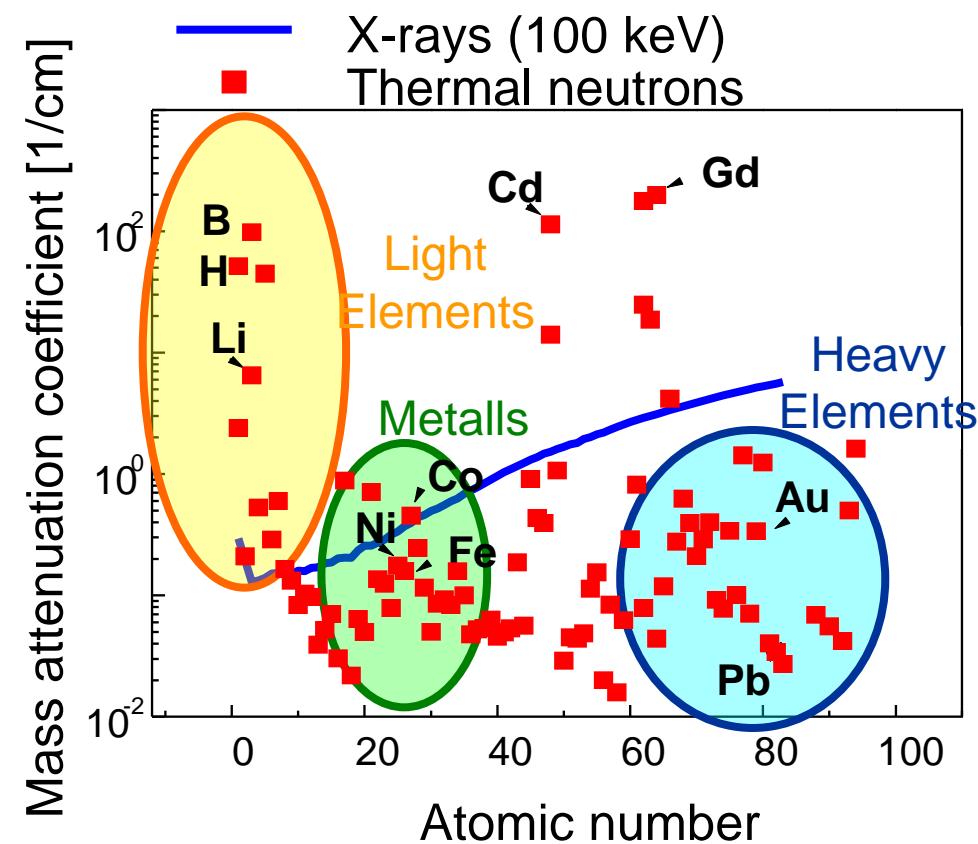
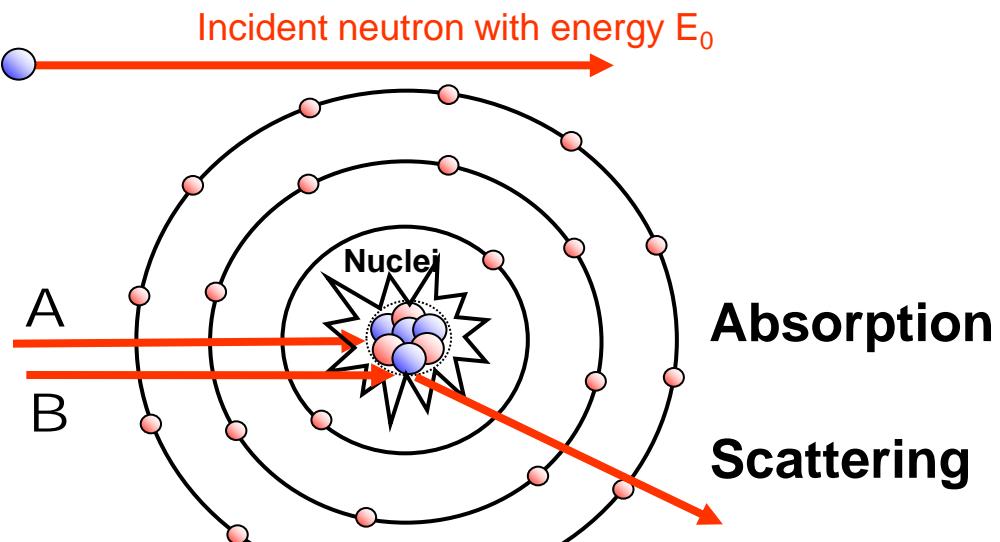
X-rays vs. neutrons

Neutrons



X-rays vs. neutrons

Neutrons



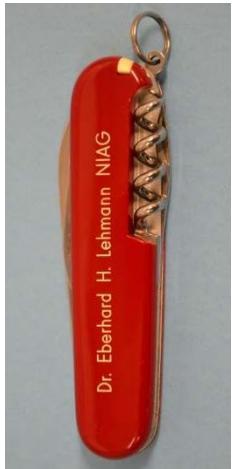
Elements vs. X-rays

Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
↓ Period																		
1	H 0.02																	He 0.02
2	Li 0.06	Be 0.22																
3	Na 0.13	Mg 0.24																
4	K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
5	Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
6	Cs 1.47	Ba 2.73		Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At -	Rn 9.77
7	Fr -	Ra 11.80		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides		La 5.04	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.17	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07		
Actinides		Ac 24.47	Th 28.95	Pa 39.65	U 49.08	Np -	Pu -	Am -	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -		

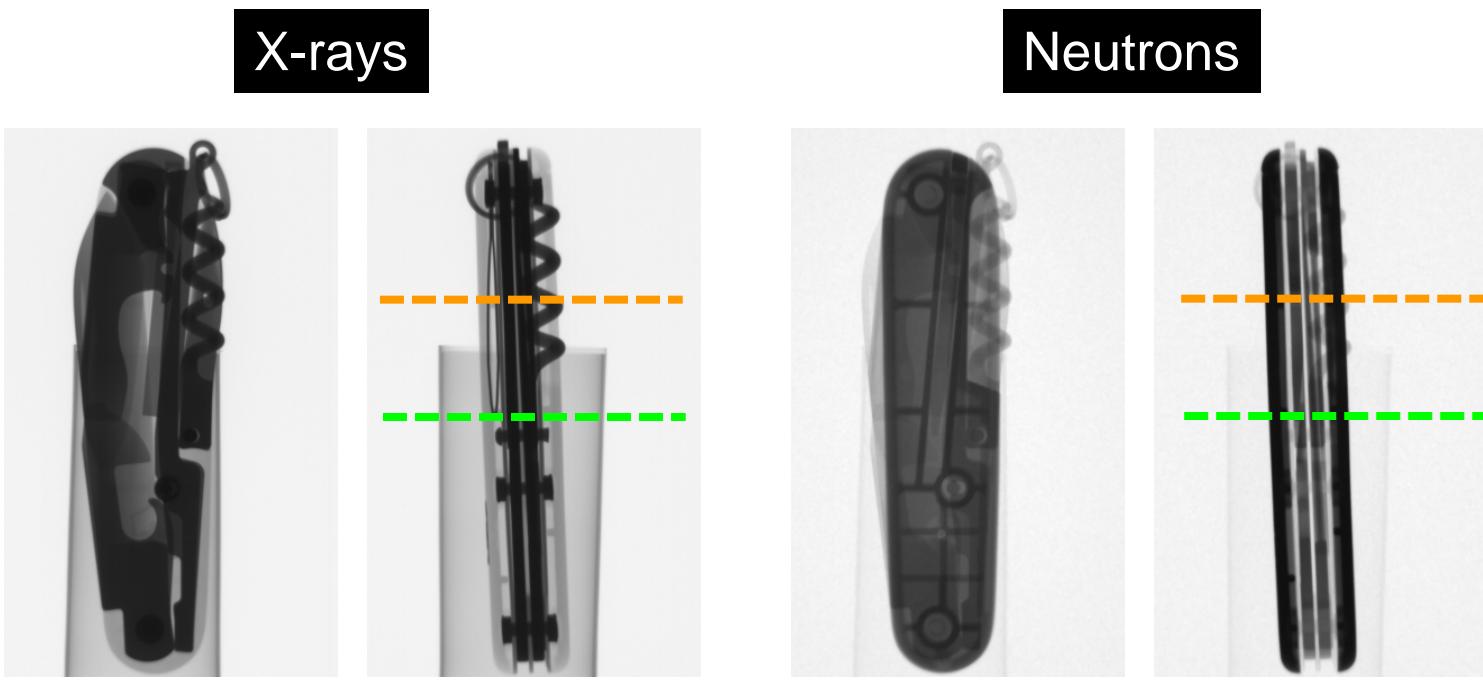
Elements vs. neutrons

Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
↓ Period																		
1	H 3.44																	He 0.02
2	Li 3.30	Be 0.79											B 101.6	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
3	Na 0.09	Mg 0.15											Al 0.1	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
4	K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
5	Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.1	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
6	Cs 0.29	Ba 0.07		Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po -	At -	Rn -
7	Fr -	Ra 0.34		Rf -	Db -	Sg -	Bh -	Hs -	Mt -	Ds -	Rg -	Uub -	Uut -	Uuq -	Uup -	Uuh -	Uus -	Uuo -
Lanthanides		La 0.52	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.0	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75		
Actinides		Ac -	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm -	Bk -	Cf -	Es -	Fm -	Md -	No -	Lr -		

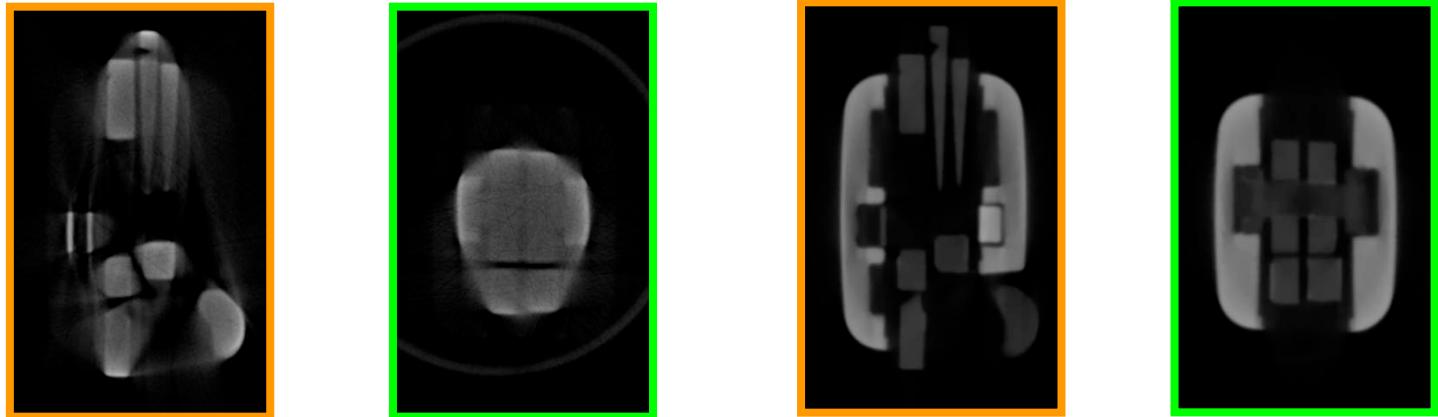
Swiss army knife: X-ray vs. neutrons



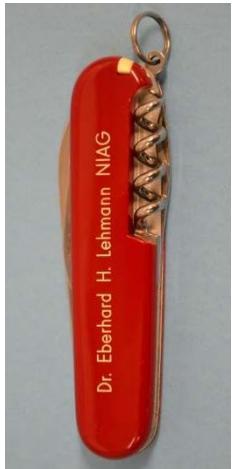
2D Projections



3D tomo slices

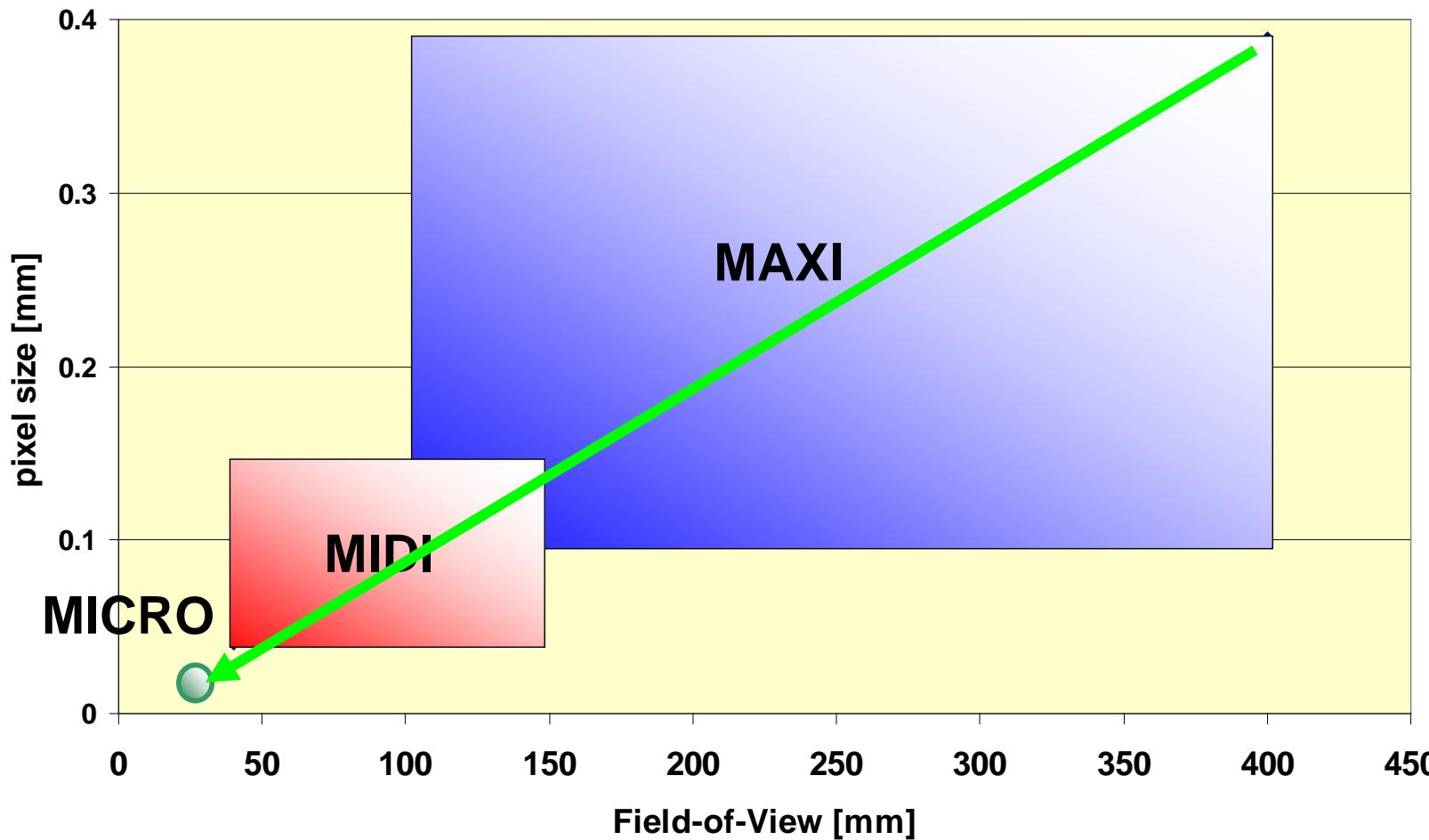


Swiss army knife: 3D lubricant distribution

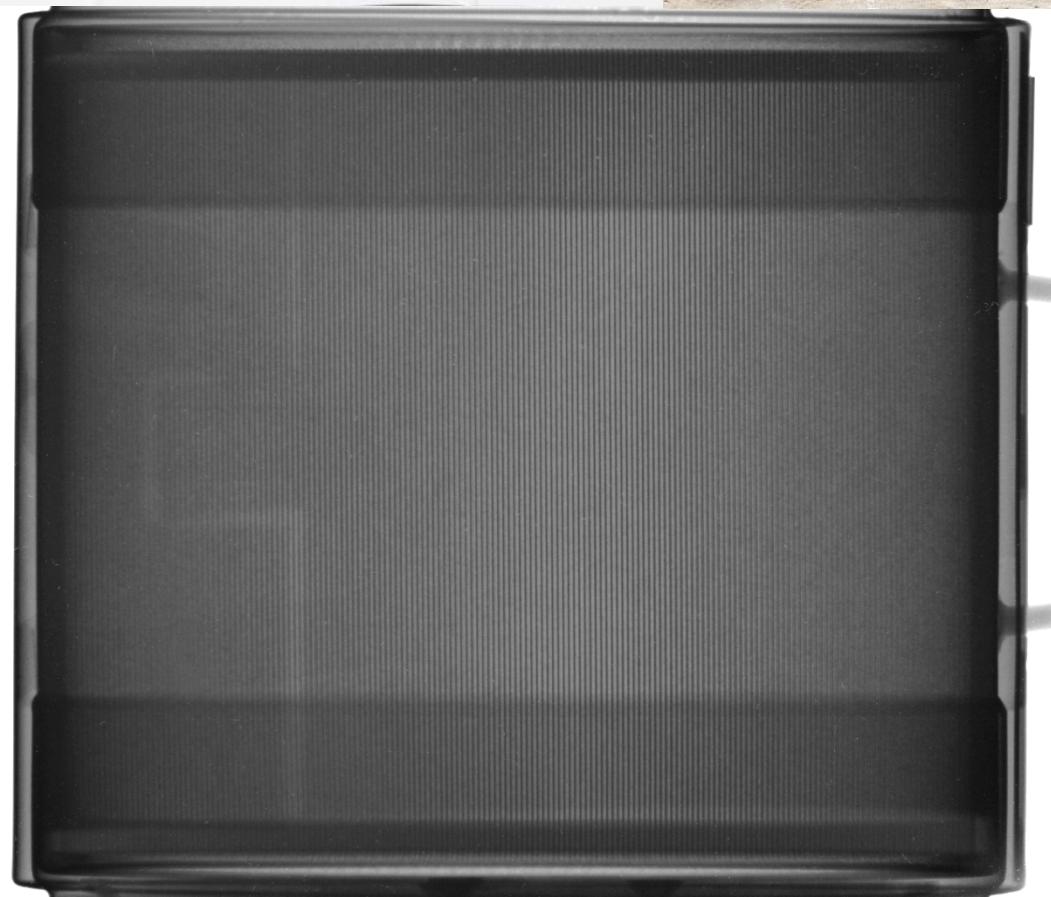


Object dimensions vs. resolution

CCD-camera based systems



Maxi setup



Midi setup



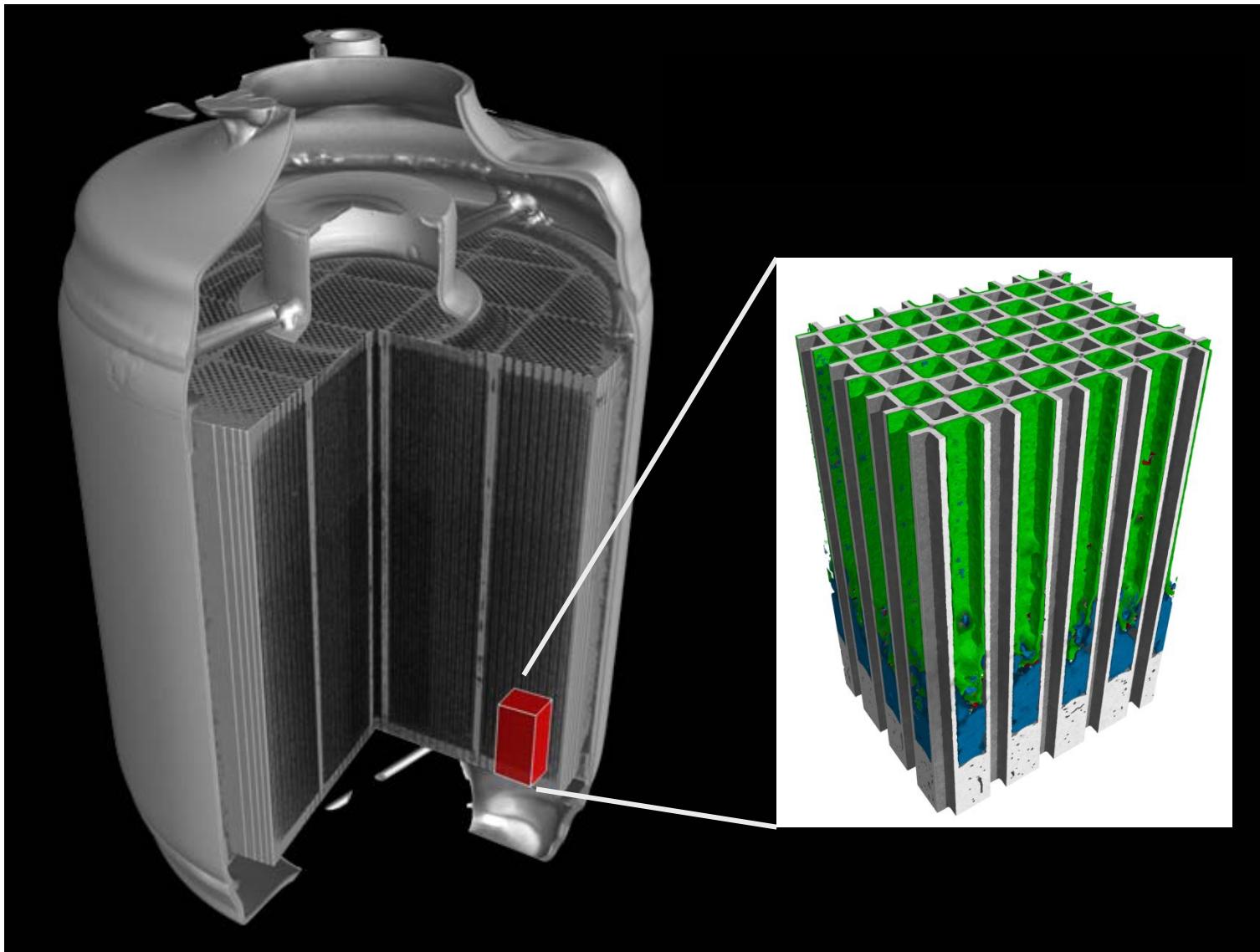
Image



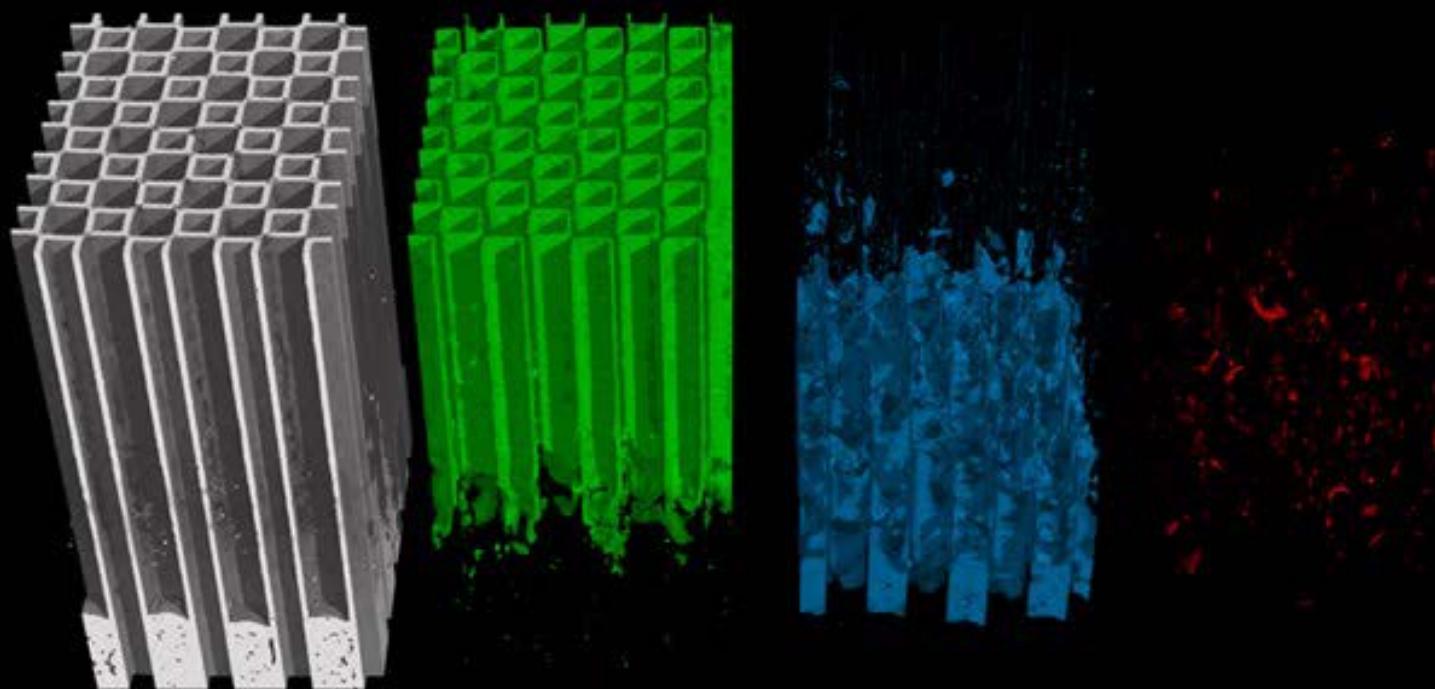
Tomography



Micro setup



Neutron microtomography Diesel particulate filter (DPF)



