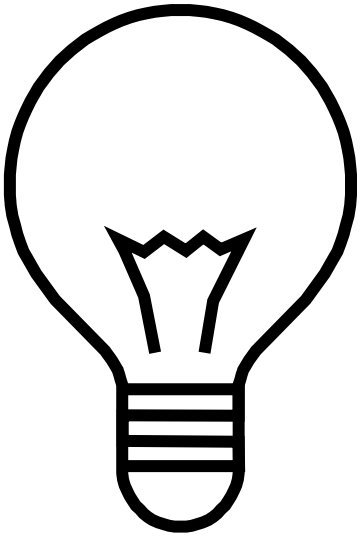
HZB Helmholtz Zentrum Berlin

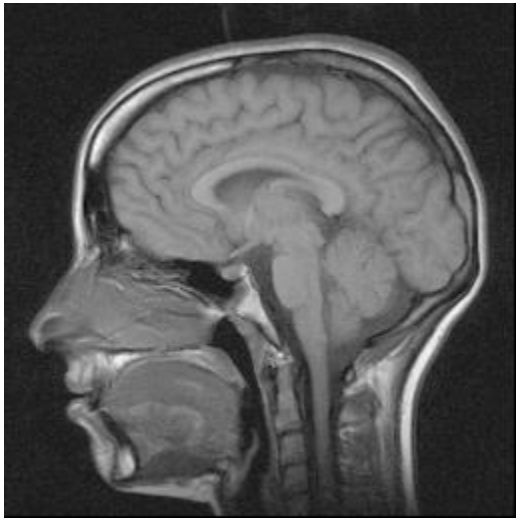
SwedNESS: Real-Space Neutron Imaging

Polarised Neutron Imaging

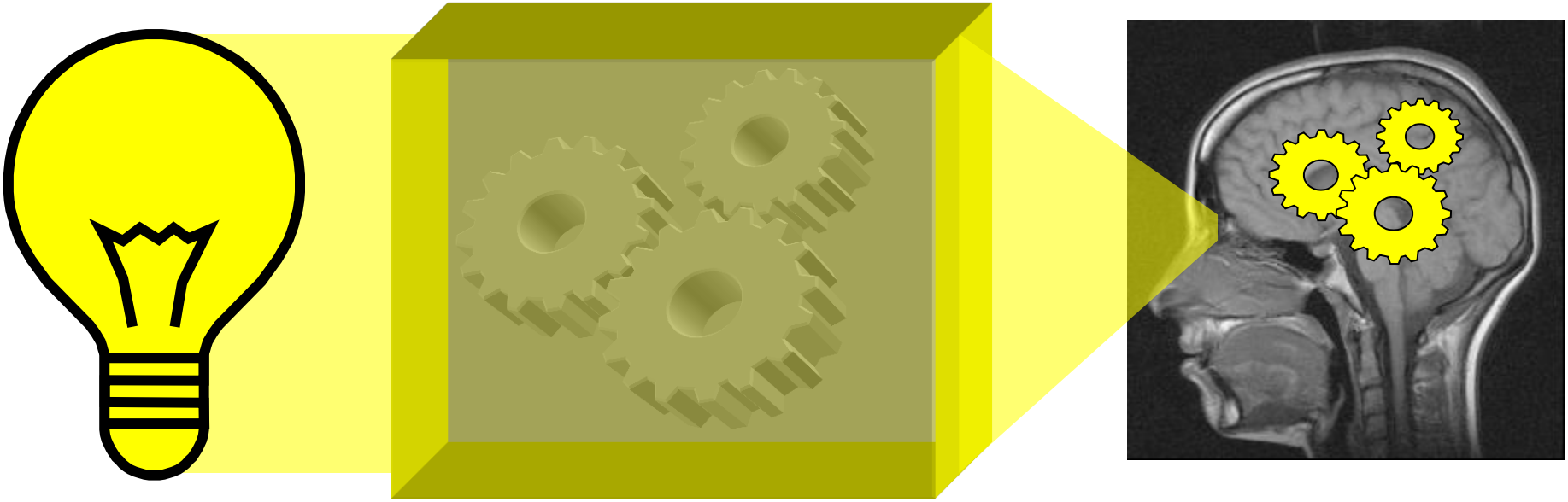
Nikolay Kardjilov, André Hilger, Henning Markötter, Ingo Manke