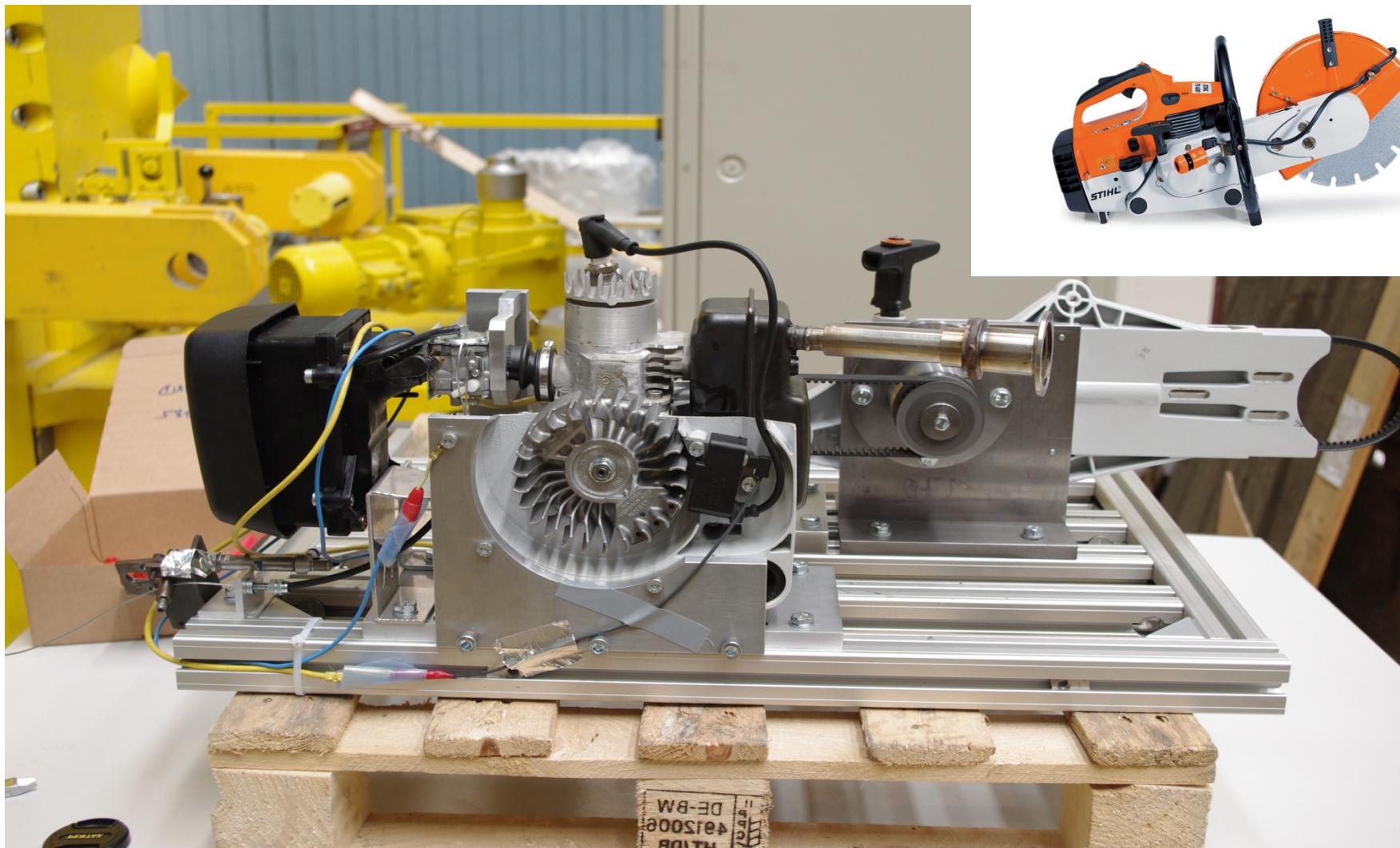
Sample size 10mm × 13mm × 18mm

Voxel size 13.5 μm^3

How neutron imaging explores time

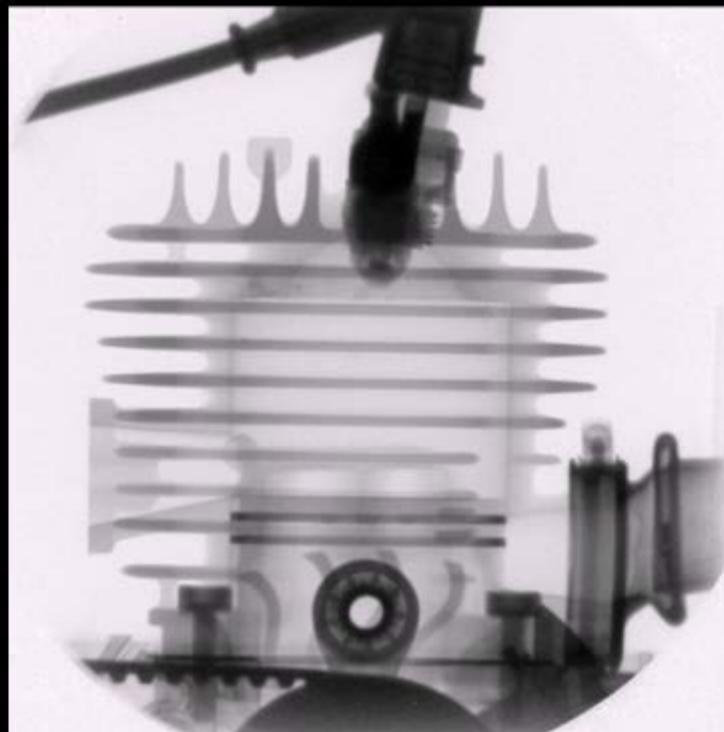


How neutron imaging explores time scales

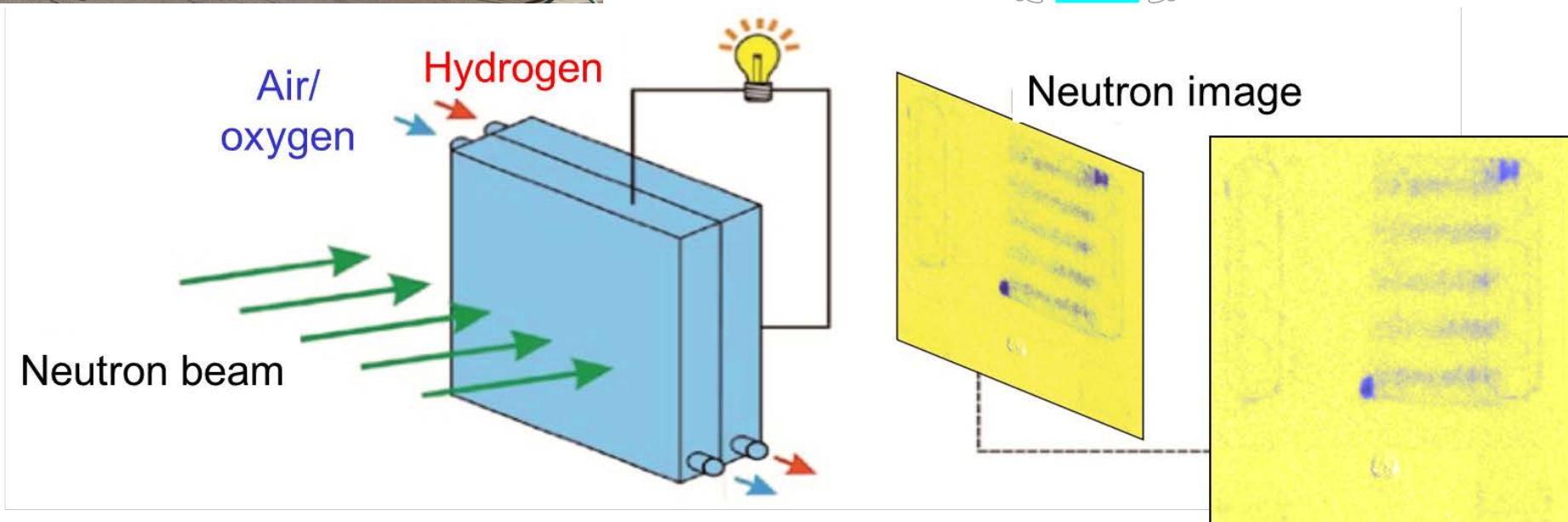
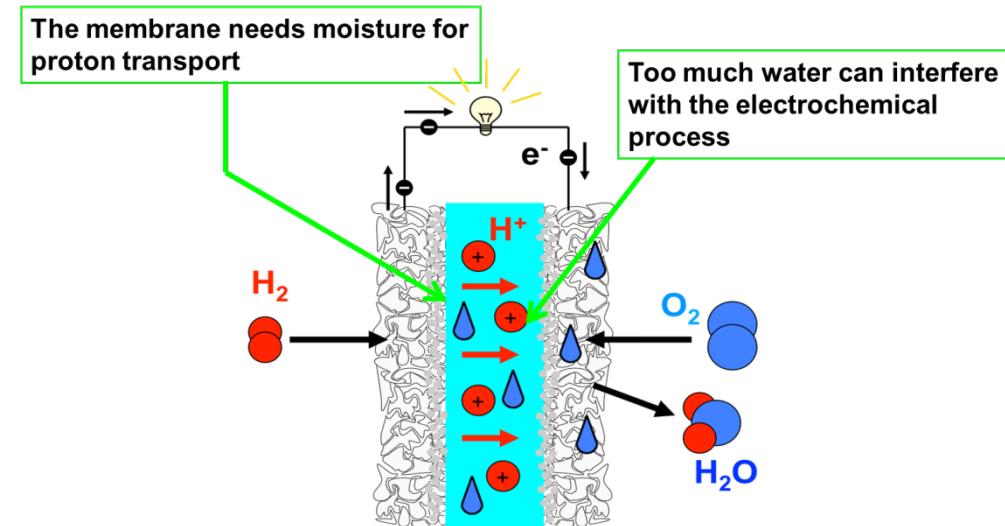


Dynamic Neutron Radiography

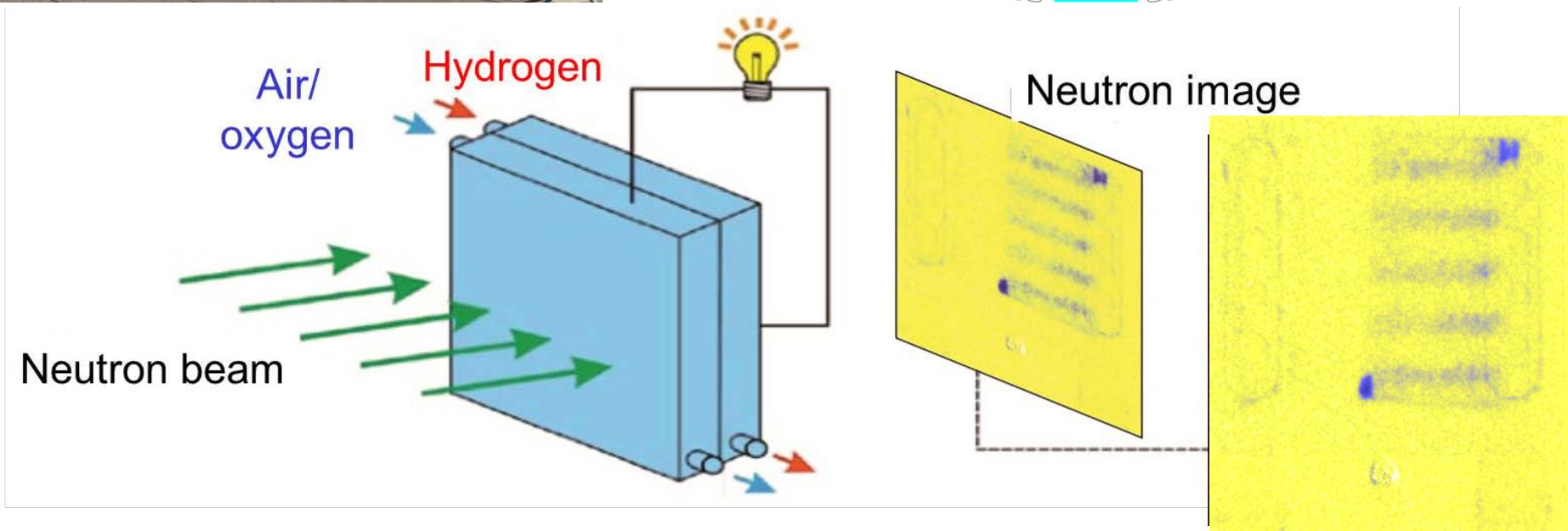
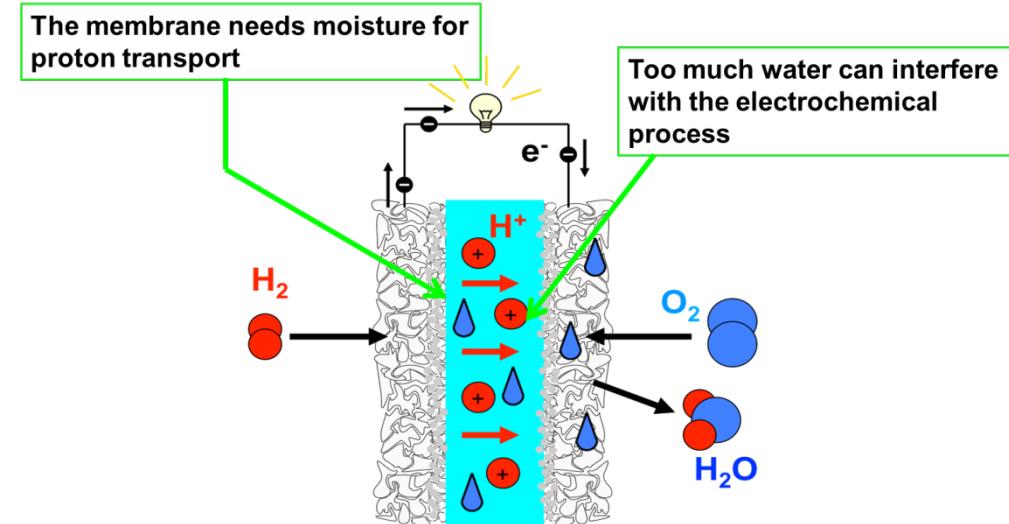
fired 64ccm two-stroke engine @ 10'000rpm
STIHL TS 400



How neutron imaging explores energy



How neutron imaging explores energy



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- Comparison of X-ray and neutron interaction with matter
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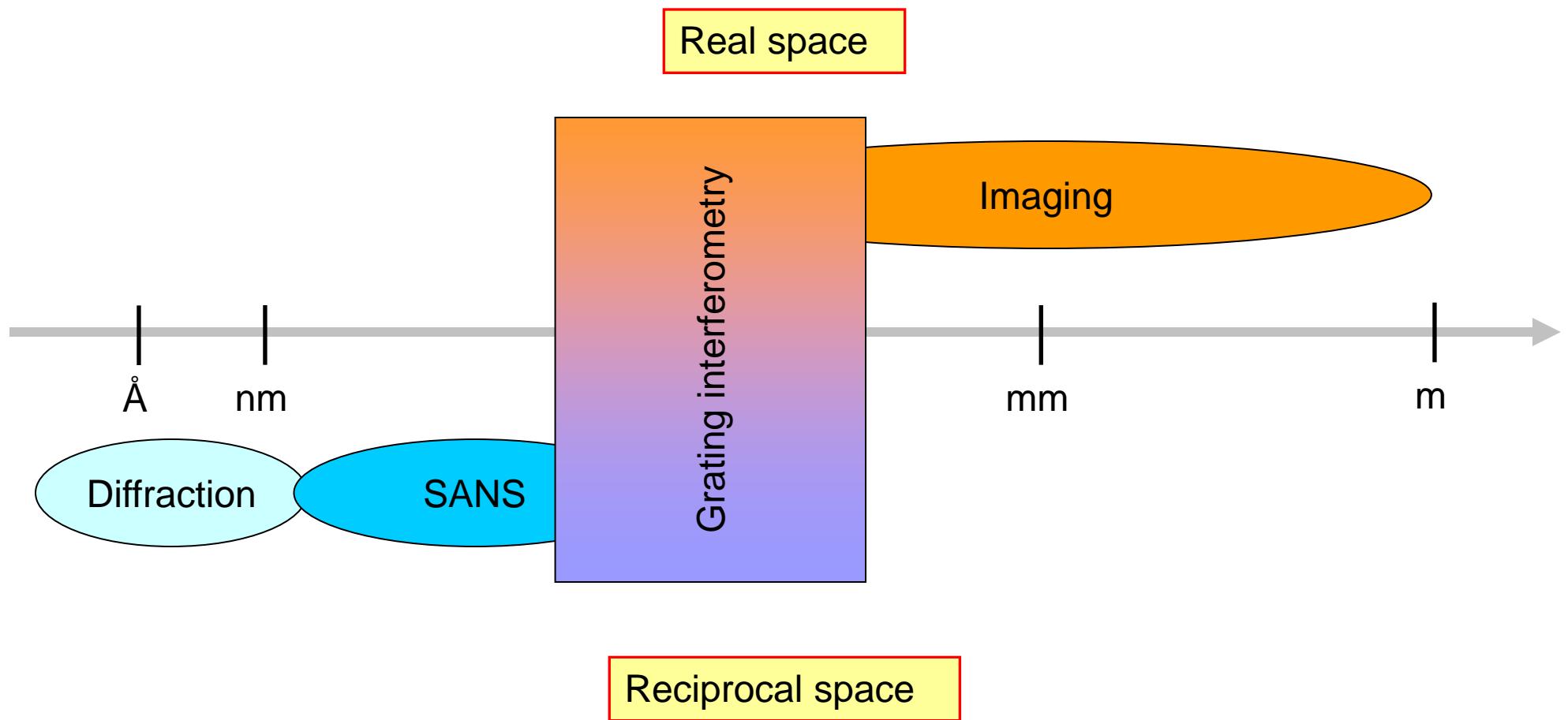
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III) DFI results of imaging bulk ferromagnetic samples

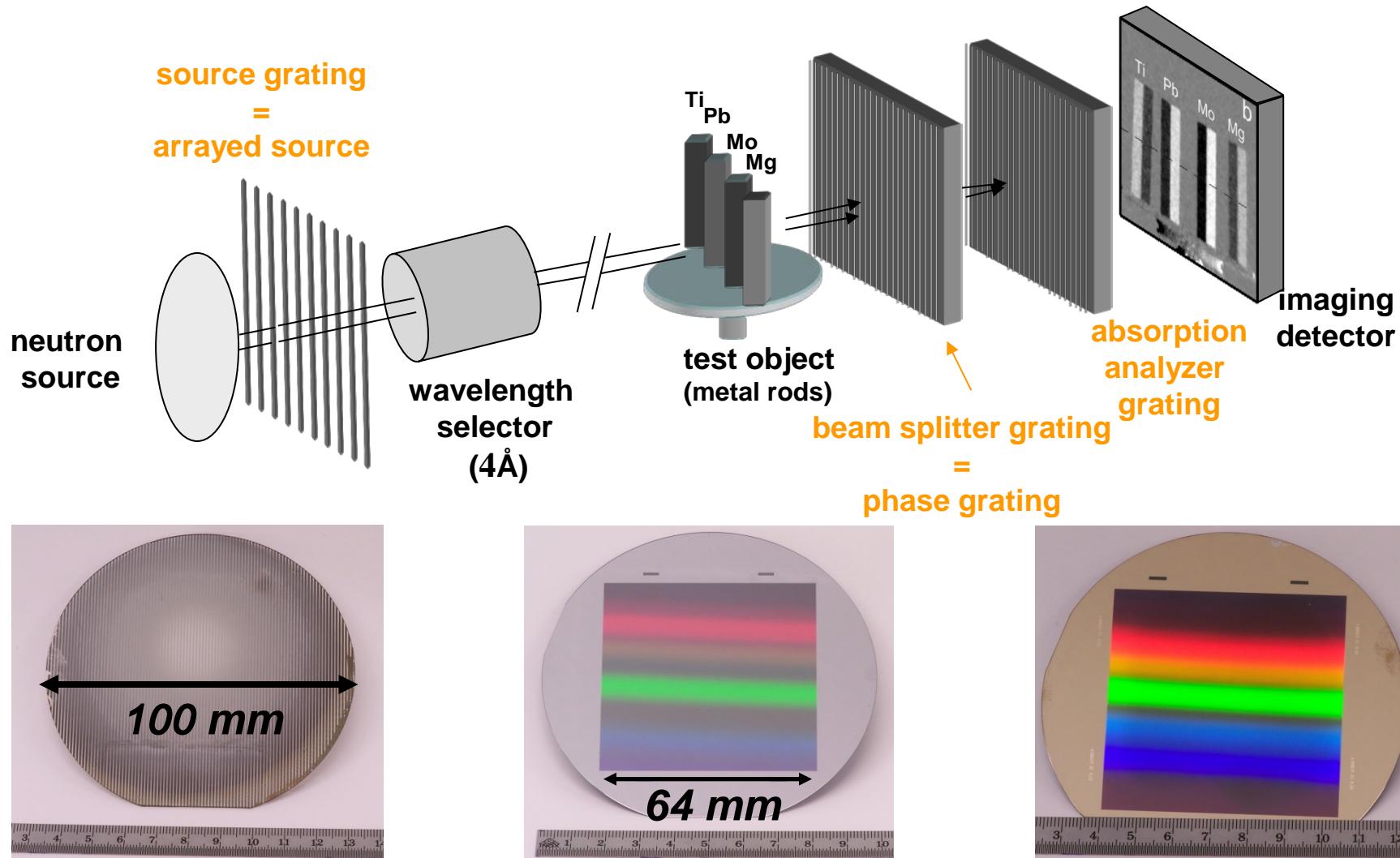
- Magnetic domain structures in 2D/3D
- Magnetic domain structures and “saving” energy

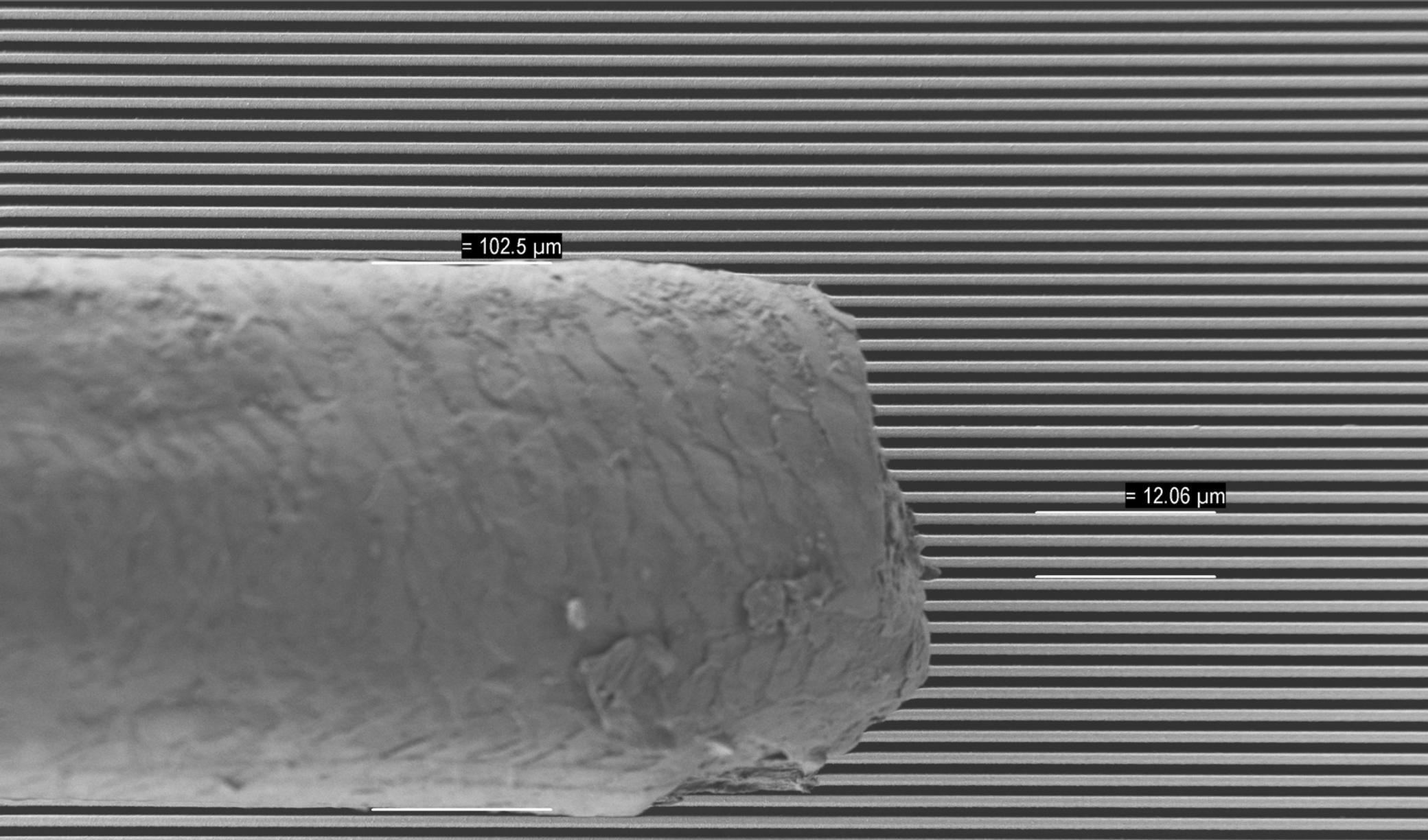
V) Summary

Length scales and techniques



Neutron grating interferometry (*nGI*)





10 μ m
A scale bar icon consisting of a vertical line with a shorter horizontal line extending from its right side.

Mag = 1.52 K X EHT = 1.00 kV Signal A = SE2 WD = 6 mm

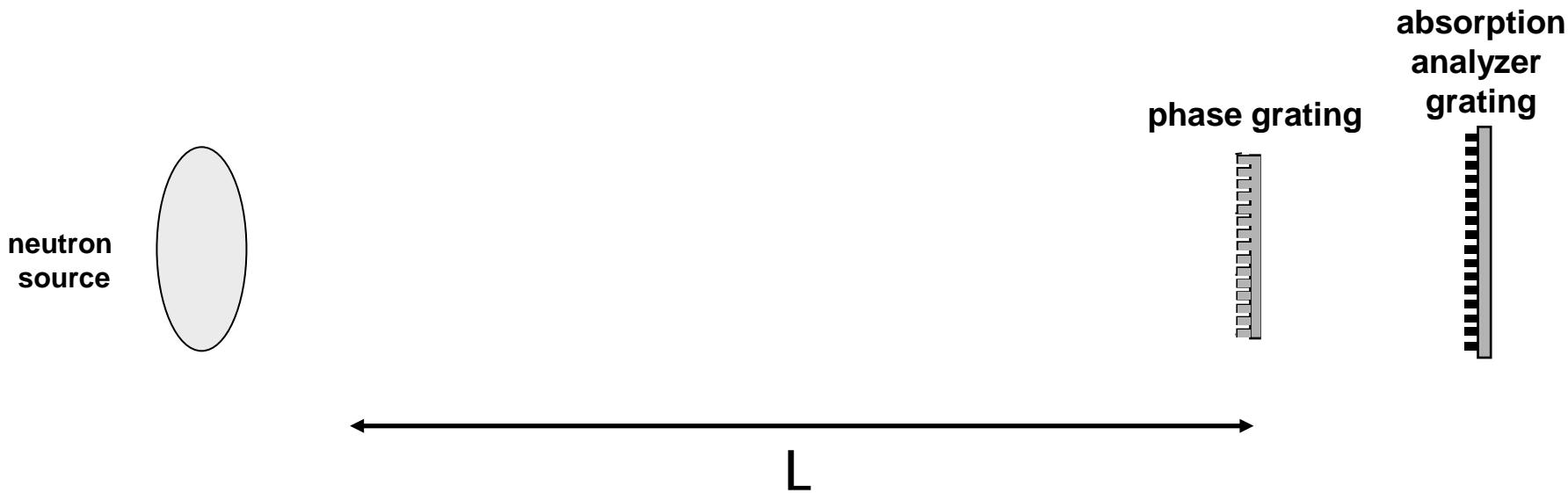
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Date :20 Apr 2007

Time :9:46:40

User Name = GRUENZWEIG

Coherence requirements: spatial coherence



Coherence requirements: spatial coherence

Required
spatial coherence length

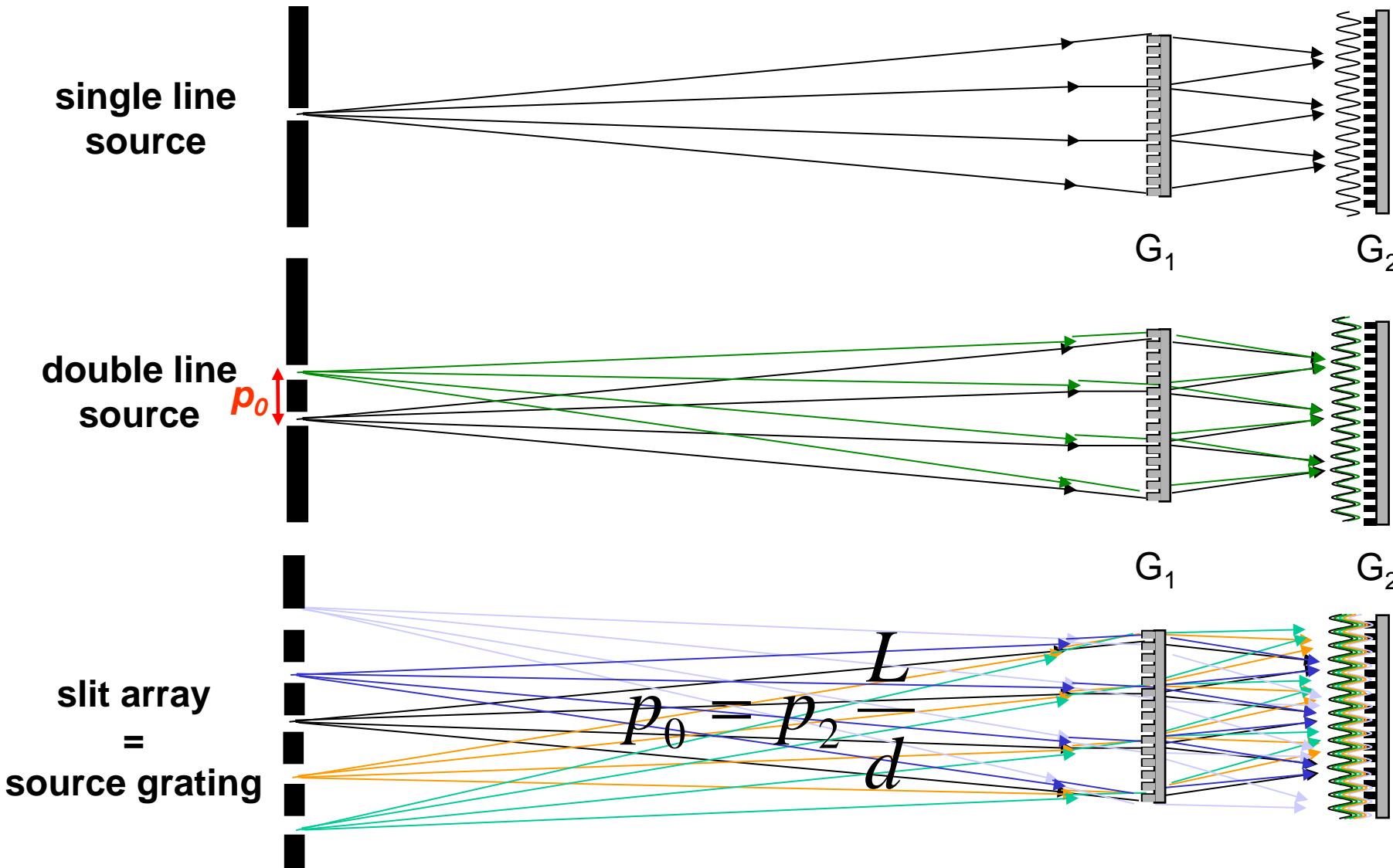
$$\xi = \lambda L / s > \frac{1}{2} p_{\text{phase grating}}$$



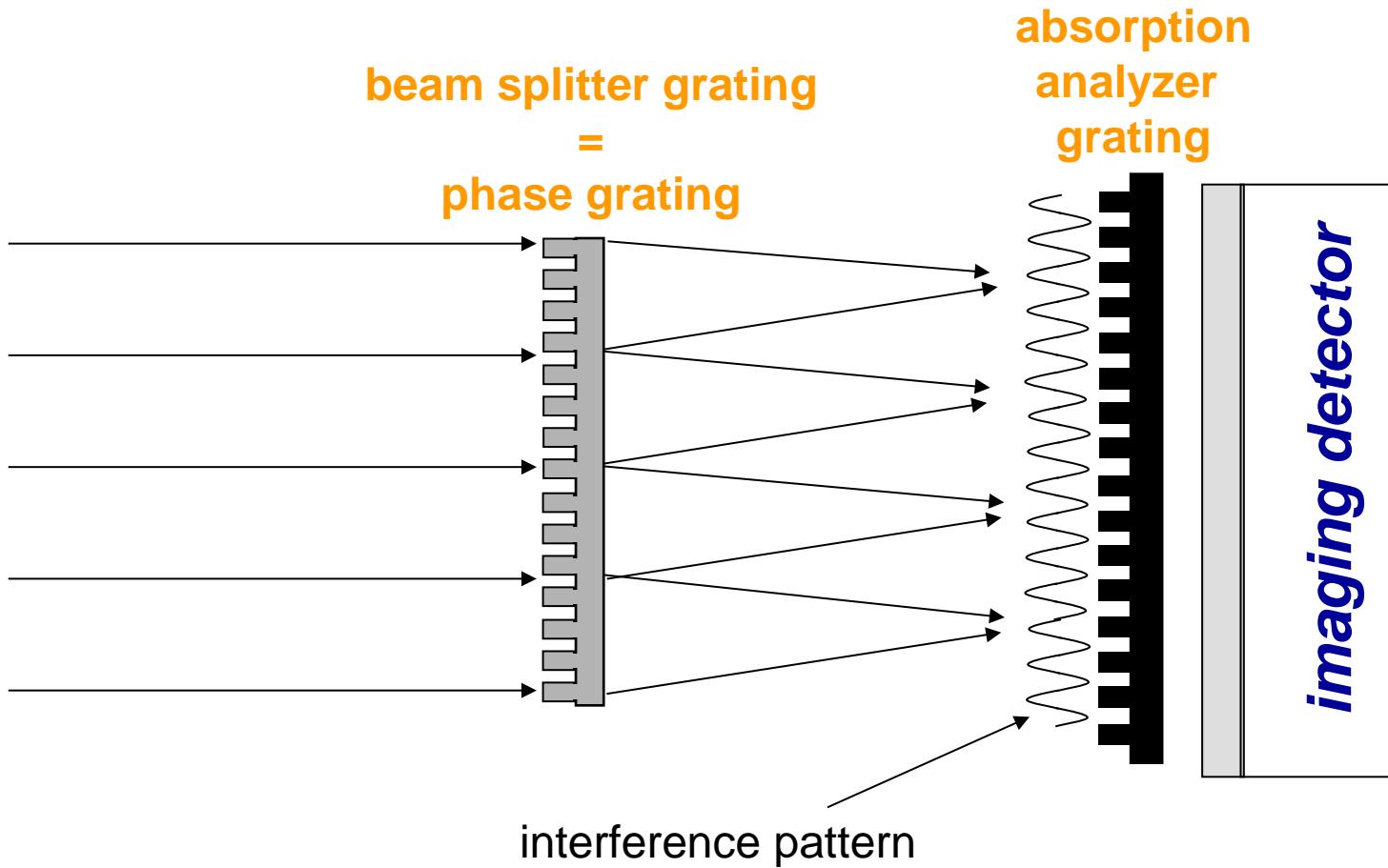
$$p_{\text{phase grating}} = 8 \mu\text{m}, \quad L = 5.23 \text{ m}, \quad \lambda = 4 \text{\AA},$$

$$\Rightarrow s \sim 500 \mu\text{m}$$

Higher efficiency with the source grating

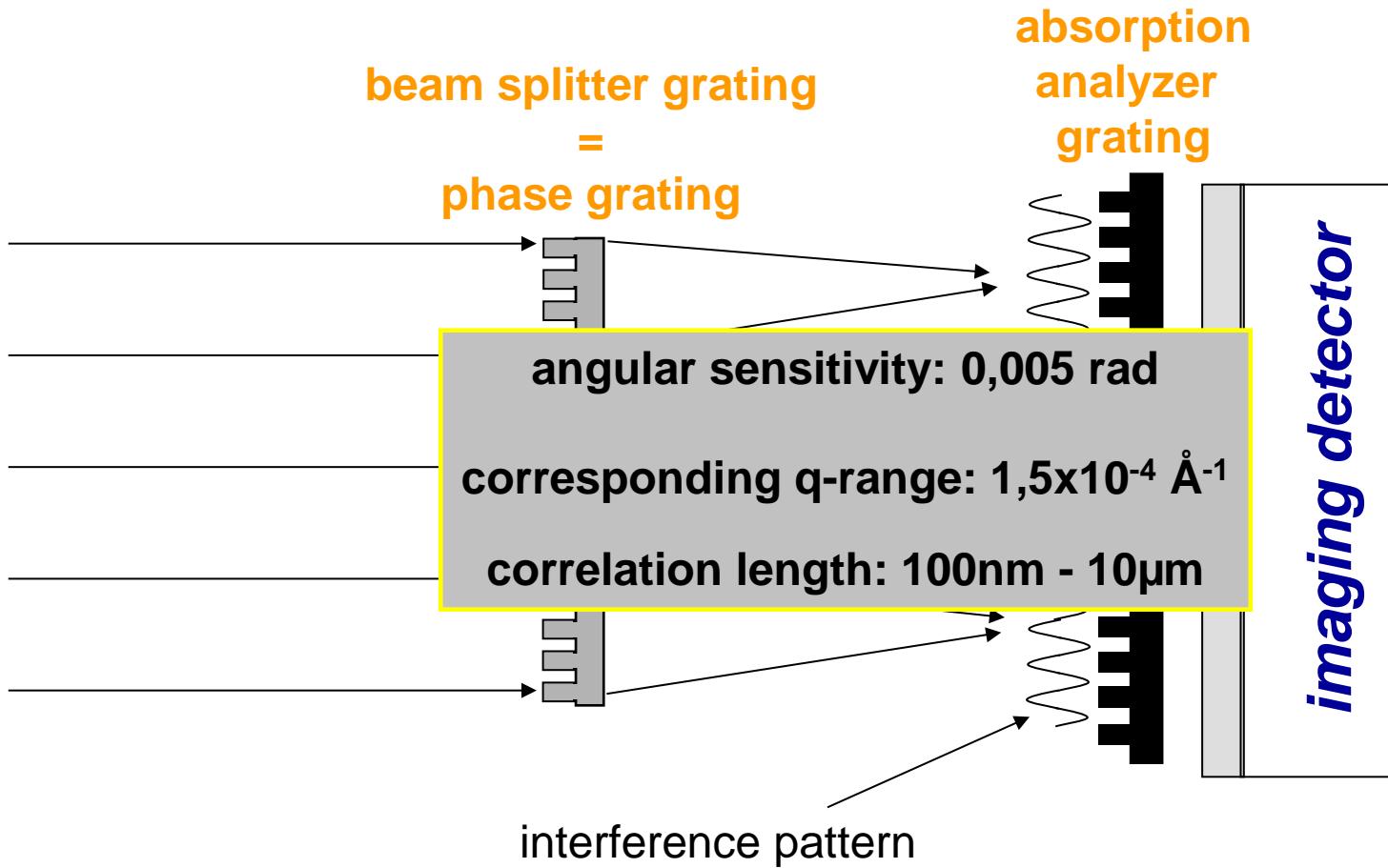


Grating interferometry: principle



Grating interferometry: principle

SOURCE



Magnetism: Why using neutrons?

Some properties of the neutron:

- No electric charge
- Interaction only with the nuclei

$$\varnothing_{\text{neutron}} \approx 1 \times 10^{-15} \text{ m}$$

$$\varnothing_{\text{nuclei}} \approx 1 \times 10^{-14} \text{ m}$$

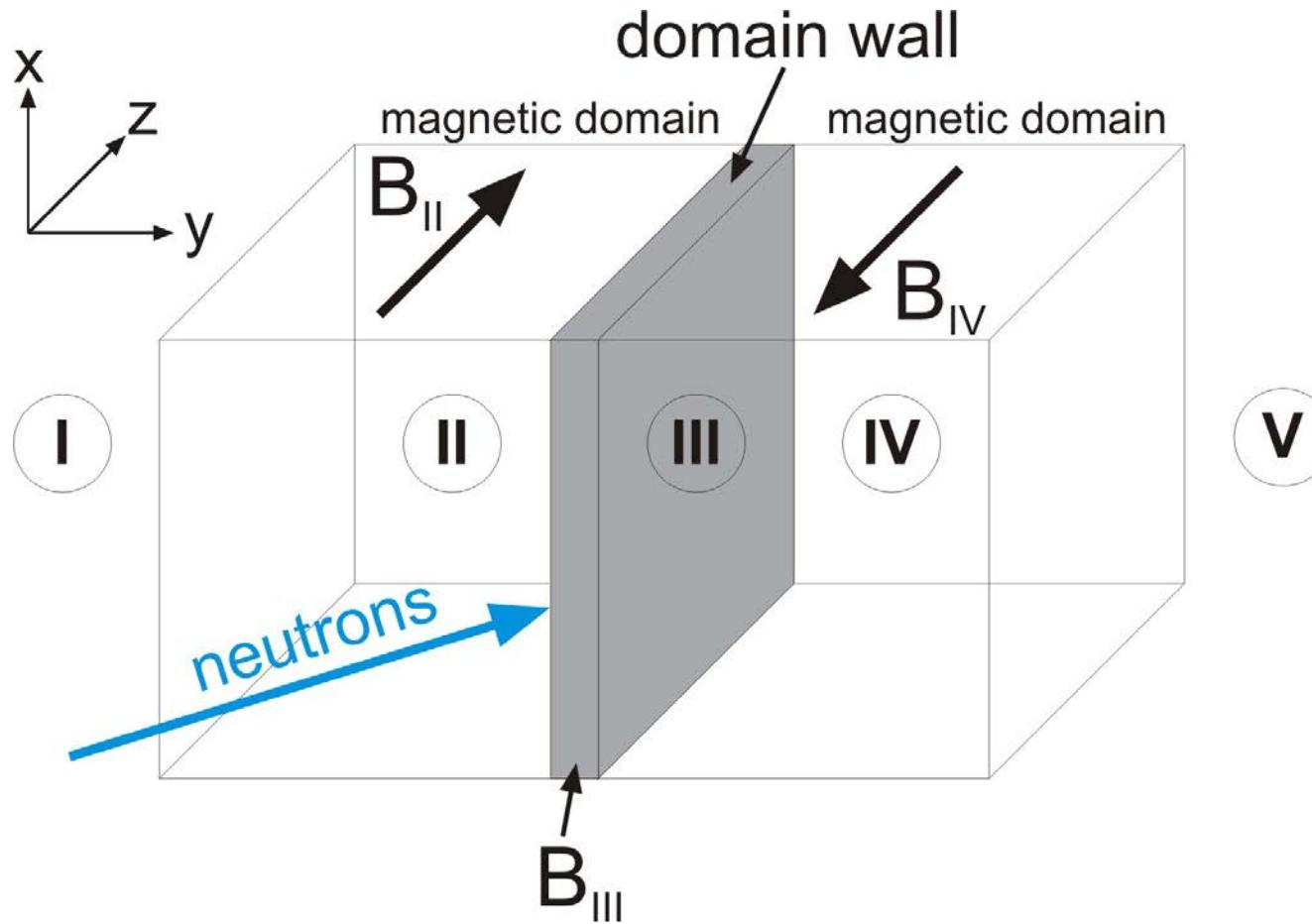
$$\varnothing_{\text{atom}} \approx 1 \times 10^{-10} \text{ m}$$

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

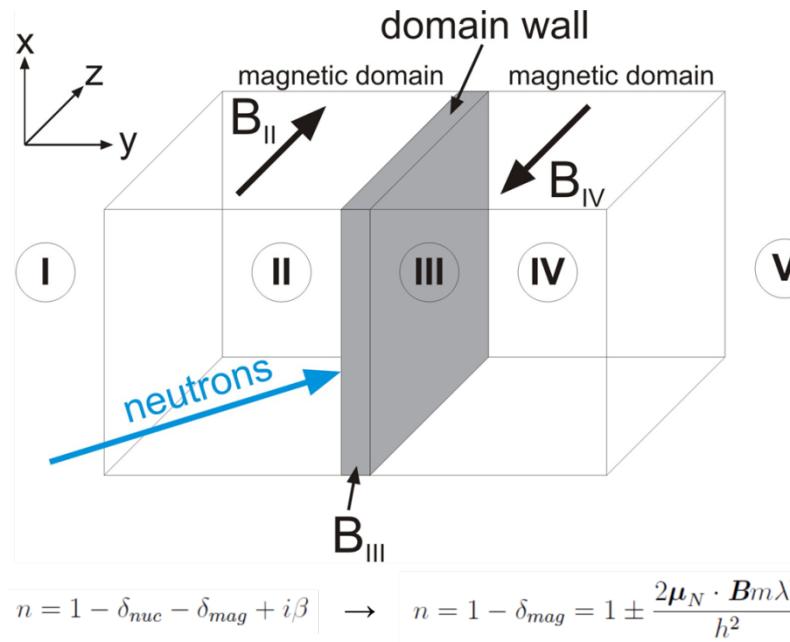
=> penetration of bulk materials

=> interaction with magnetic materials

Refraction of unpolarized neutrons at domain walls



Refraction of unpolarized neutrons at domain walls

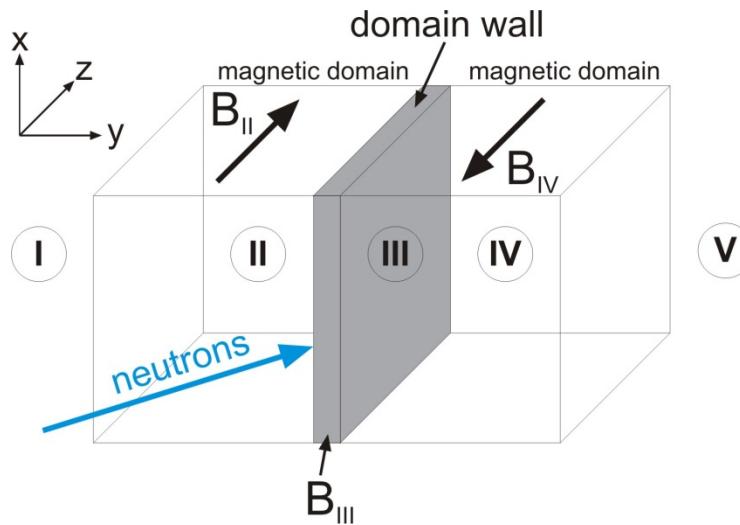


- Refraction of **unpolarized neutrons** is described by the Schrödinger equation with a spin-dependent potential, which depends on the **average homogeneous magnetic induction B**
- Domain walls are considered as **plane parallel plates** and regarded as **infinitely thin**
- **Refraction angles** are given by the two **refractive indices of the adjacent media**