Neutron imaging



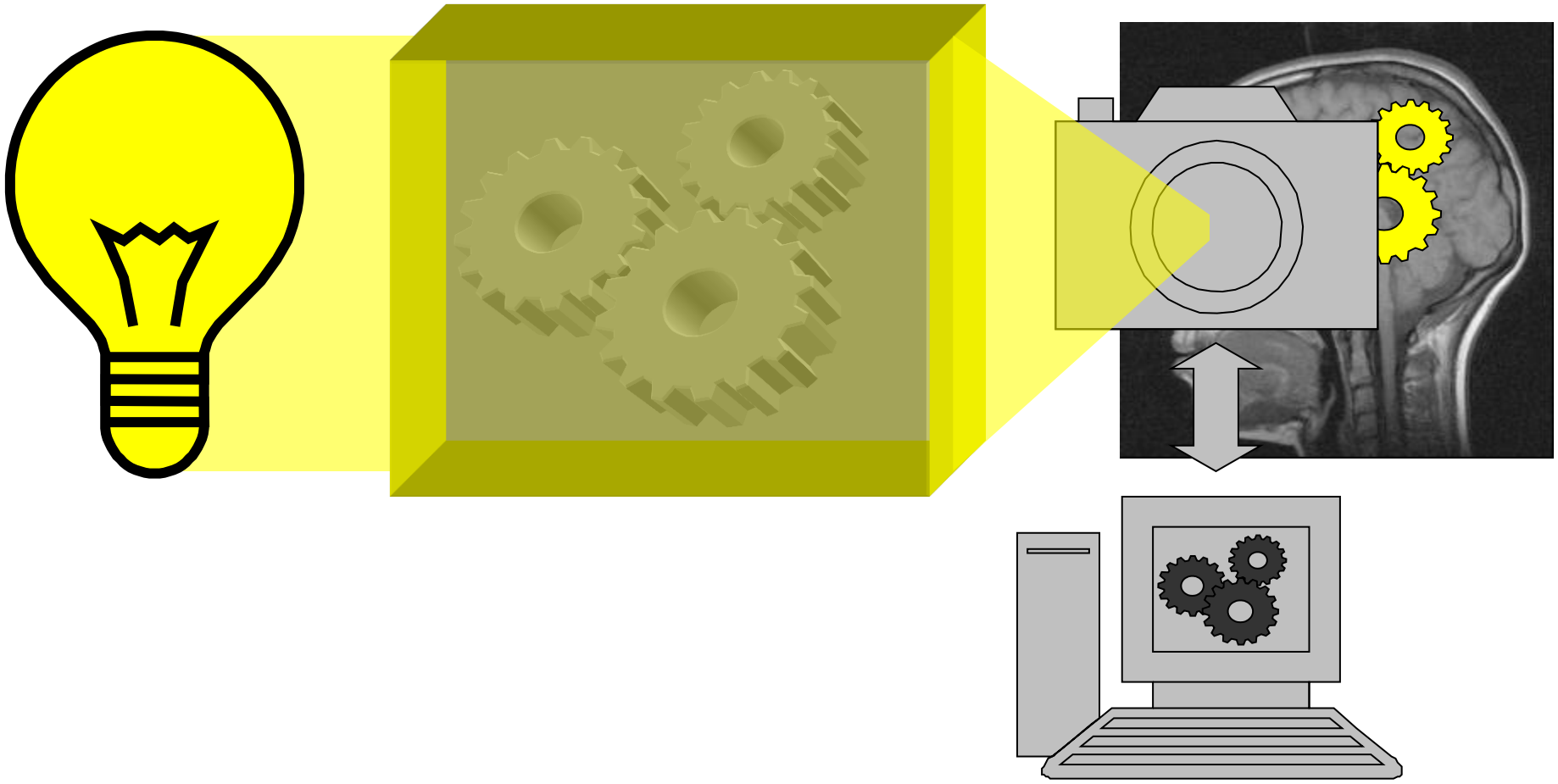


Neutron imaging



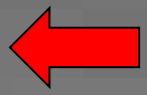
Neutron imaging

Source Sample Detector

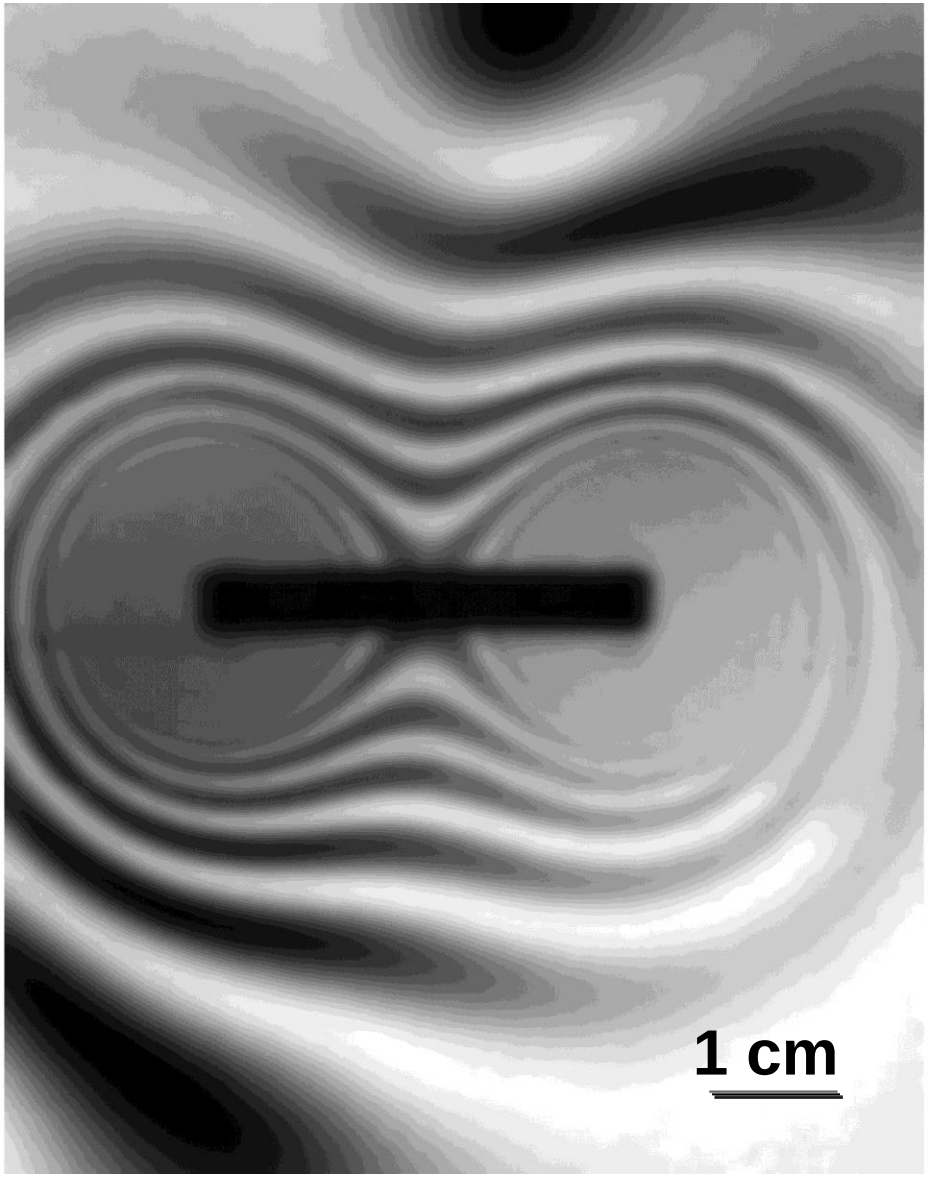


Introduction

Contrast Resolution

- Neutron interaction with matter
  - attenuation contrast
  - diffraction contrast
  - phase/dark-field contrast
  - magnetic contrast 
- Beam optimisation
- Detector development

Magnetic Contrast



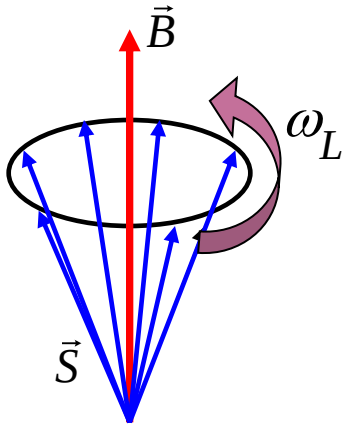
Introduction

How neutrons can visualize magnetic fields?