=> Analogy to the Snell's law in optics

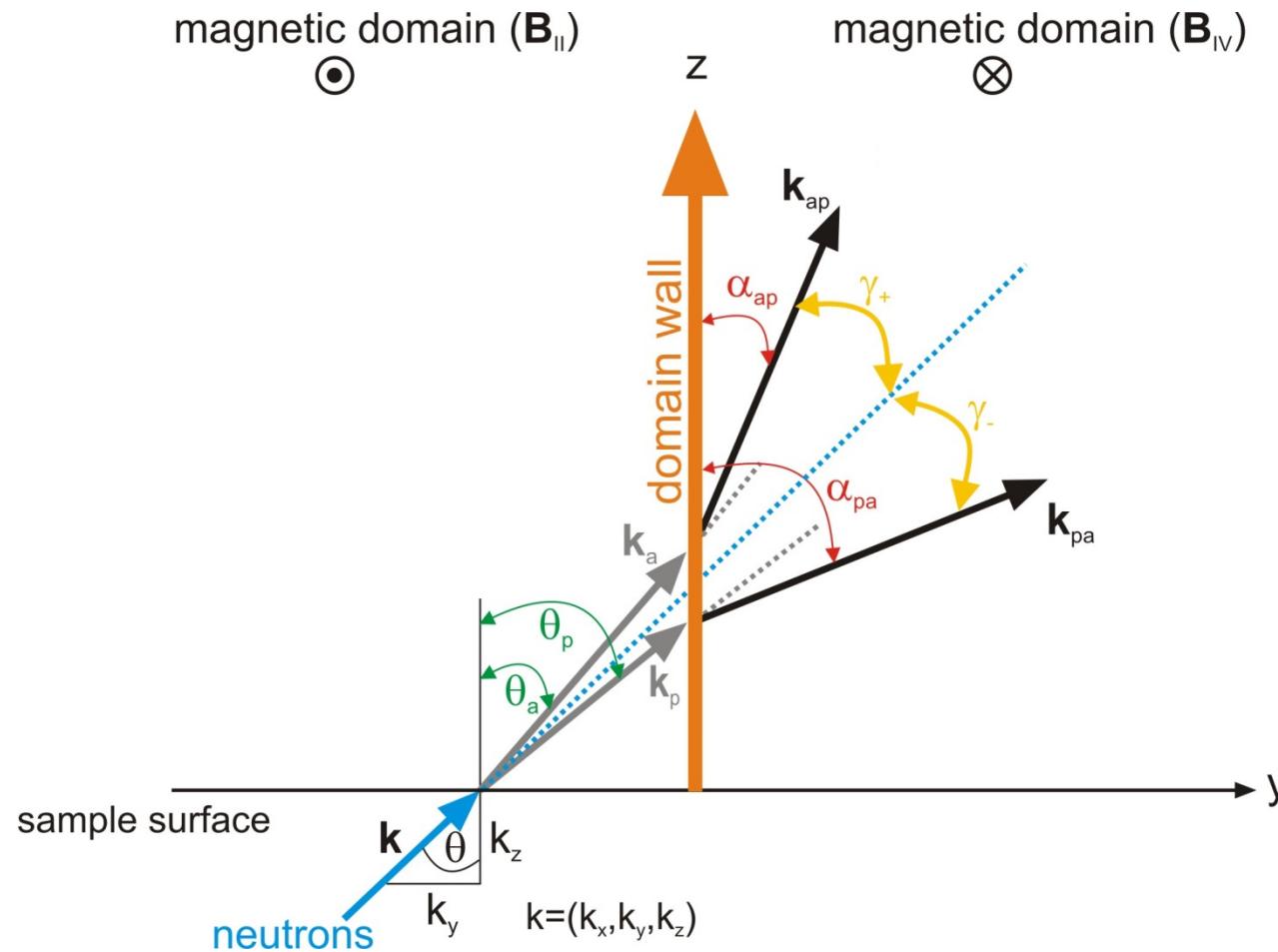
$$n_1 \sin \Theta_2 = n_2 \sin \Theta_1 \Leftrightarrow k_1 \sin \Theta_2 = k_2 \sin \Theta_1$$

Refraction of unpolarized neutrons at domain walls

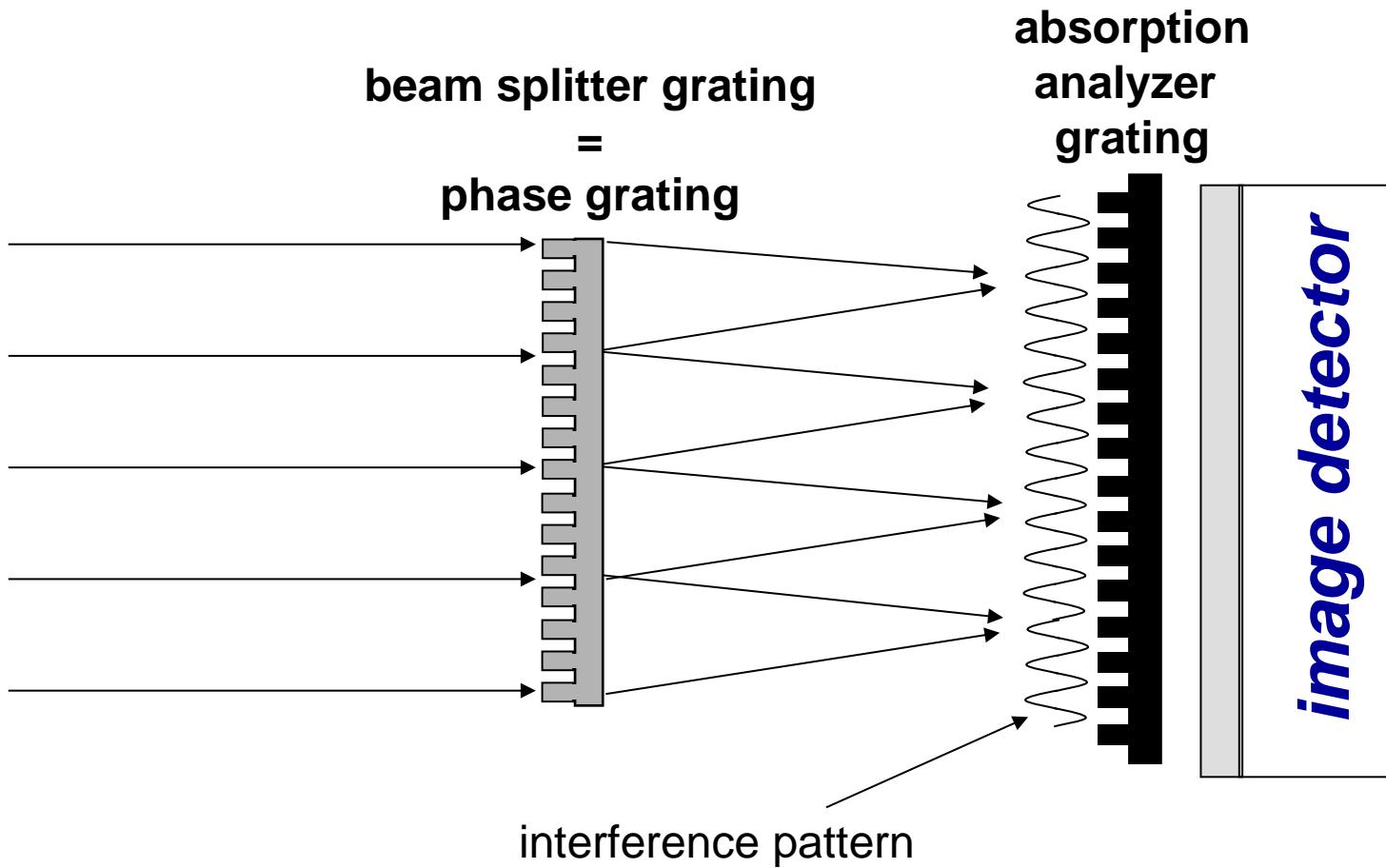


\approx mrad

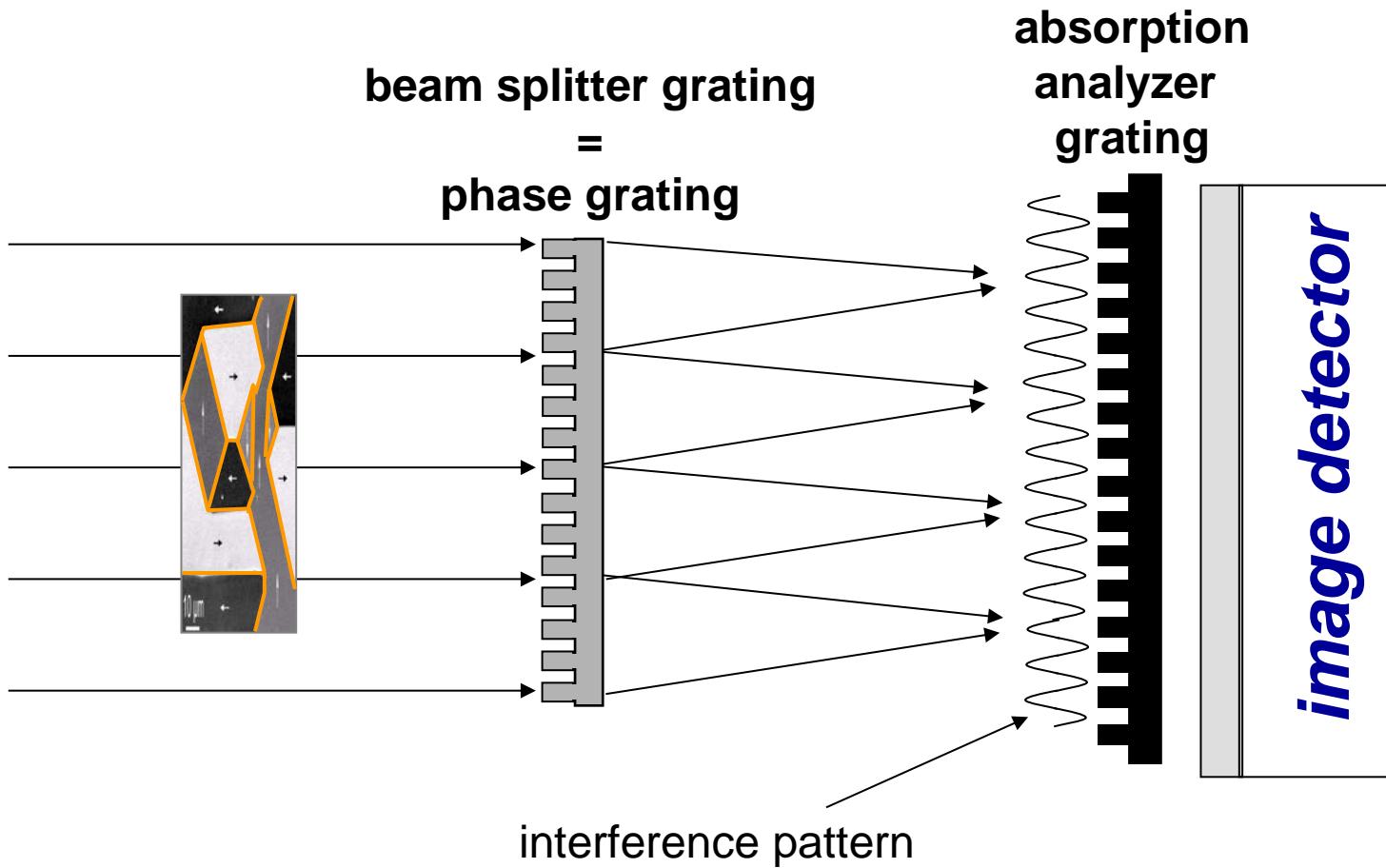
$$n = 1 - \delta_{\text{mag}} = 1 \pm \frac{2\mu_N \cdot B_m \lambda^2}{h^2}$$



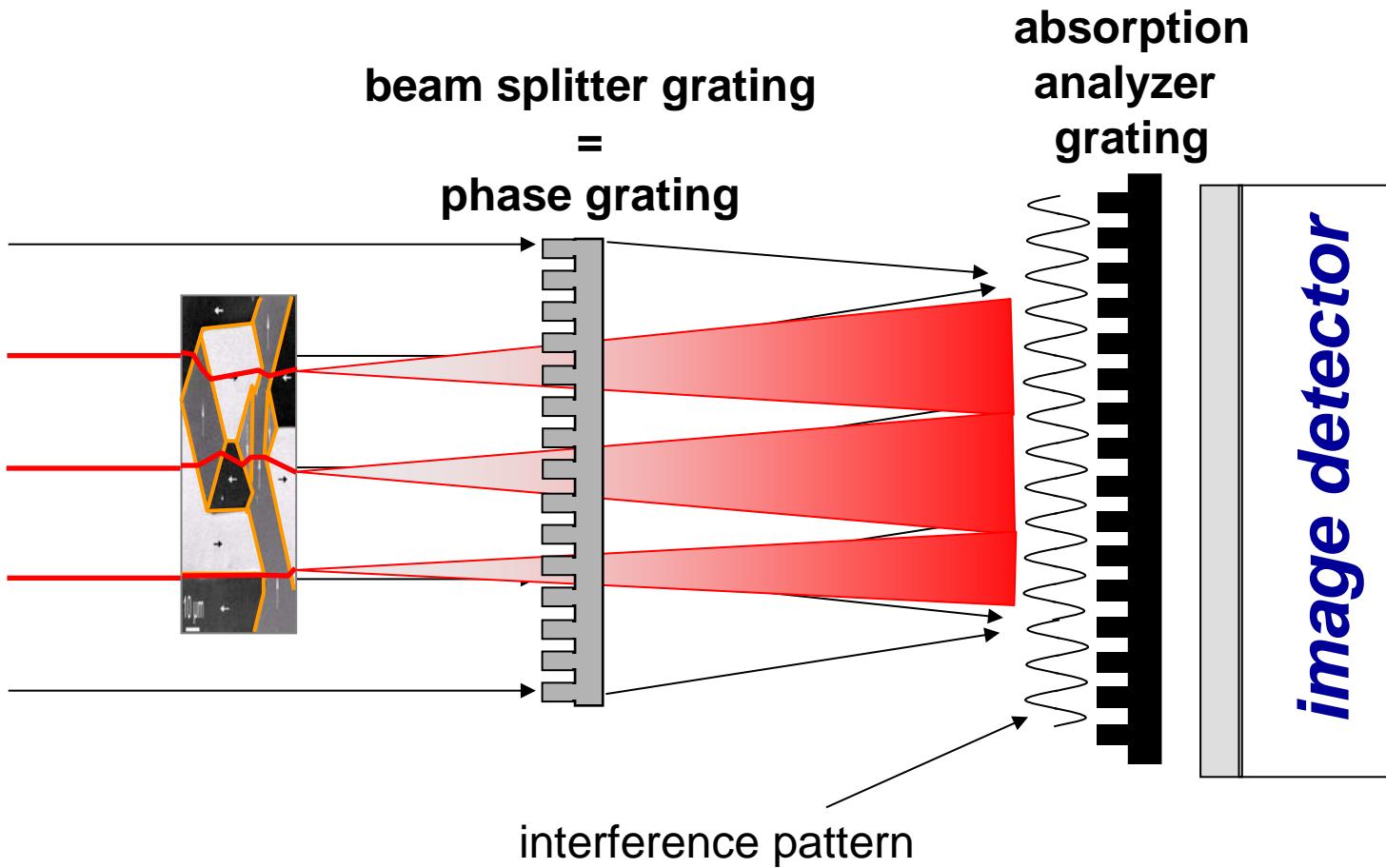
Magnetic contrast: Dark-field image (DFI)



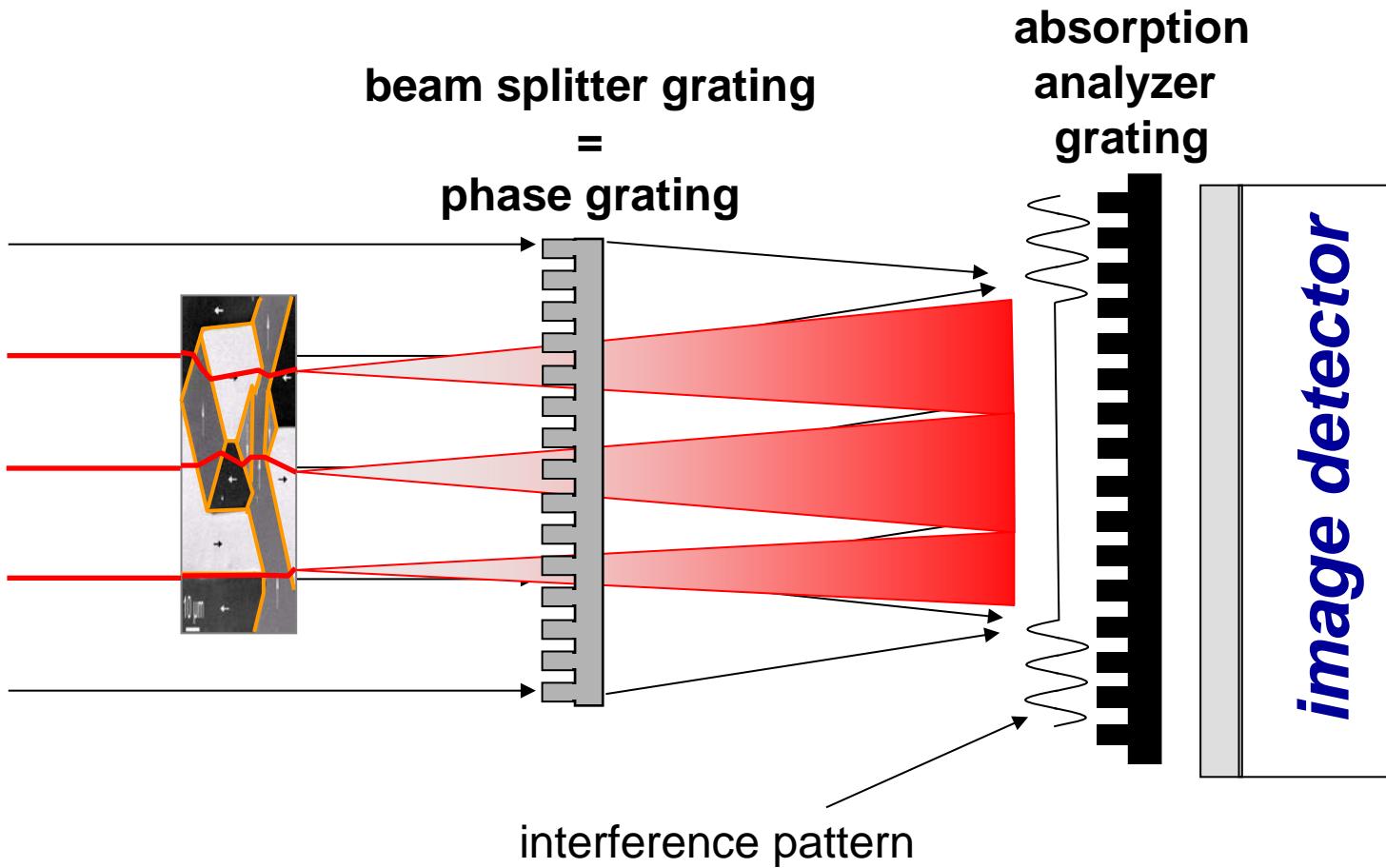
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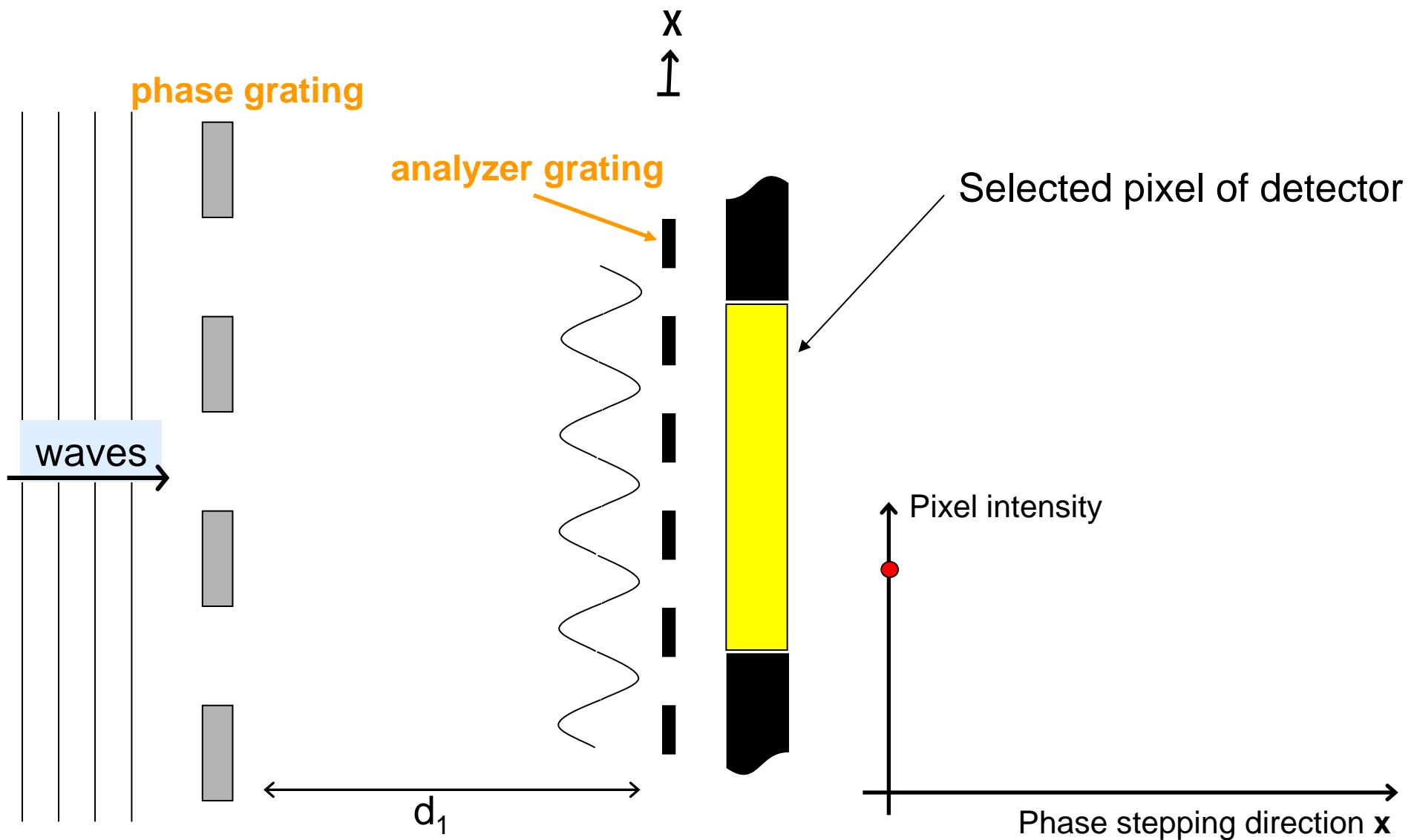
Principle:

Unpolarized neutrons refracted at domain walls

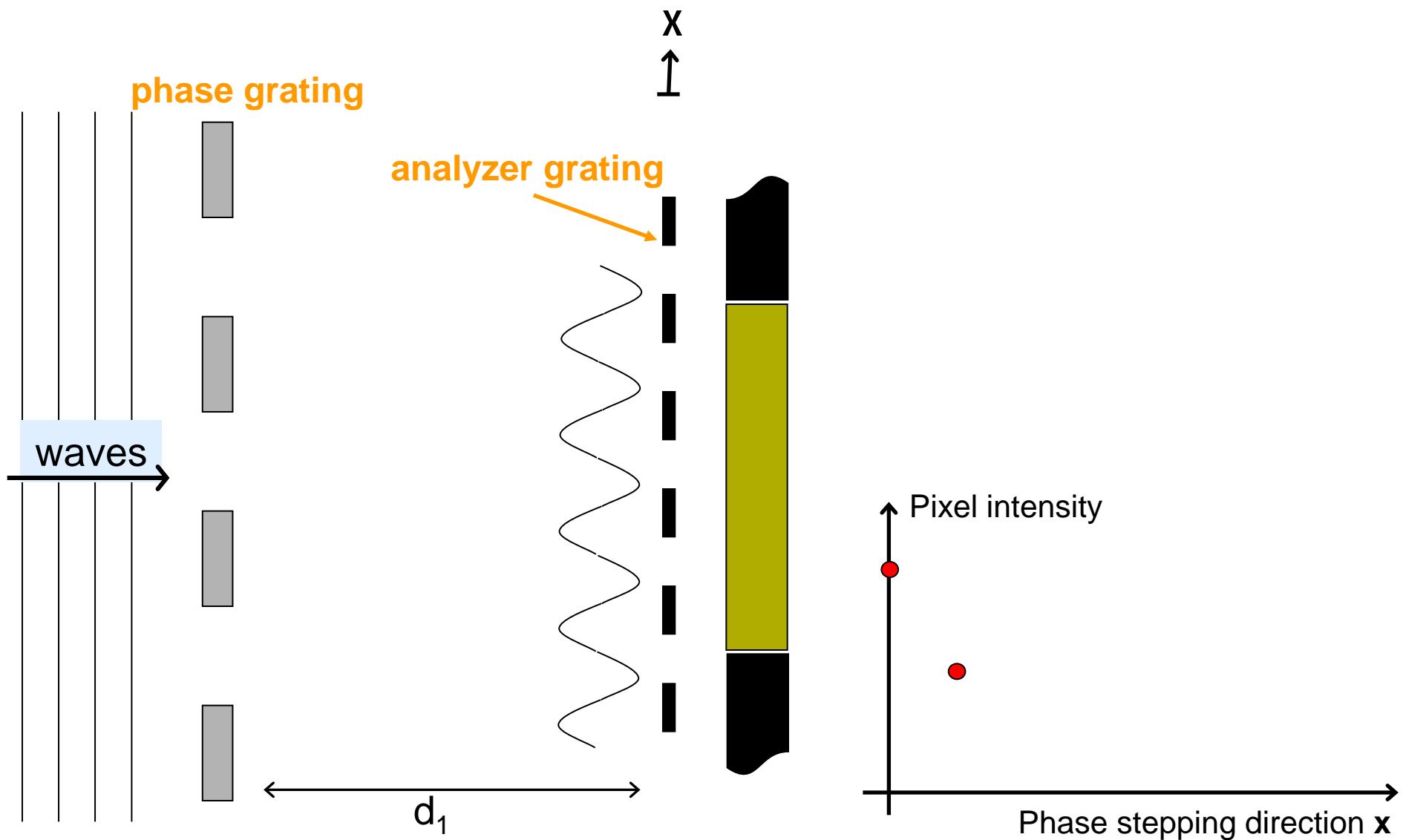
are locally destroying the interference pattern



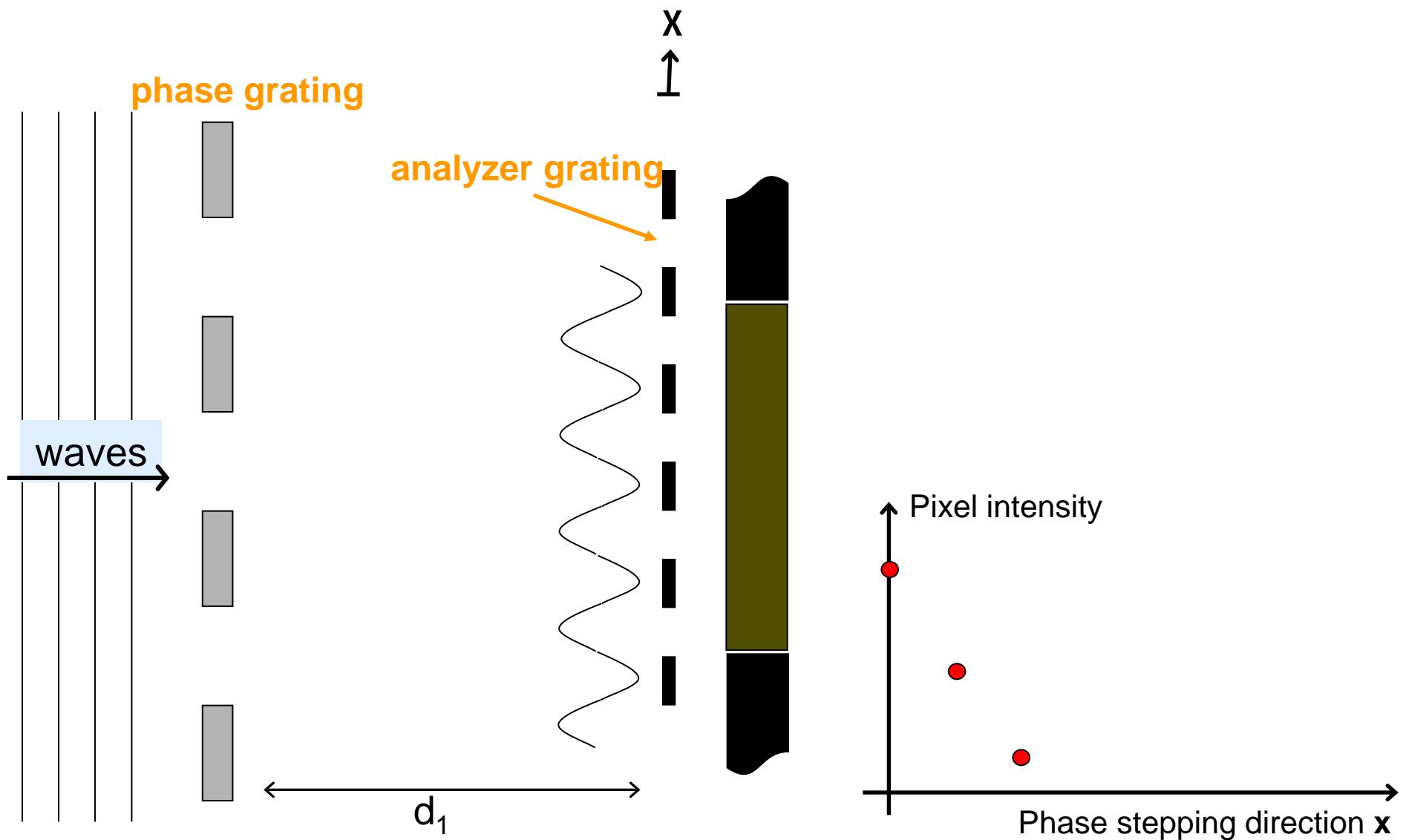
Phase stepping analysis



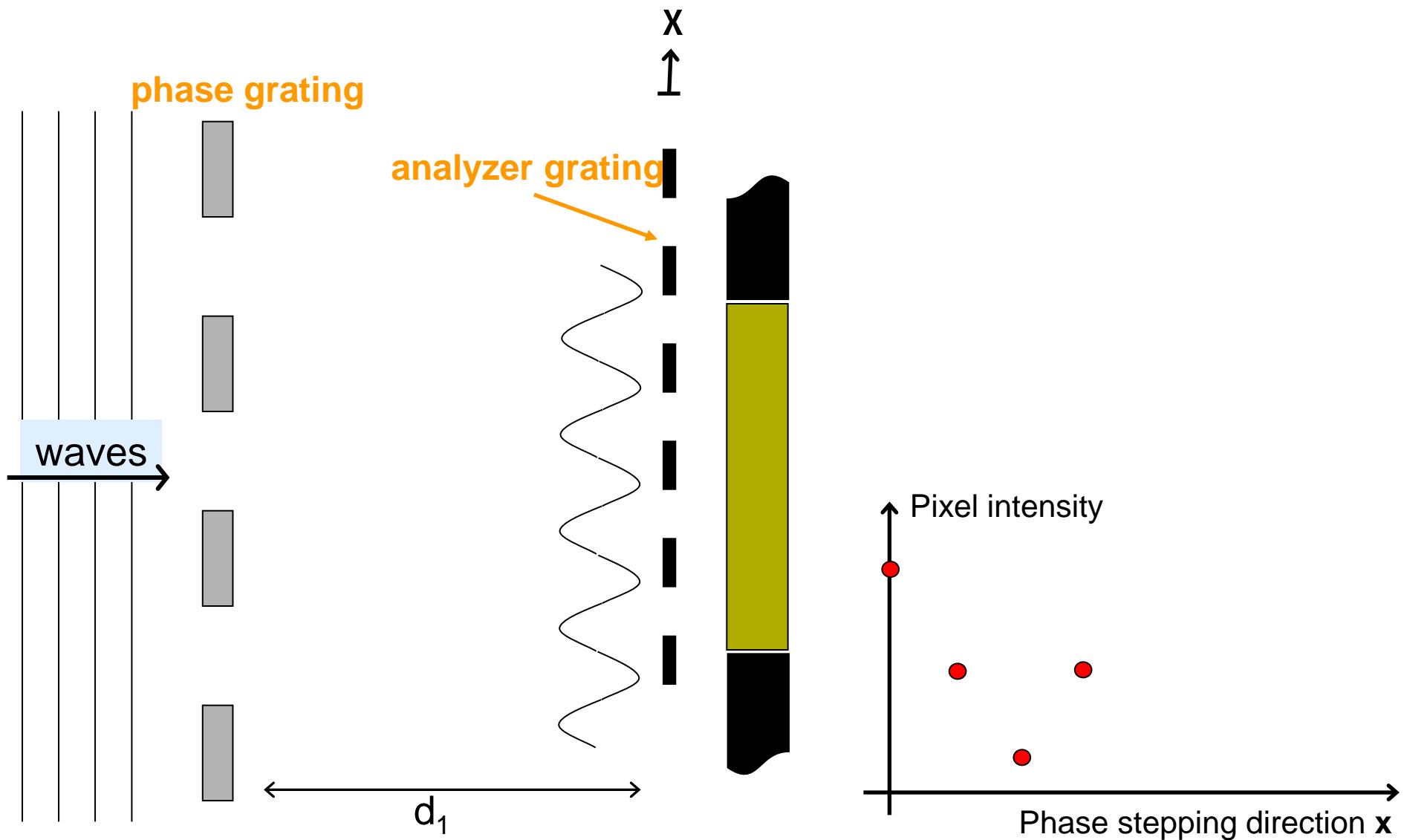
Phase stepping analysis



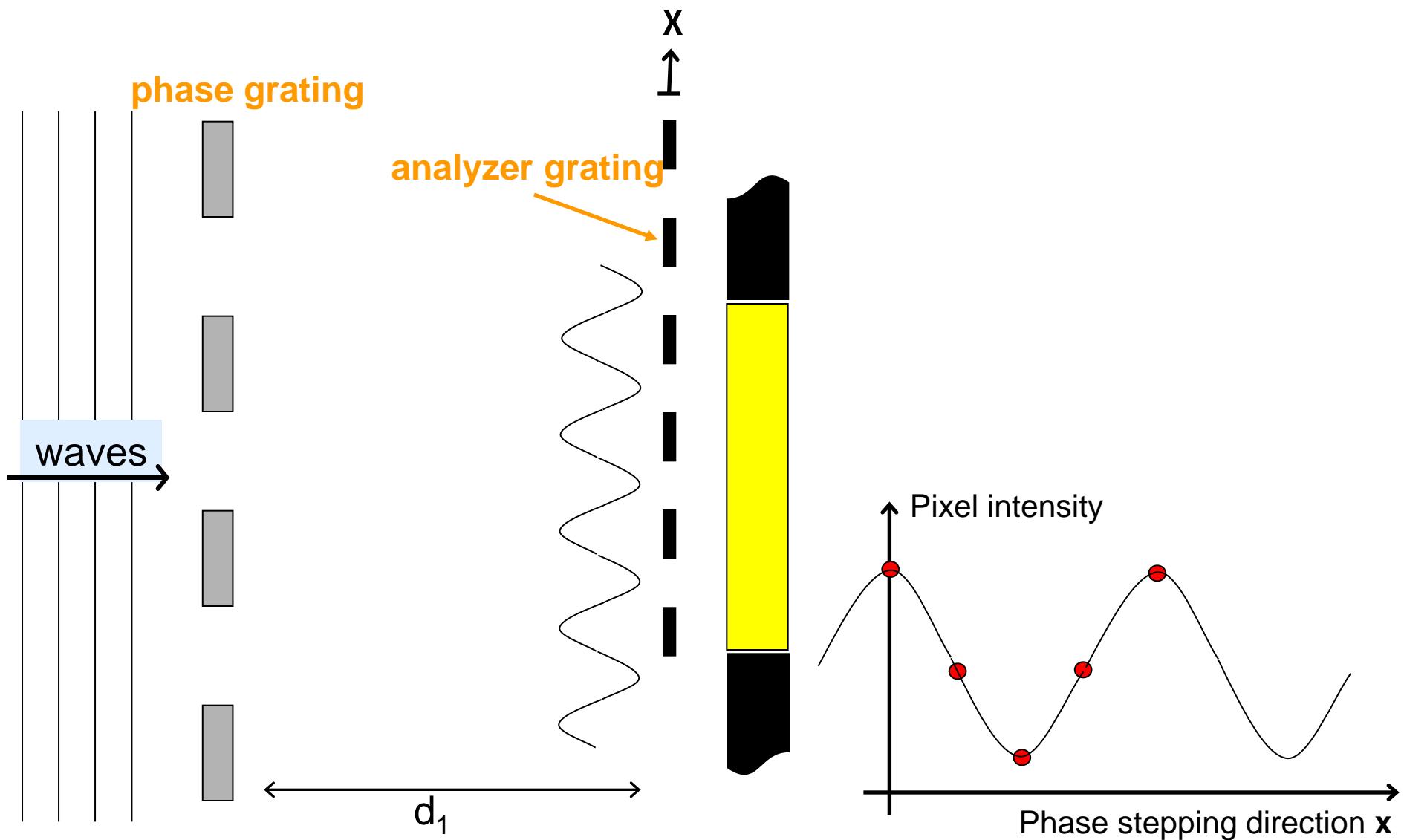
Phase stepping analysis



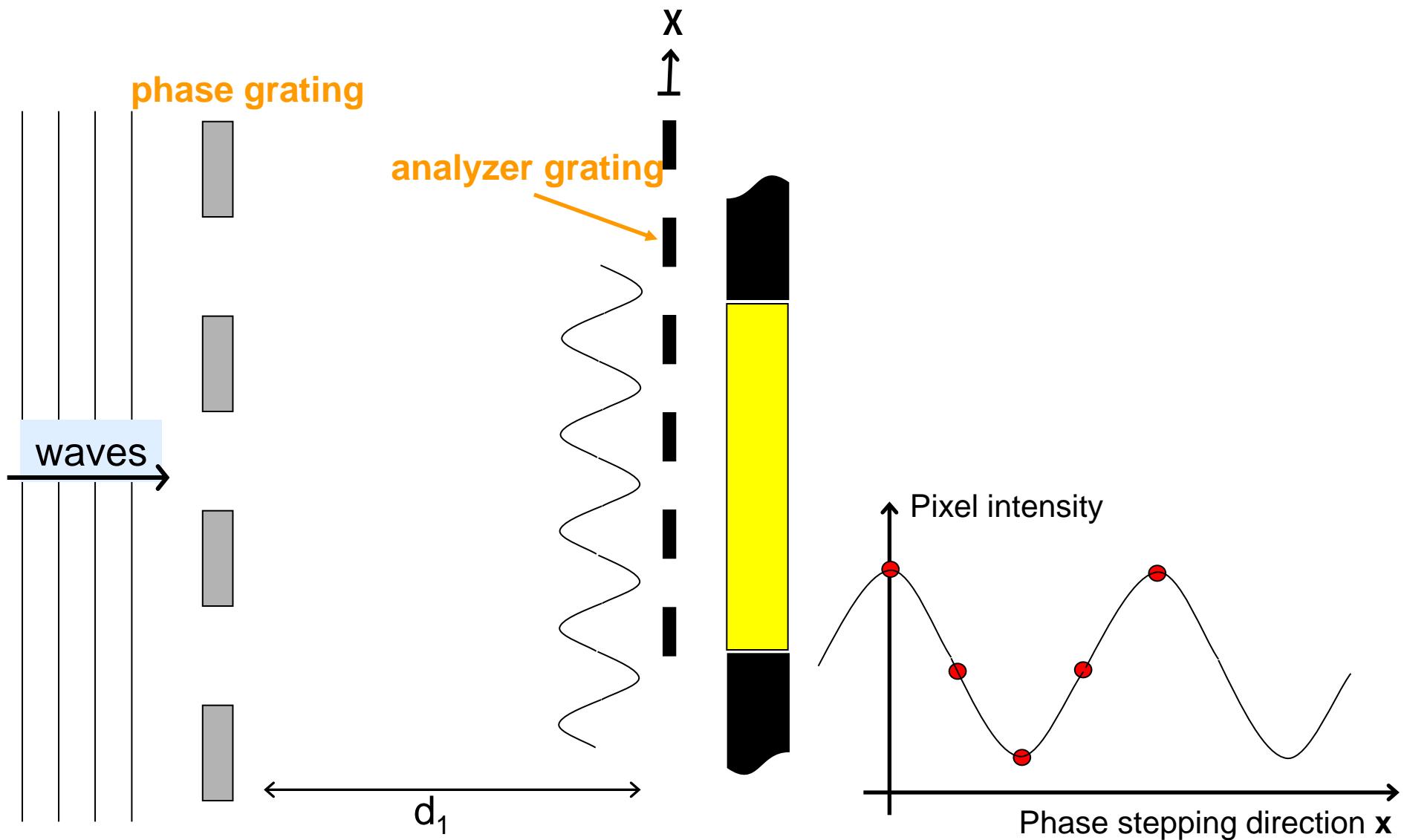
Phase stepping analysis



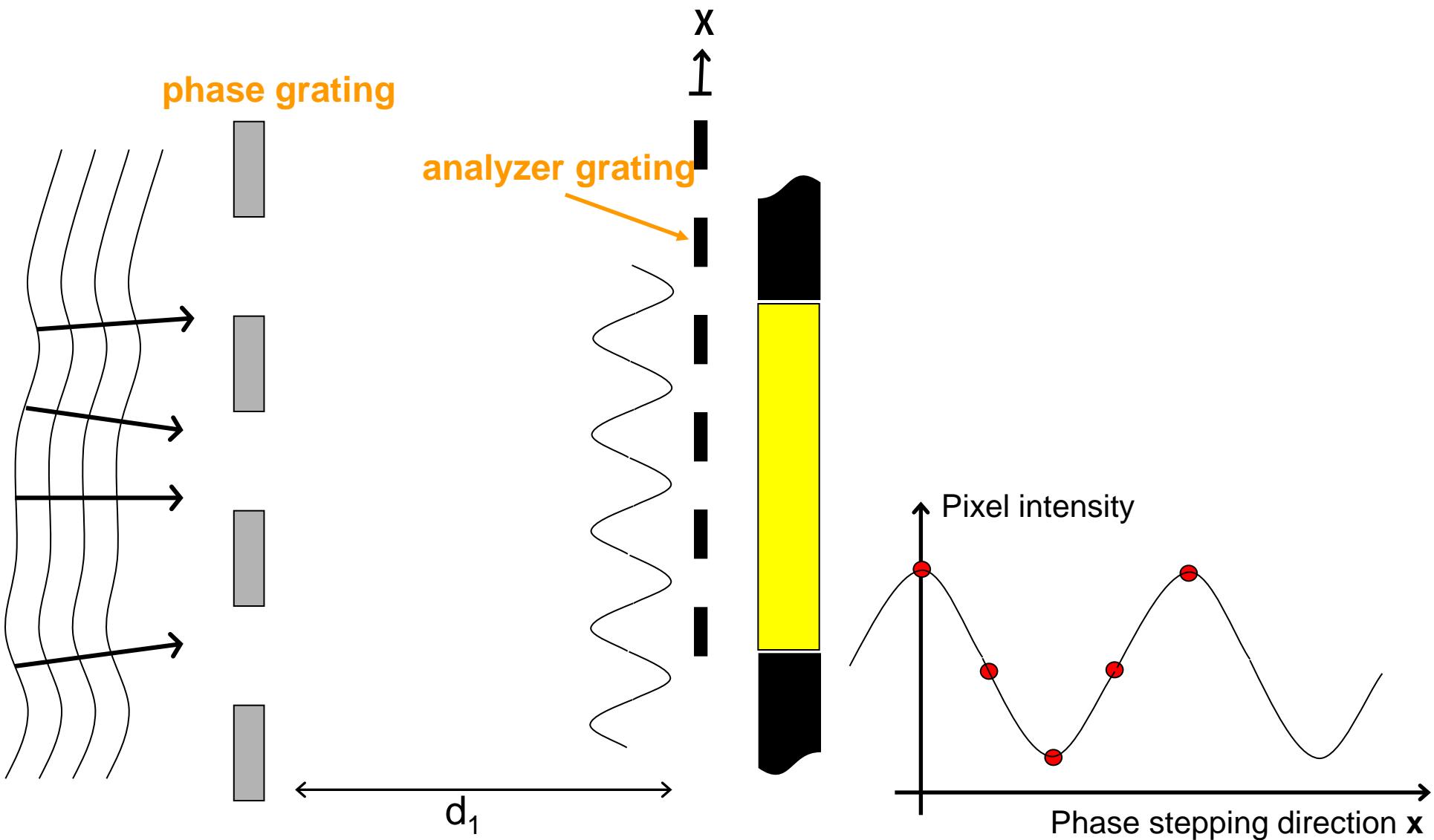
Phase stepping analysis



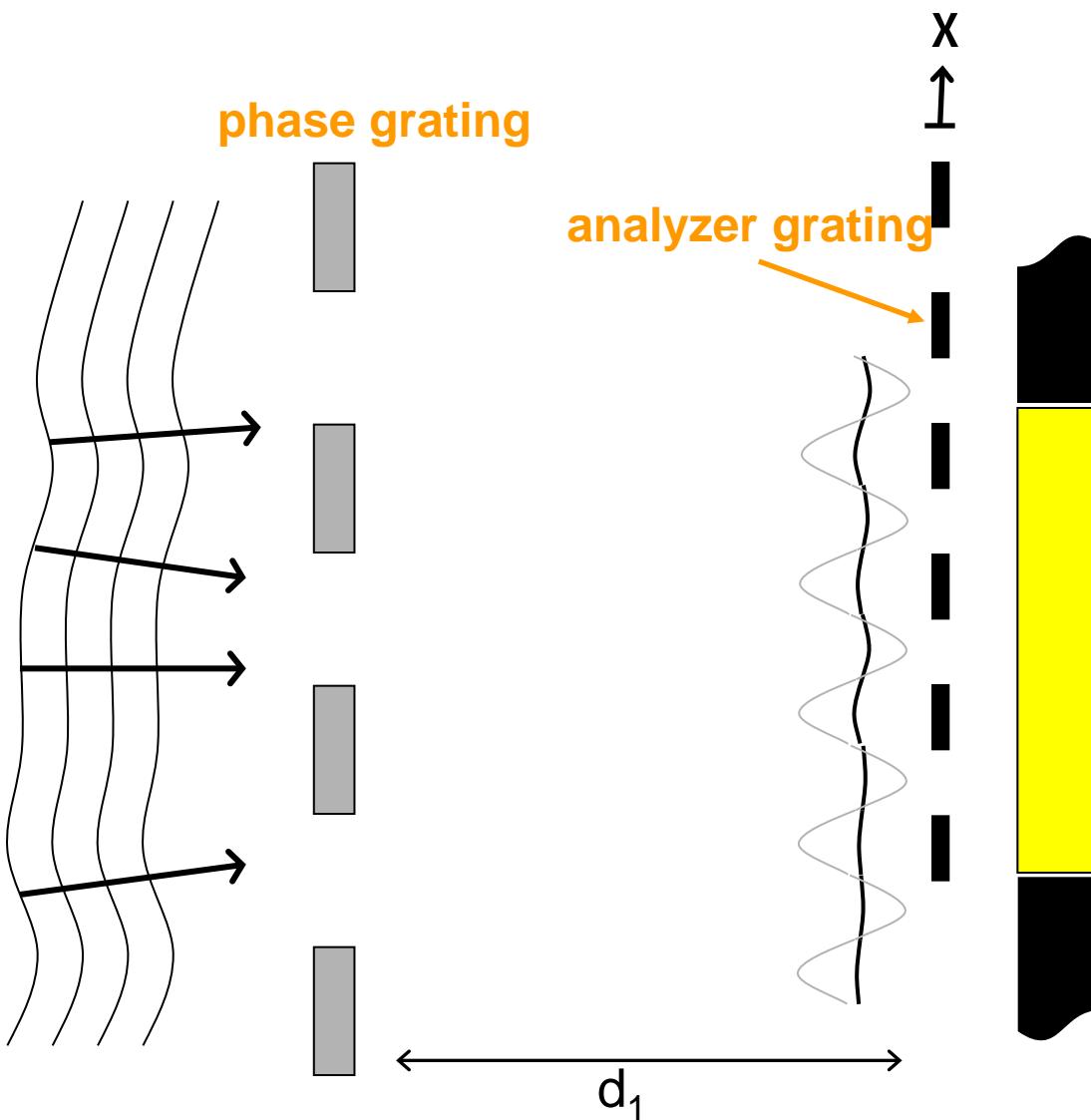
Phase stepping analysis



Phase stepping analysis

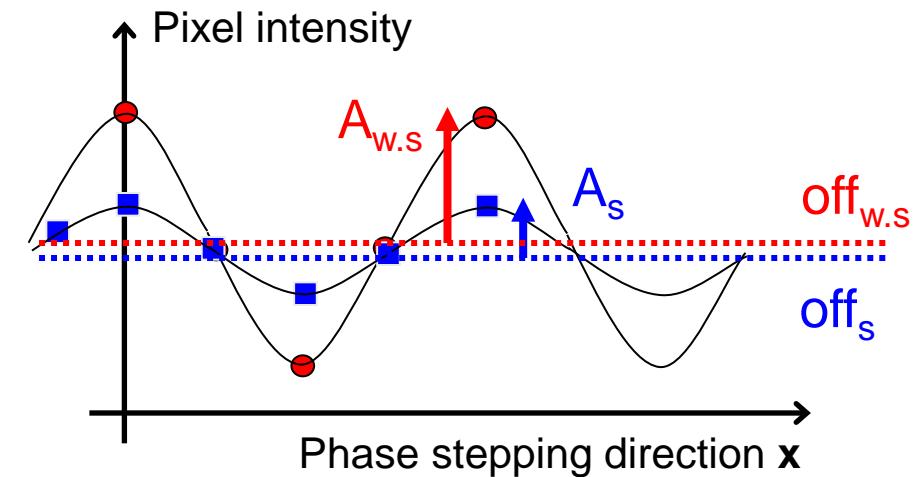


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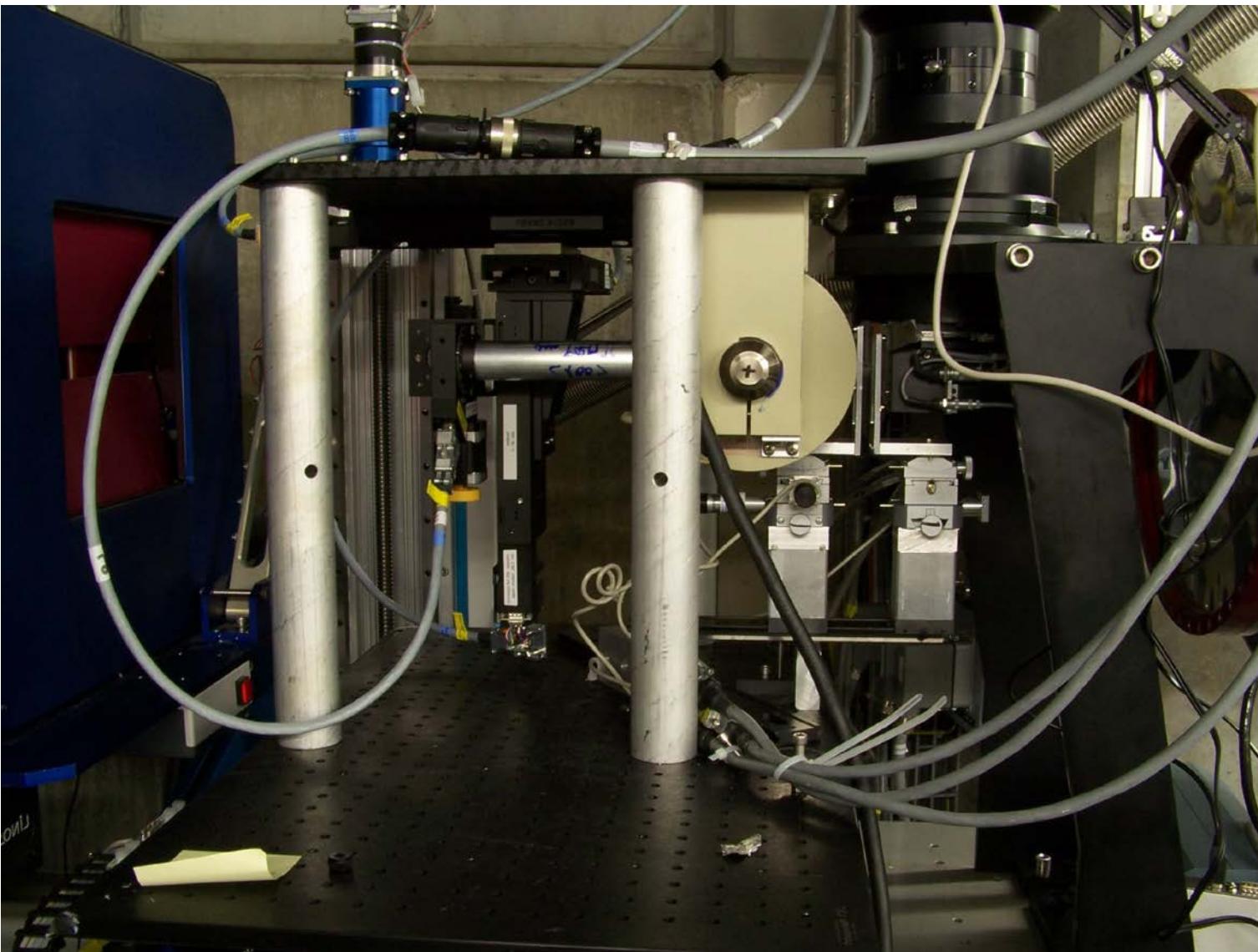


$$DFI = \frac{\frac{A_s}{off_s}}{\frac{A_{w.s}}{off_{w.s}}} = \frac{A_s \cdot off_{w.s}}{A_{w.s} \cdot off_s}$$

dark-field contrast

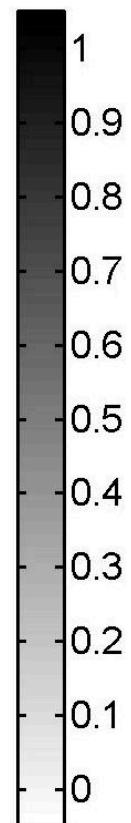
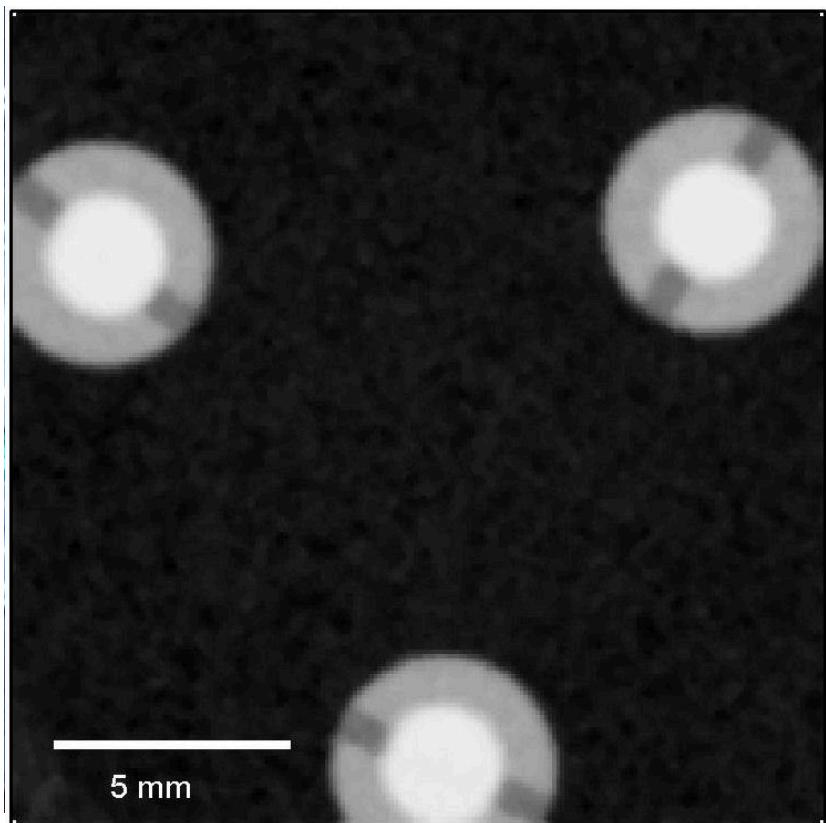


Neutron grating interferometry: the setup

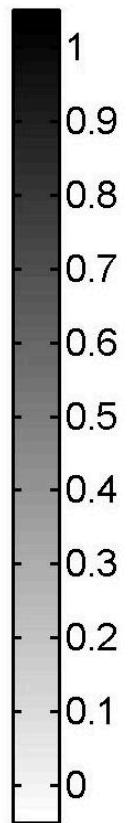
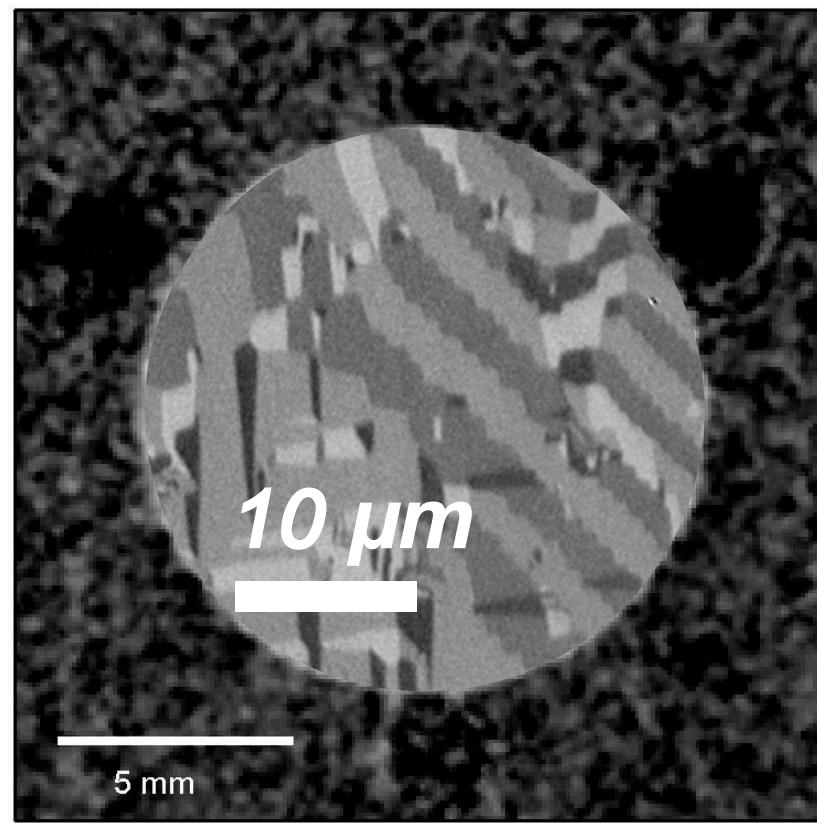


Experimental results: <100> FeSi(3%), 400 µm thick

transmission



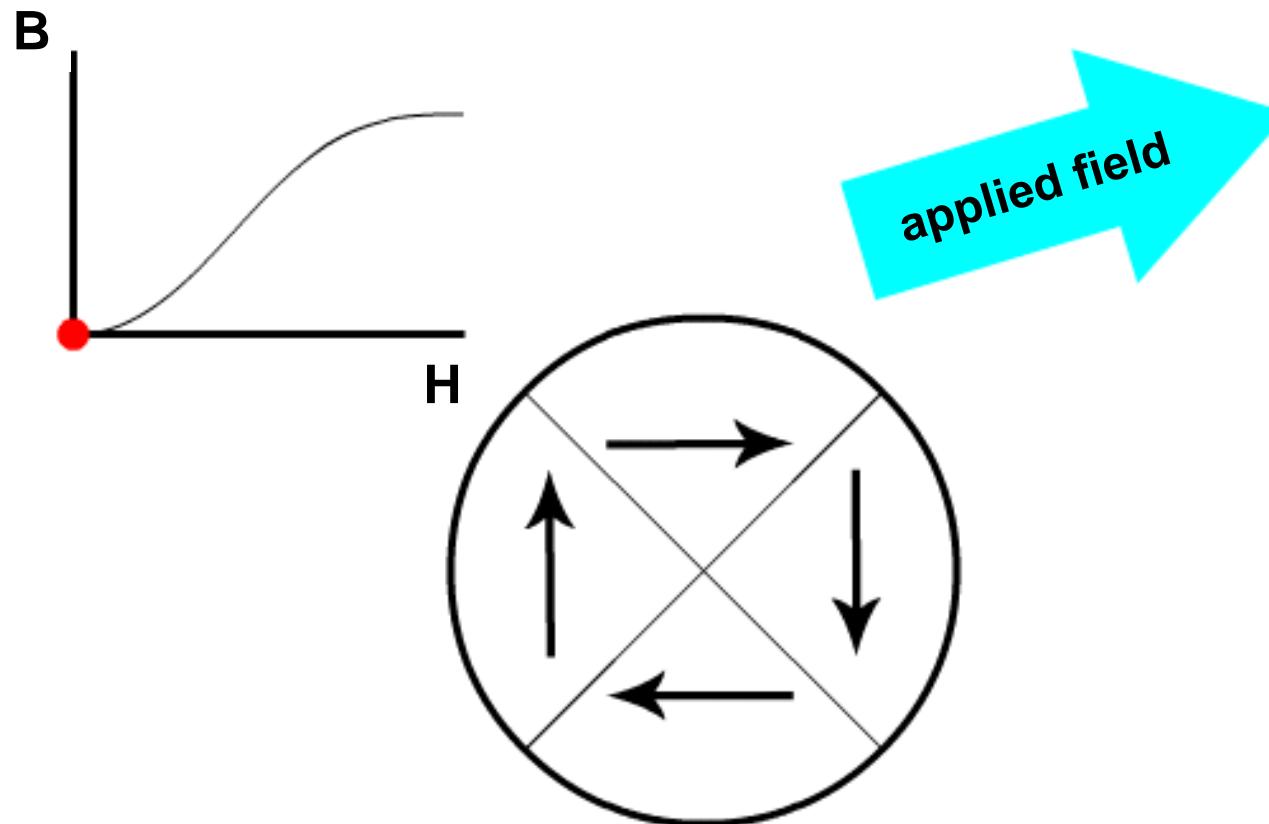
DFI



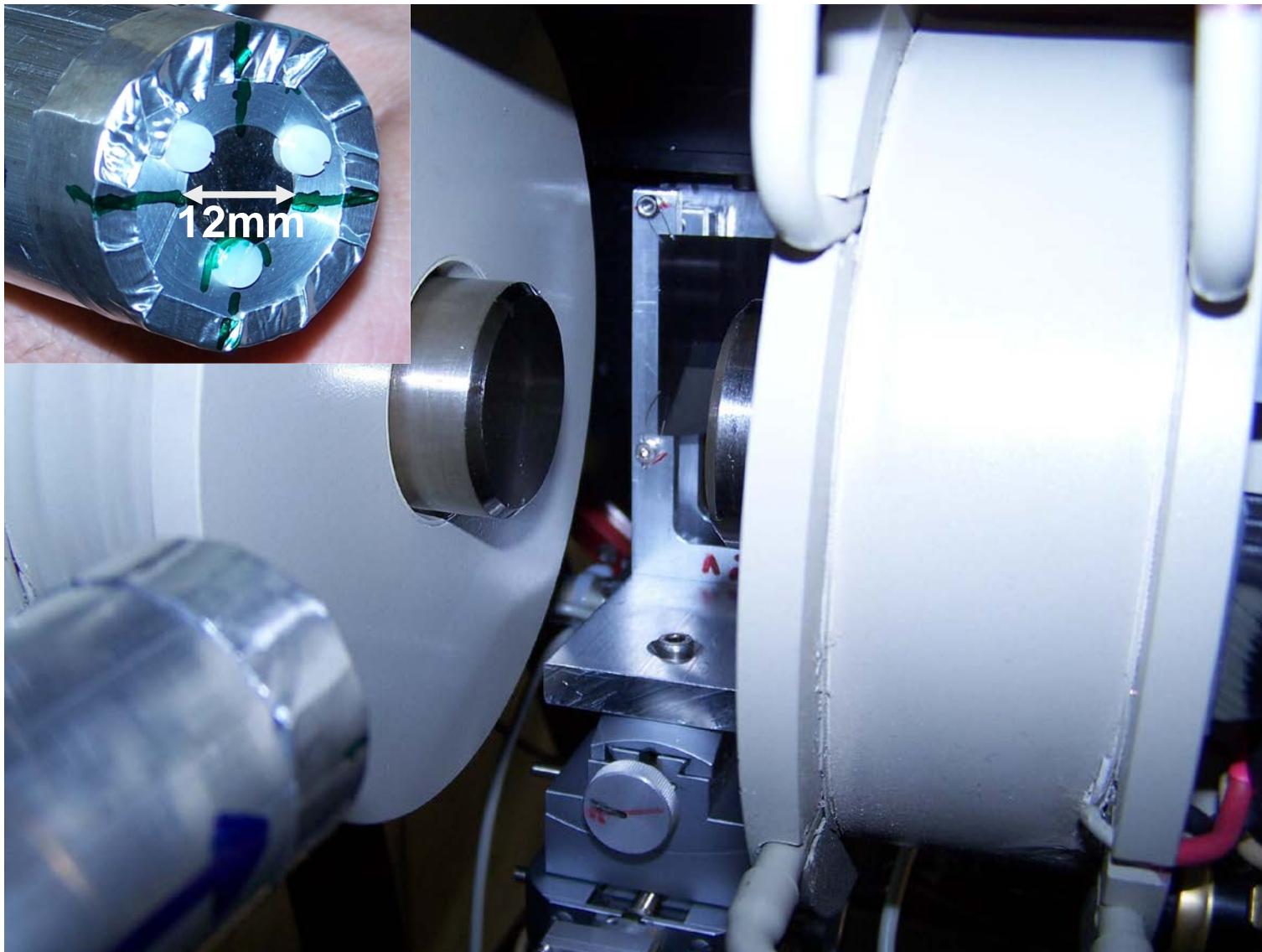
C. Grünzweig, C. David, O. Bunk, M. Dierolf, G. Frei, G. Kühne,
J. Kohlbrecher, R. Schäfer, P. Lejcek, H. Rønnow, and F. Pfeiffer.
Neutron decoherence imaging for visualizing bulk magnetic domain structures.
Phys. Rev. Lett. **101**, 025504 (2008).

magnetic field $\not\equiv 0$?

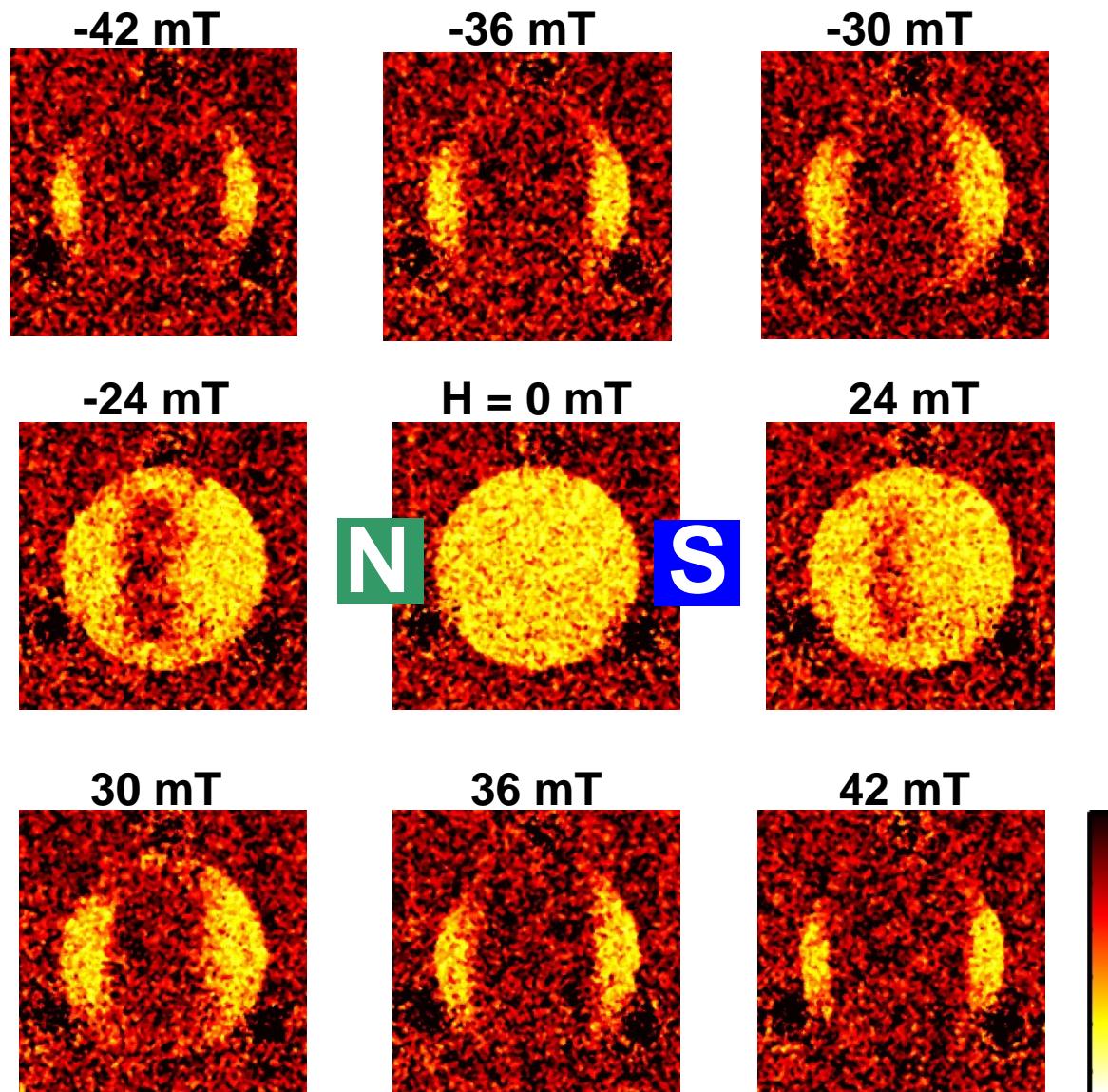
Magnetization process



Ramping of magnetic field



Magnetization process



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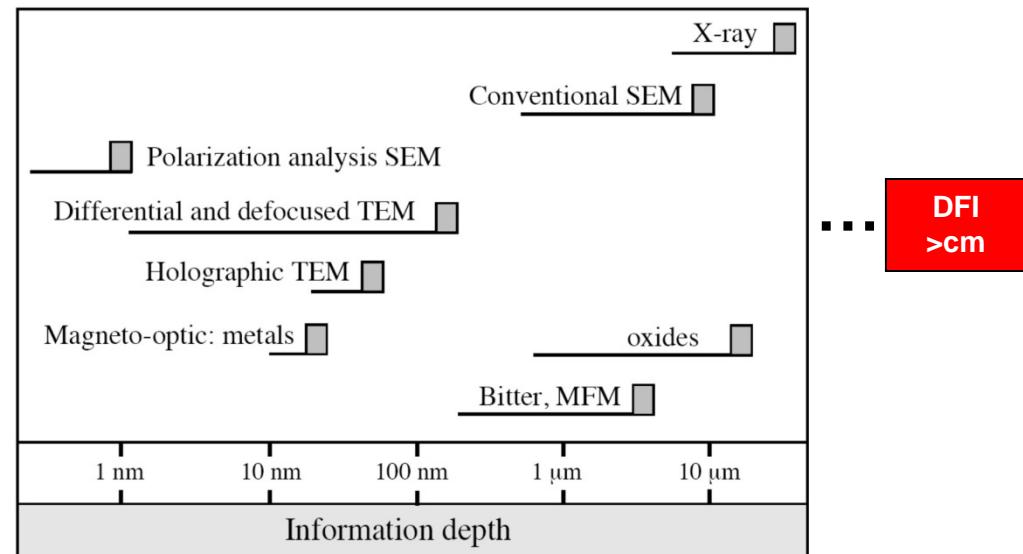
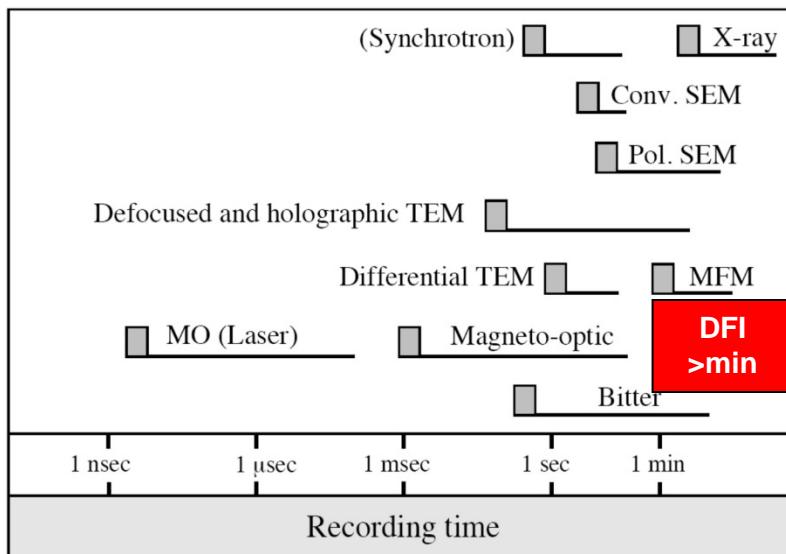
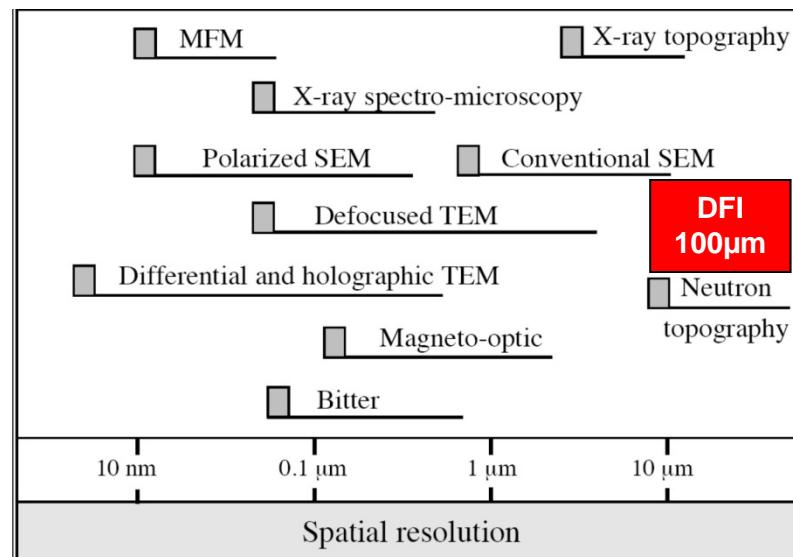
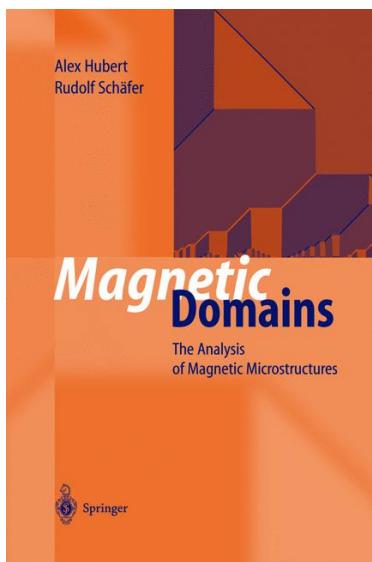
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Existing observation techniques for magnetic structures

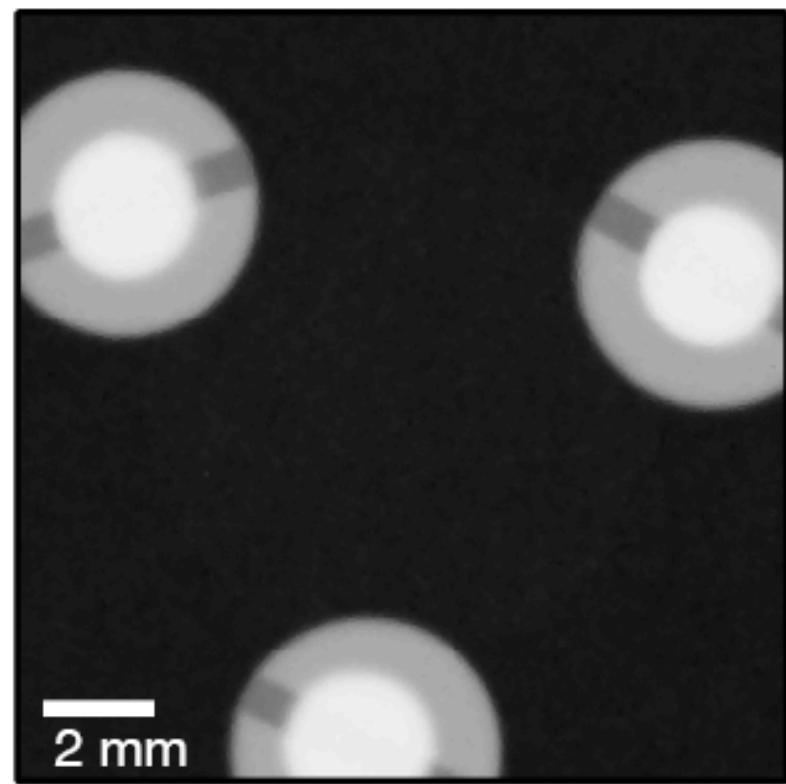


DFI
>cm

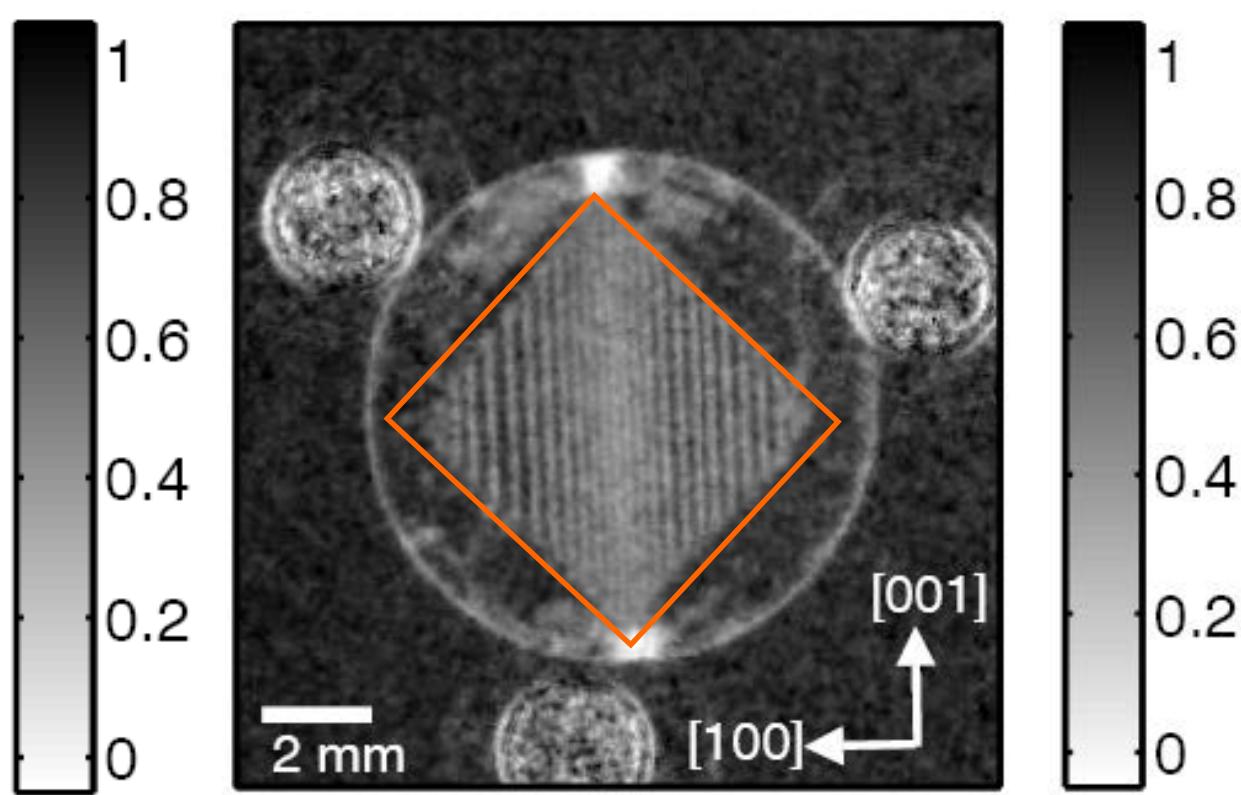
Magnetic domain structures

$<110>$ FeSi(3%), 300 μm thick

transmission

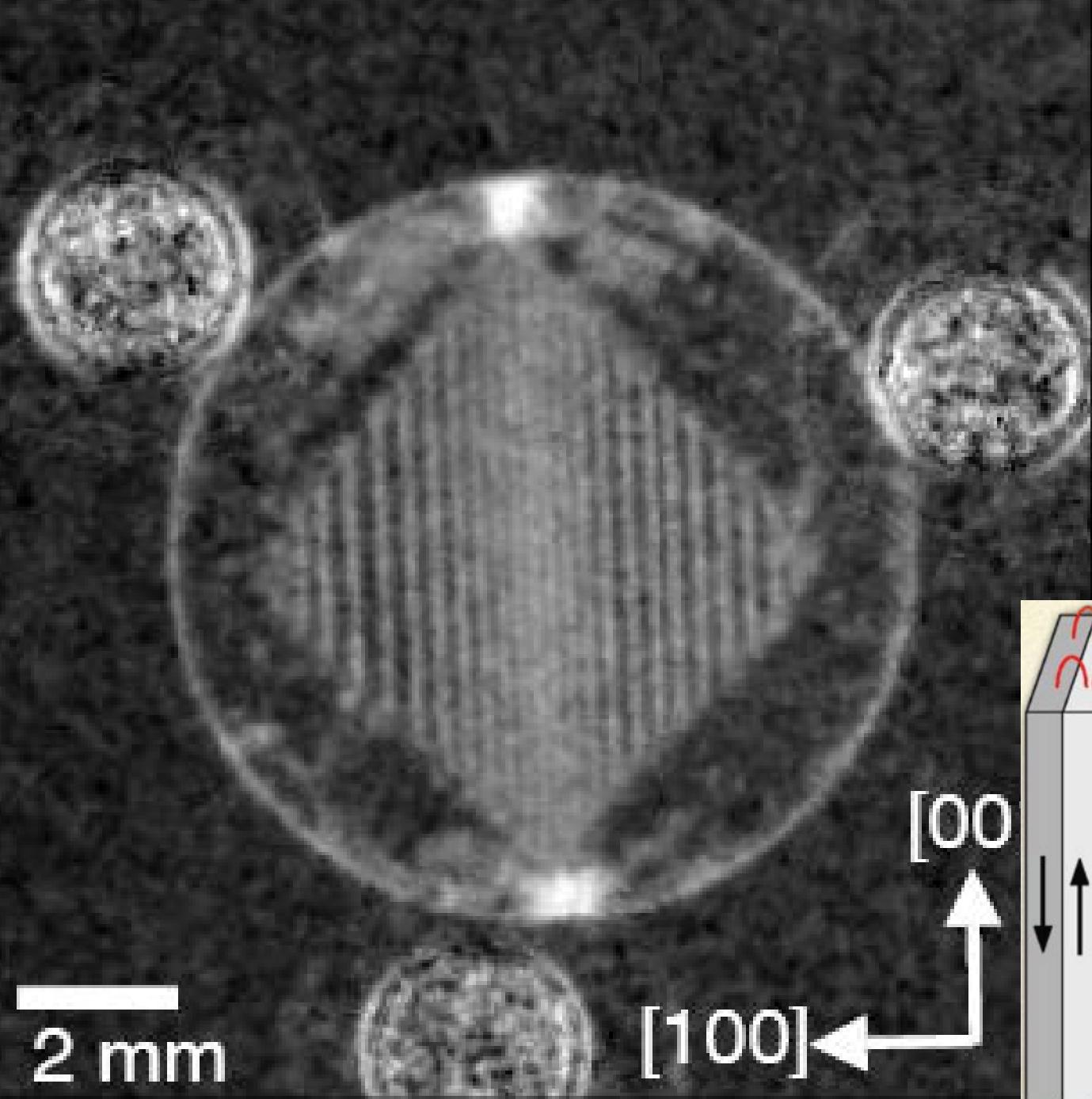


DFI

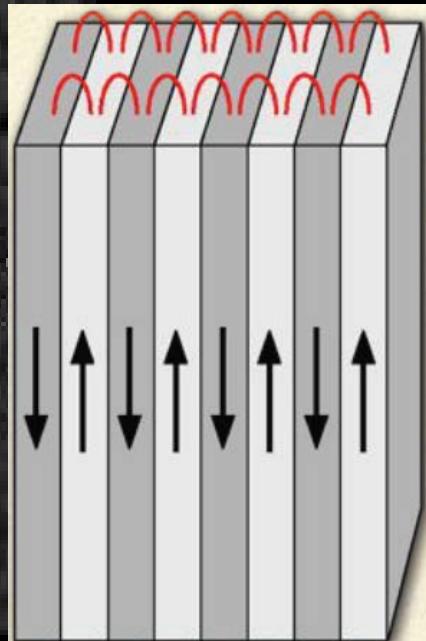


C. Grünzweig, C. David, O. Bunk, M. Dierolf, G. Frei, G. Kühne, R. Schäfer, S. Pofahl, H. Rønnow, and F. Pfeiffer.

Bulk magnetic domain structures visualized by neutron dark-field imaging.
Appl. Phys. Lett. **93**, 112504 (2008).

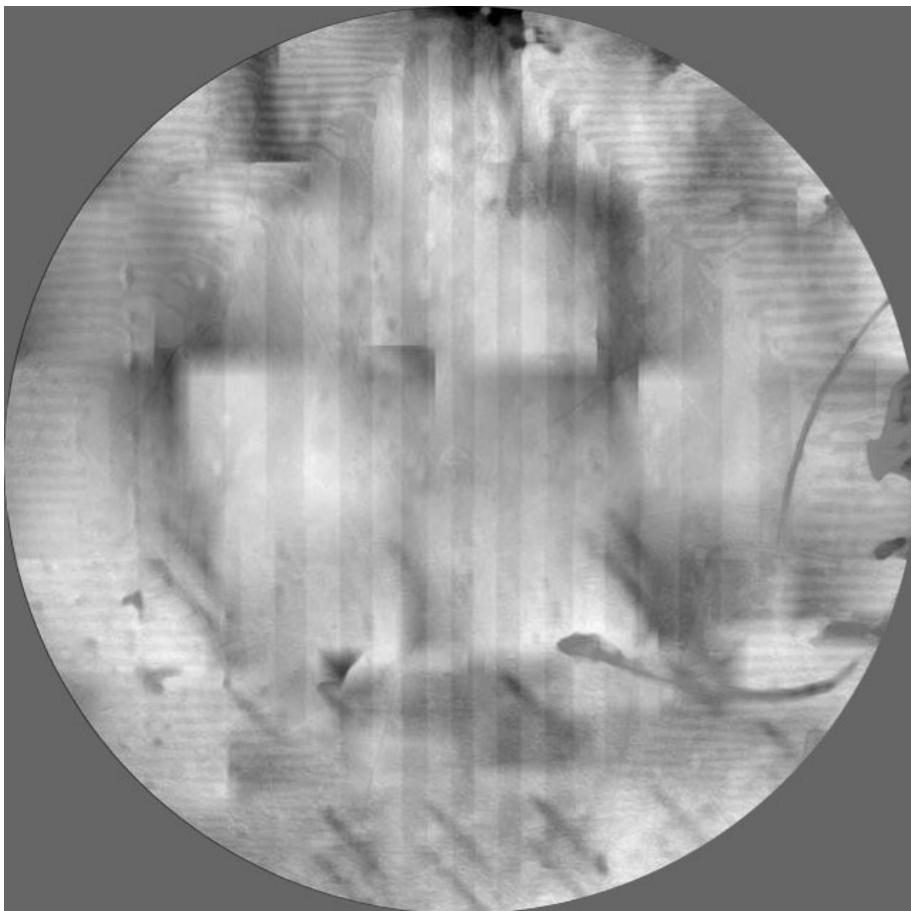


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[100]

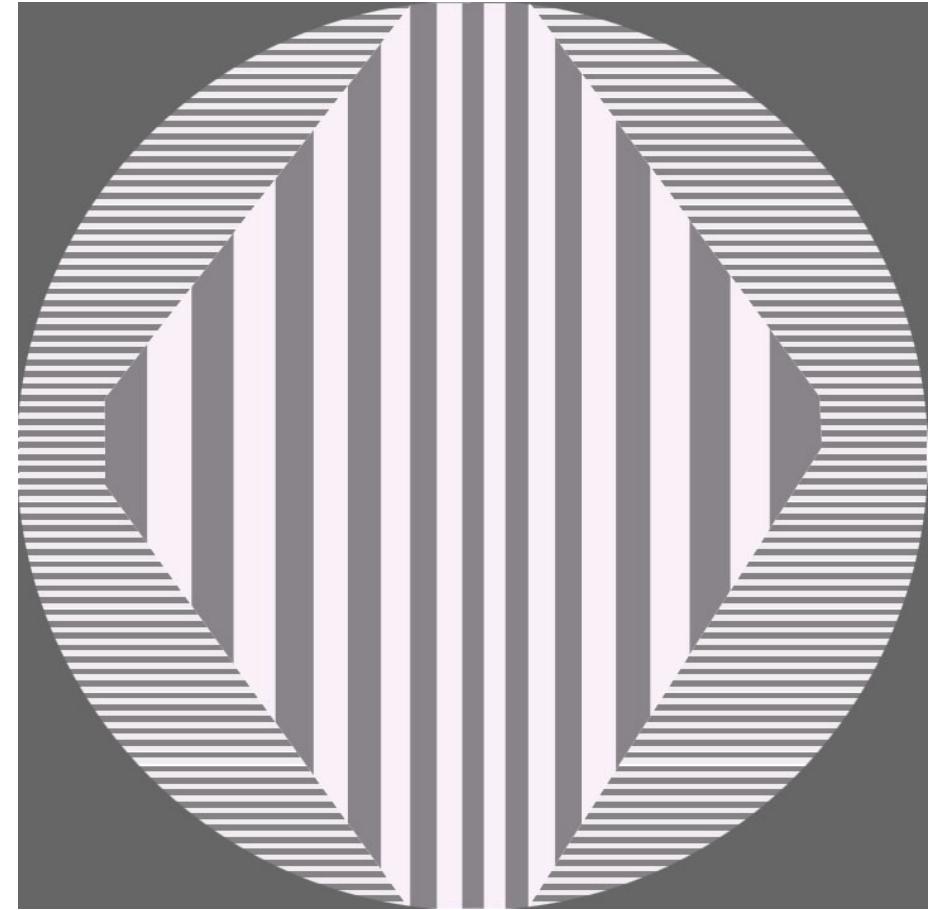


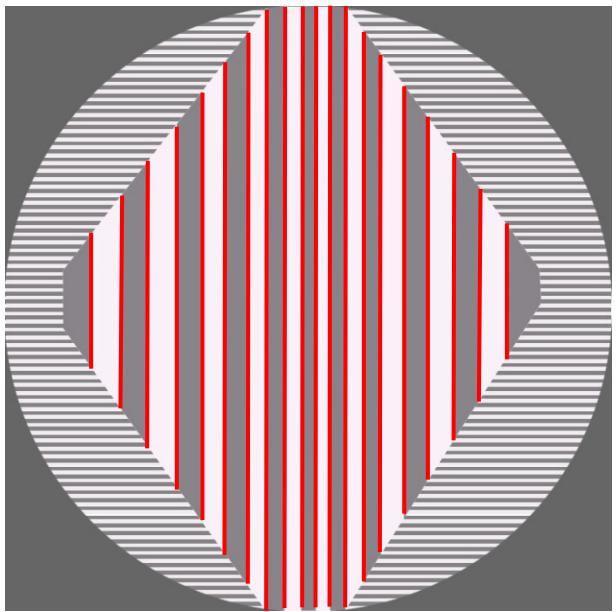
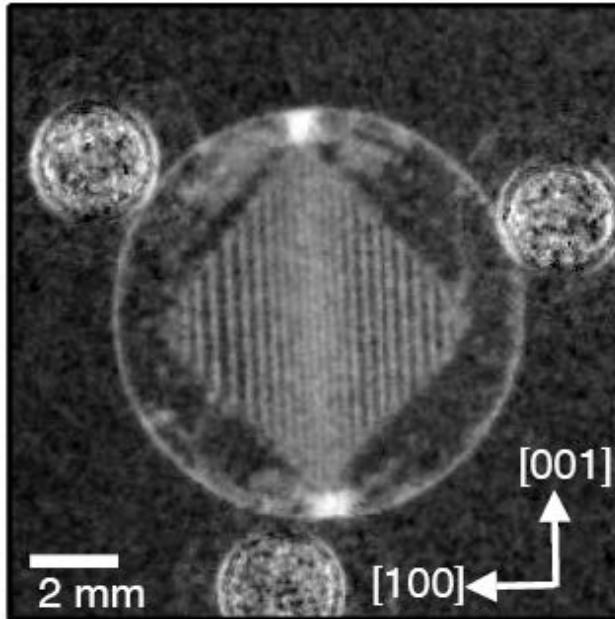
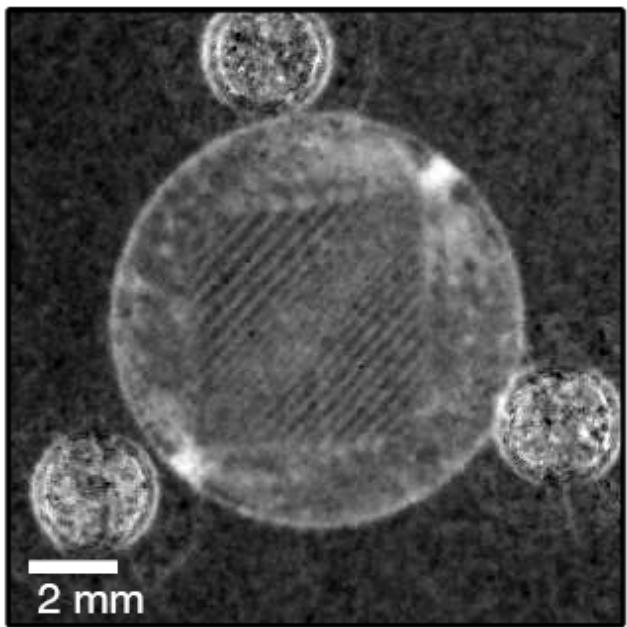
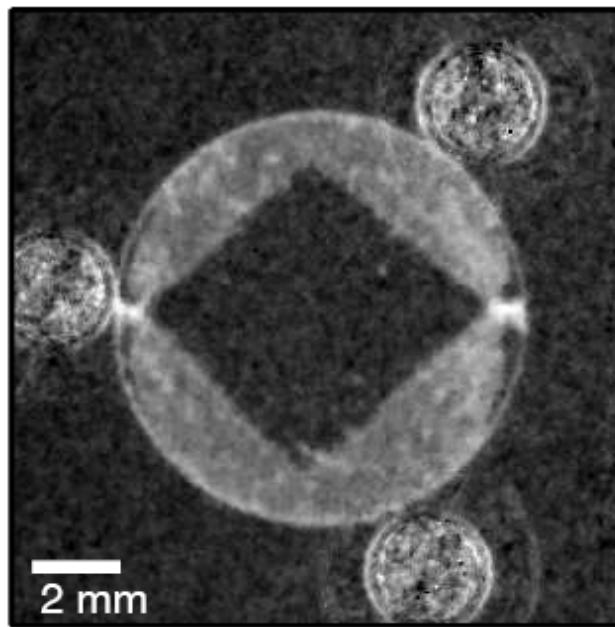
MOKE measurements: Verification of the DFI

MOKE



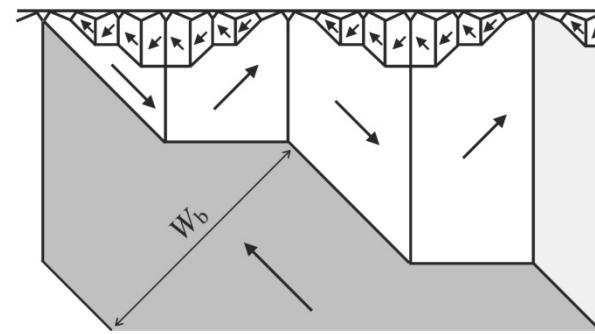
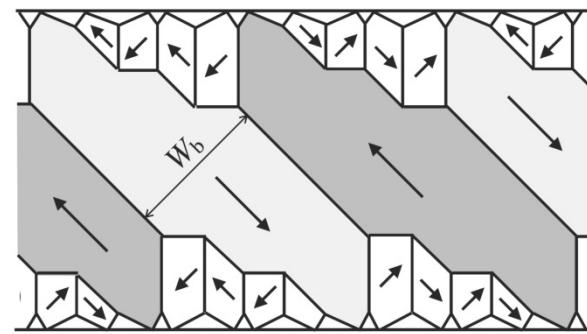
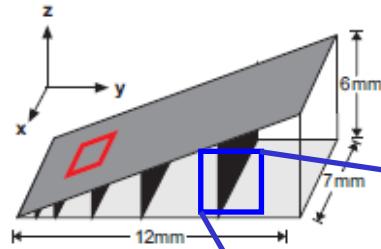
schematical map



$\omega = 0^\circ$  $\omega = 0^\circ$  $\omega = 45^\circ$  $\omega = 90^\circ$ 

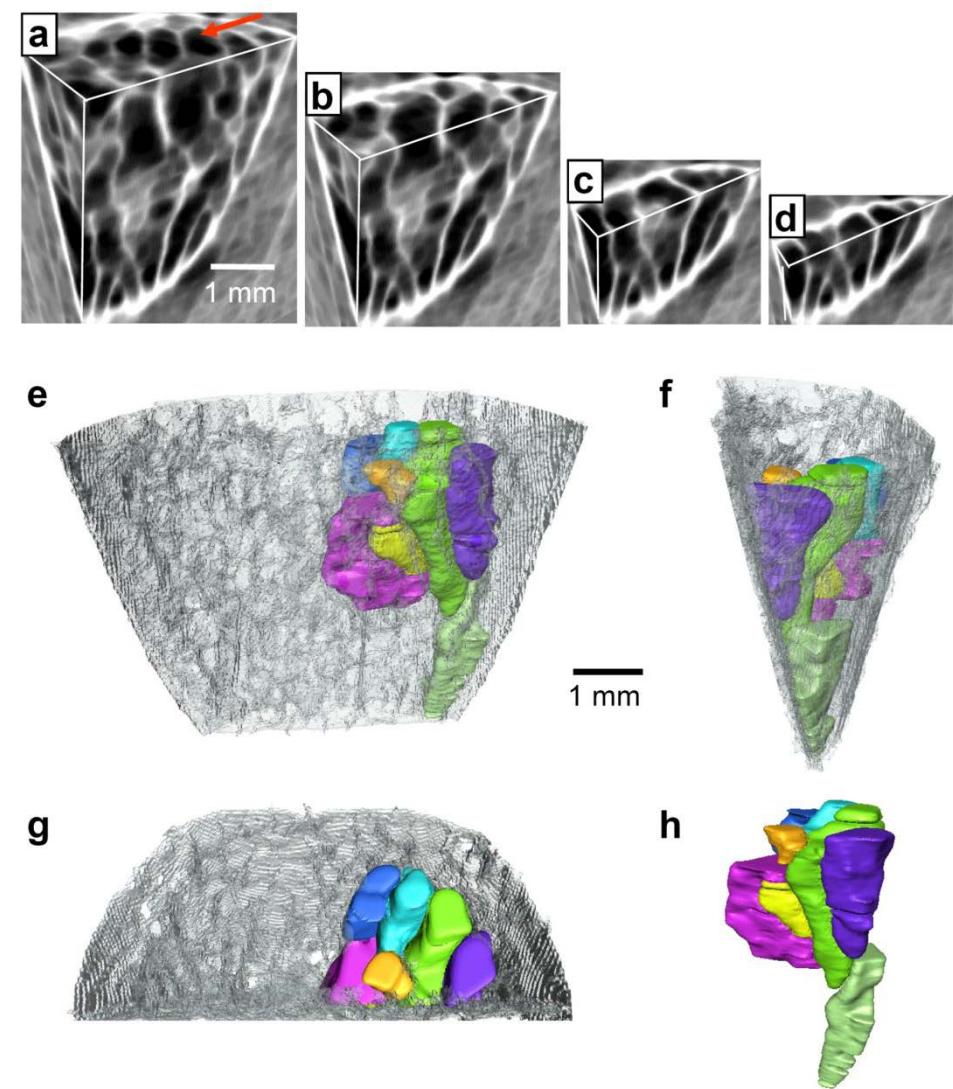
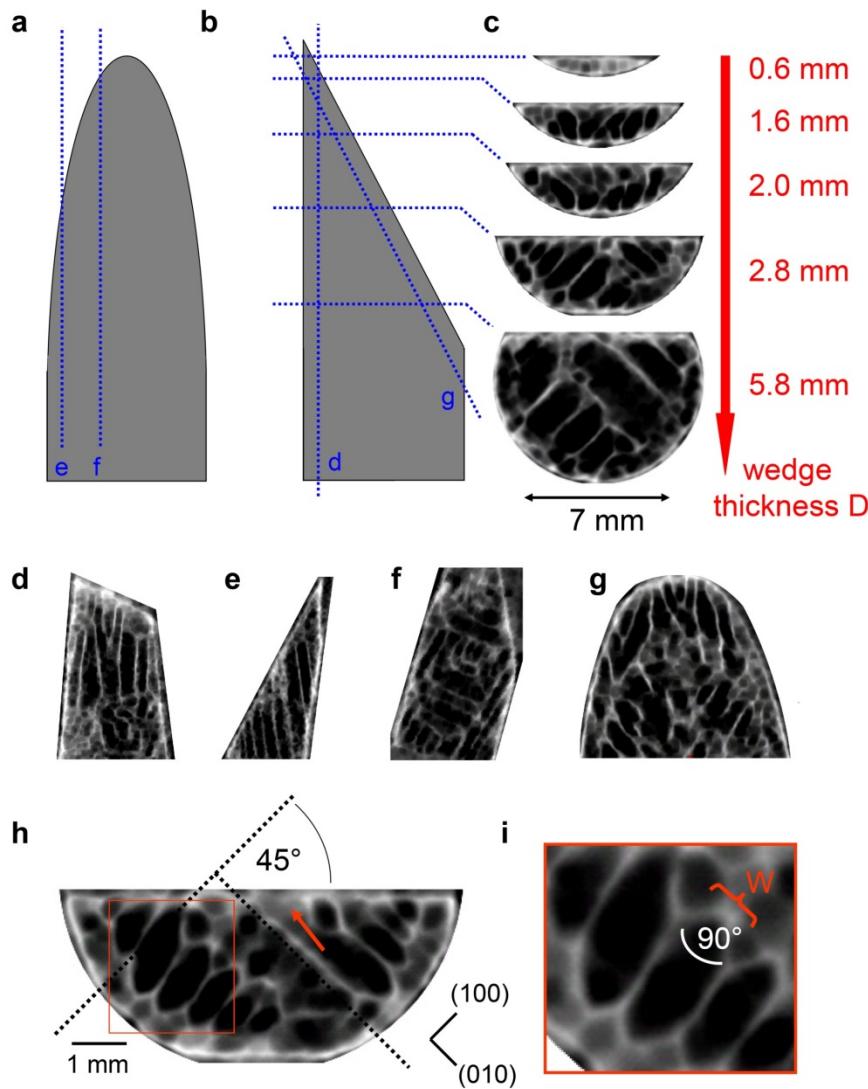
Tomography of magnetic domains

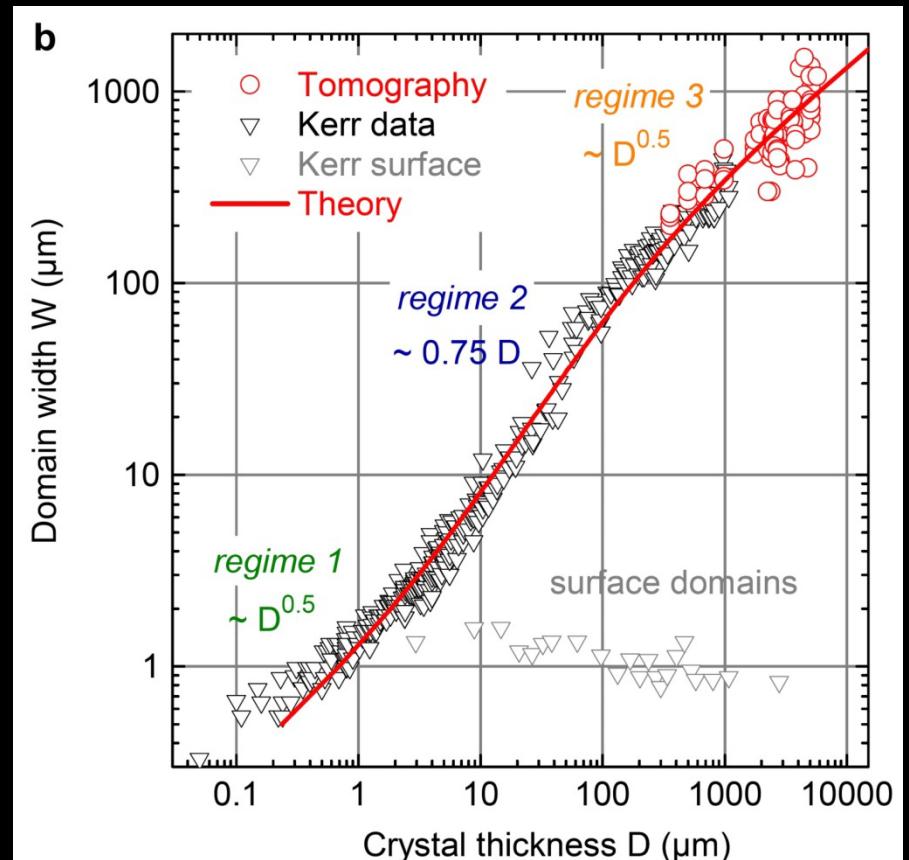
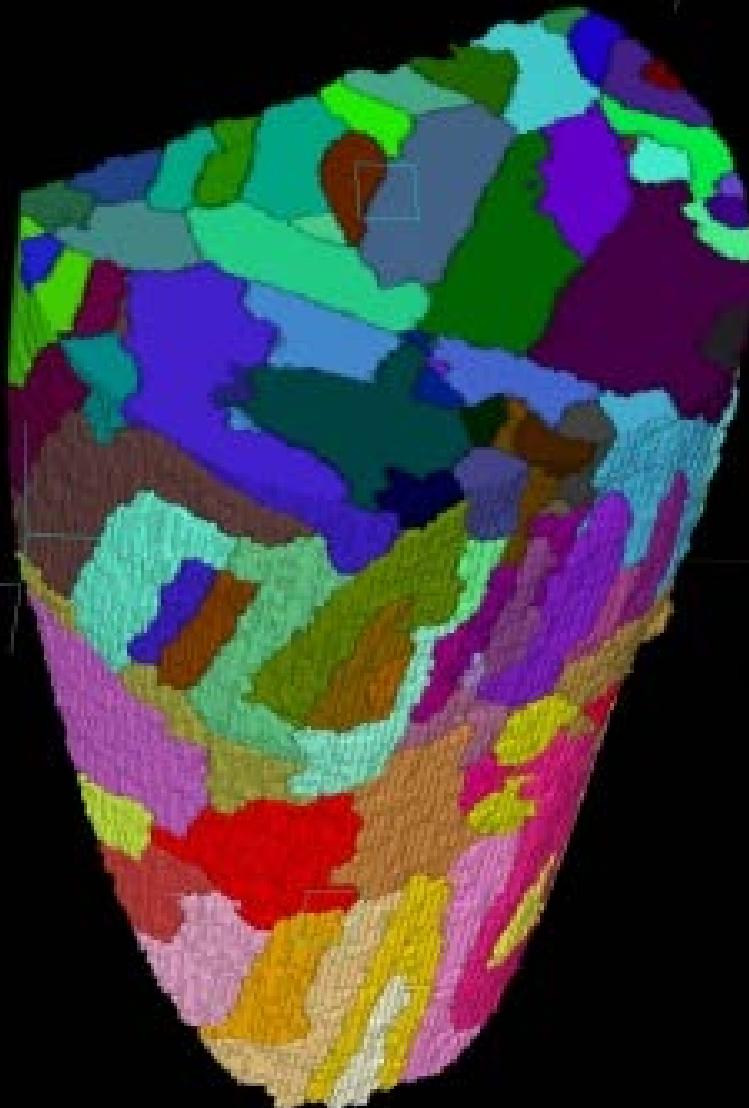
(a)



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

Tomography of magnetic domains





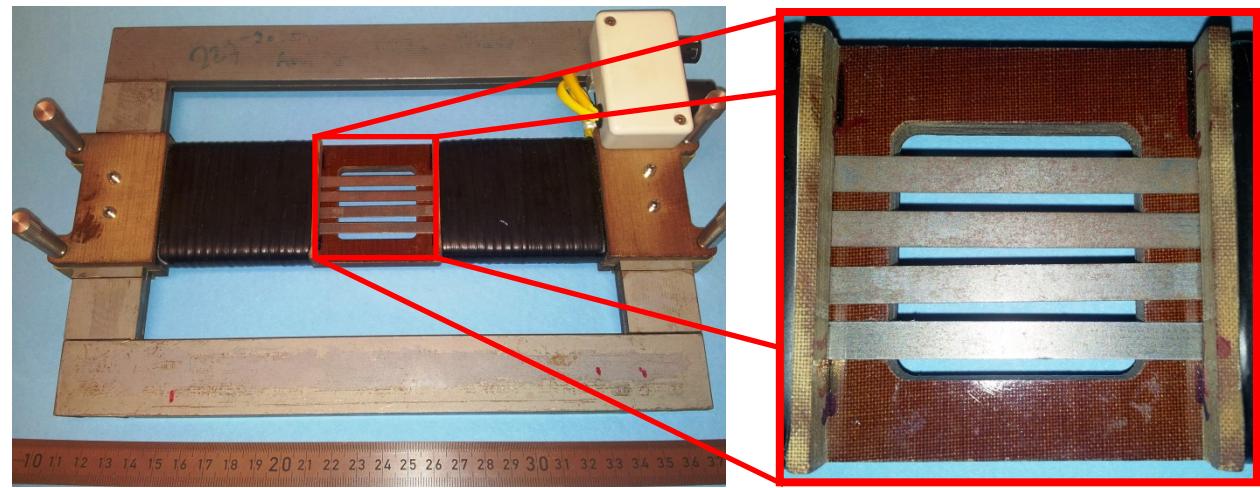
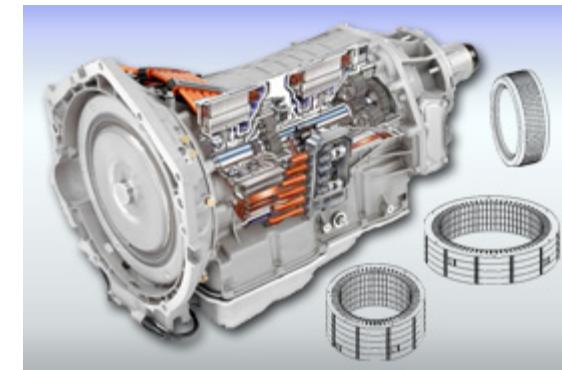
I. Manke, N. Kardjilov, R. Schäfer, A. Hilger, M. Strobl, M. Dawson,
C. Grünzweig, G. Behr, M. Hentschel, C. David, A. Kupsch, A. Lange, J. Banhart.
Three-dimensional imaging of magnetic domains.
Nature Communications 1 (8), p.125 (2010).

Deterioration effects in NO steel laminations

Non-oriented (NO) electrical steel have :

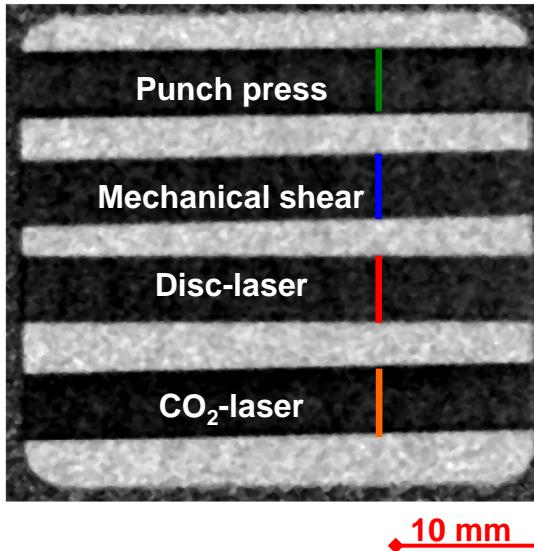
- isotropic domains
- domains size $\sim 5 \mu\text{m}$

and used e.g. in electrical motors/generators

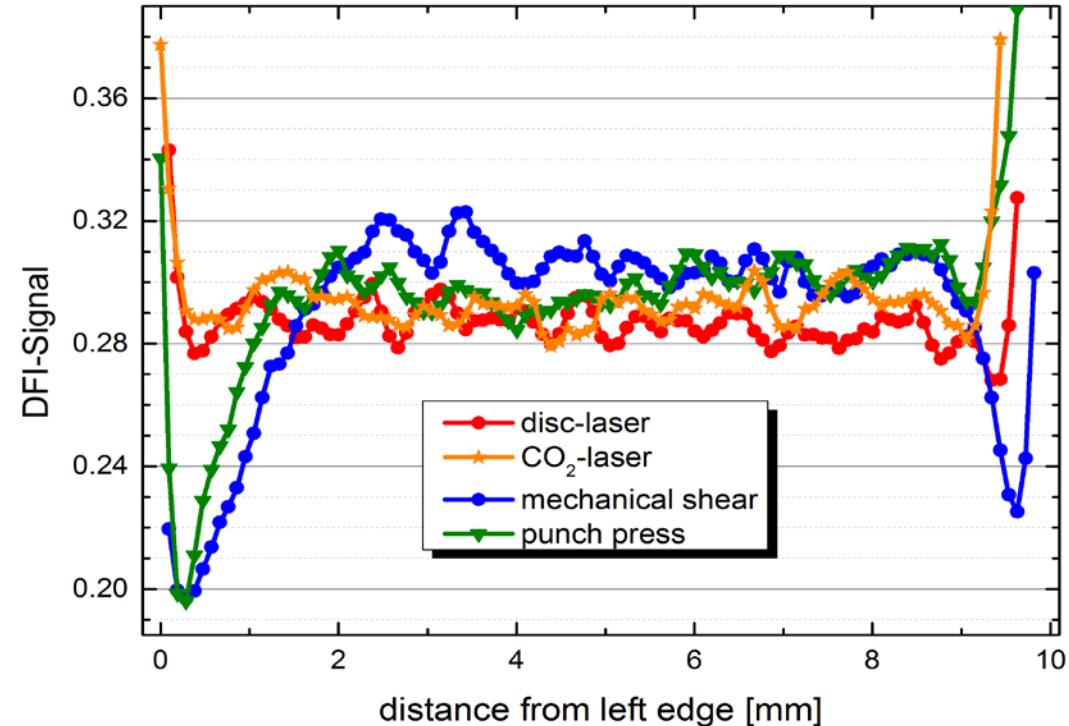


Deterioration effects in NO steel laminations

DFI at 1500 A/m



DFI at 1500 A/m



4 different types of cutting:

- punch press (one side)
- mechanical shear
- Disc-laser
- CO₂-laser

Due to the cutting process,
magnetic properties are influenced !
-> Increasing the efficiency of electrical machines

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)

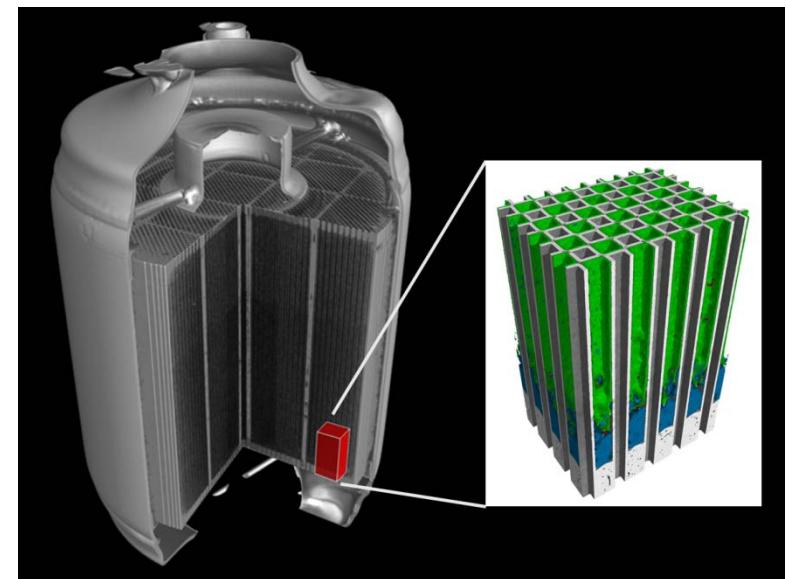
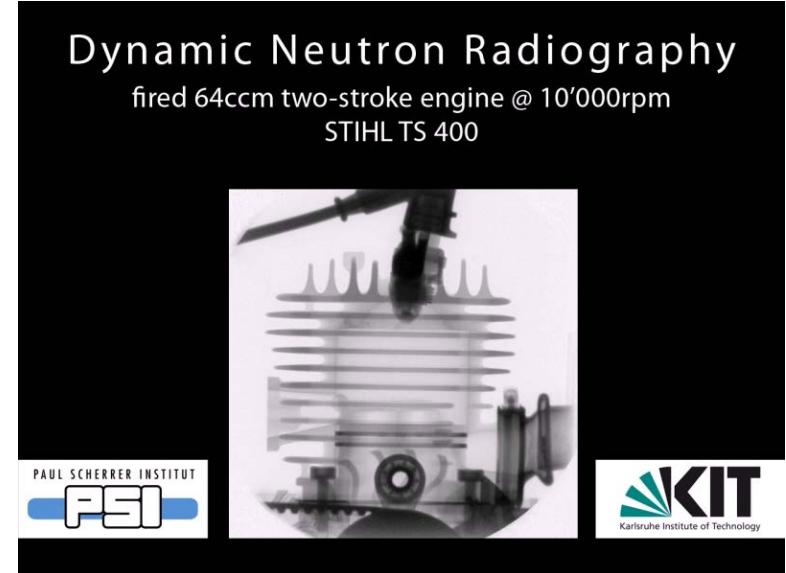
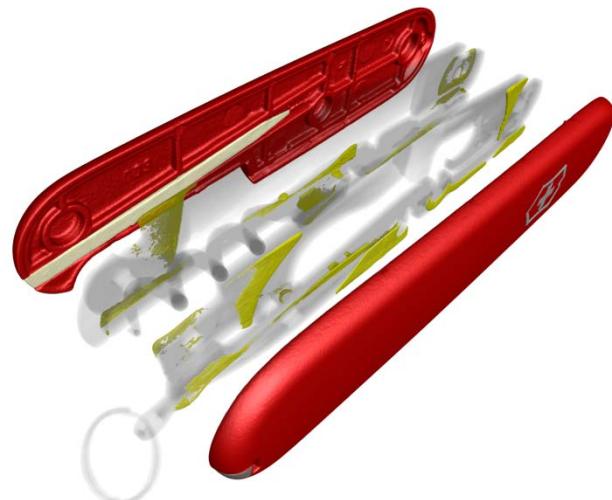
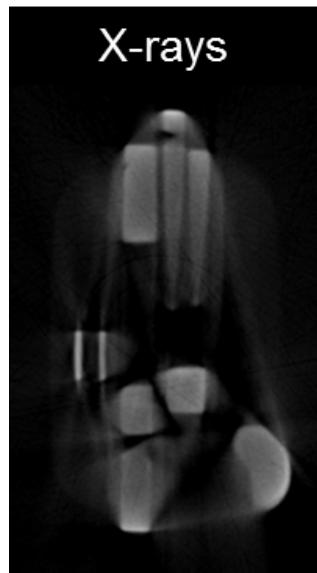
- The setup and working principle
- Refraction of unpolarized neutrons at magnetic domain walls
- Magnetic contrast: Dark-field image (DFI)

III) DFI results of imaging bulk ferromagnetic samples

- Magnetic domain structures in 2D/3D
- Magnetic domain structures and “saving” energy

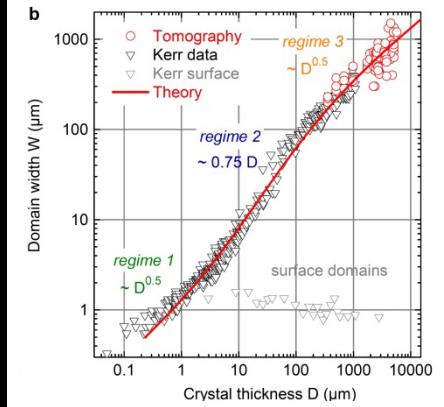
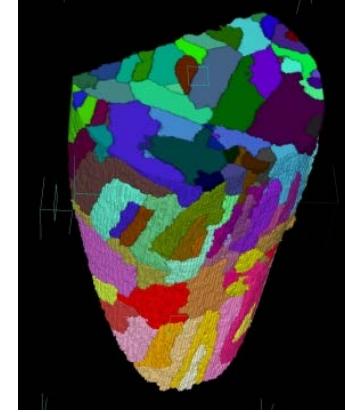
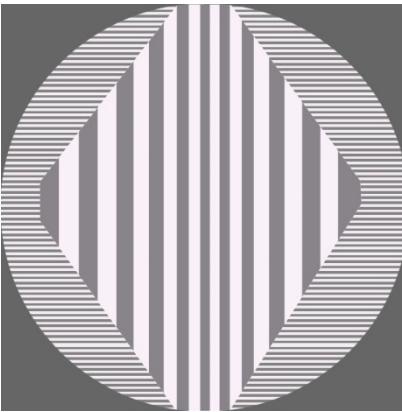
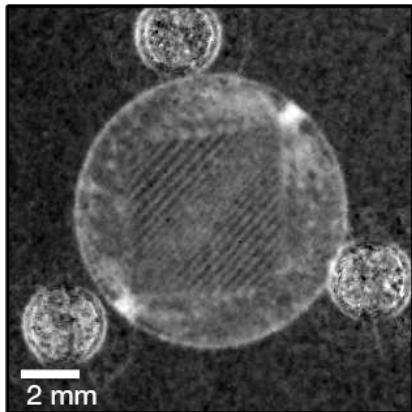
V) Summary

Summary I: classical neutron imaging



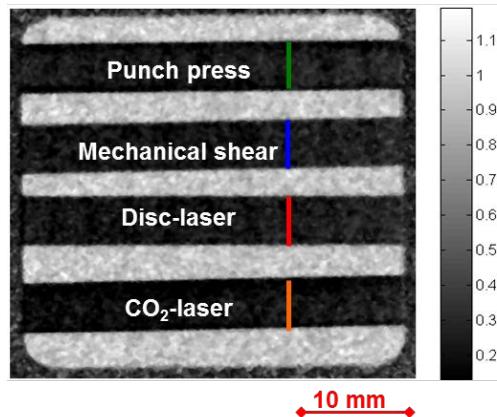
Summary II: neutron grating interferometry

Imaging bulk magnetic domain structures

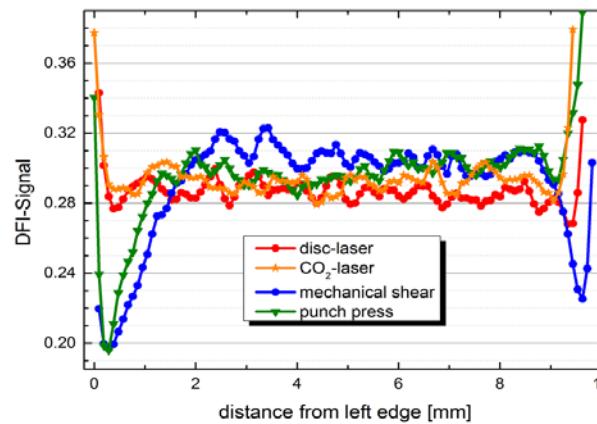


Improving electrical machines

DFI at 1500 A/m



DFI at 1500 A/m



Announcement: open PhD position



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

Laboratory for Neutron Scattering and Imaging

AUSBILDUNG & STELLEN VERANST

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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 you for the attention !



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