- Magnetic moment
- Interacts with magnetic fields
- Larmor precession can be used as signal for imaging
- Visualisation of magnetic fields in bulk materials

Introduction

Spin precession



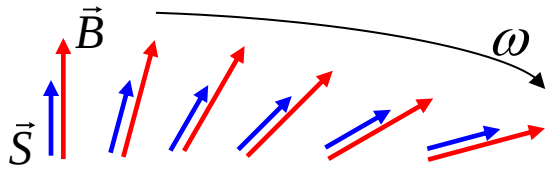
Larmor frequency:

$$\omega_L = \gamma B$$

Gyromagnetic ratio:

$$\gamma = 1.83 \cdot 10^8 \frac{rad}{s \cdot T}$$

Adiabatic spin rotation



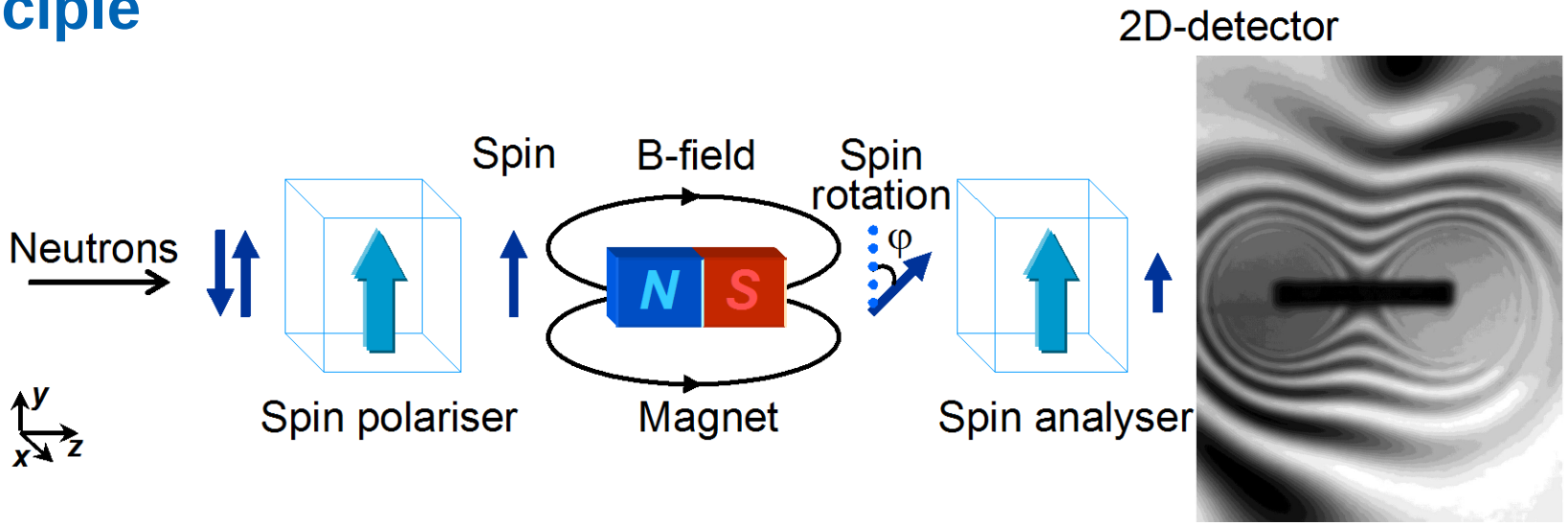
$\vec{B}$ **= magnetic flux density**

$\vec{S}$ **= Spin vector**

$$\omega << \omega_L$$

Magnetic Contrast

Principle



$$I(x,y) = I_0(x,y) \cdot \underbrace{\exp\left[-\int \mu(s)\,ds\right]}_{attenuation} \cdot \underbrace{\tfrac{1}{2}\left(1-\cos\varphi(x,y)\right)}_{precession}$$

Experimental parameters

- Solid state polarazing benders
- Beam size (WxH): 20 x 4 cm^2
- Exposure times: ~10 min / image

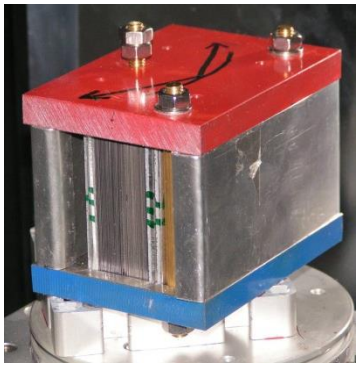
$$\varphi = \omega_L t = \frac{\gamma_L}{v}\int_{path} H ds$$

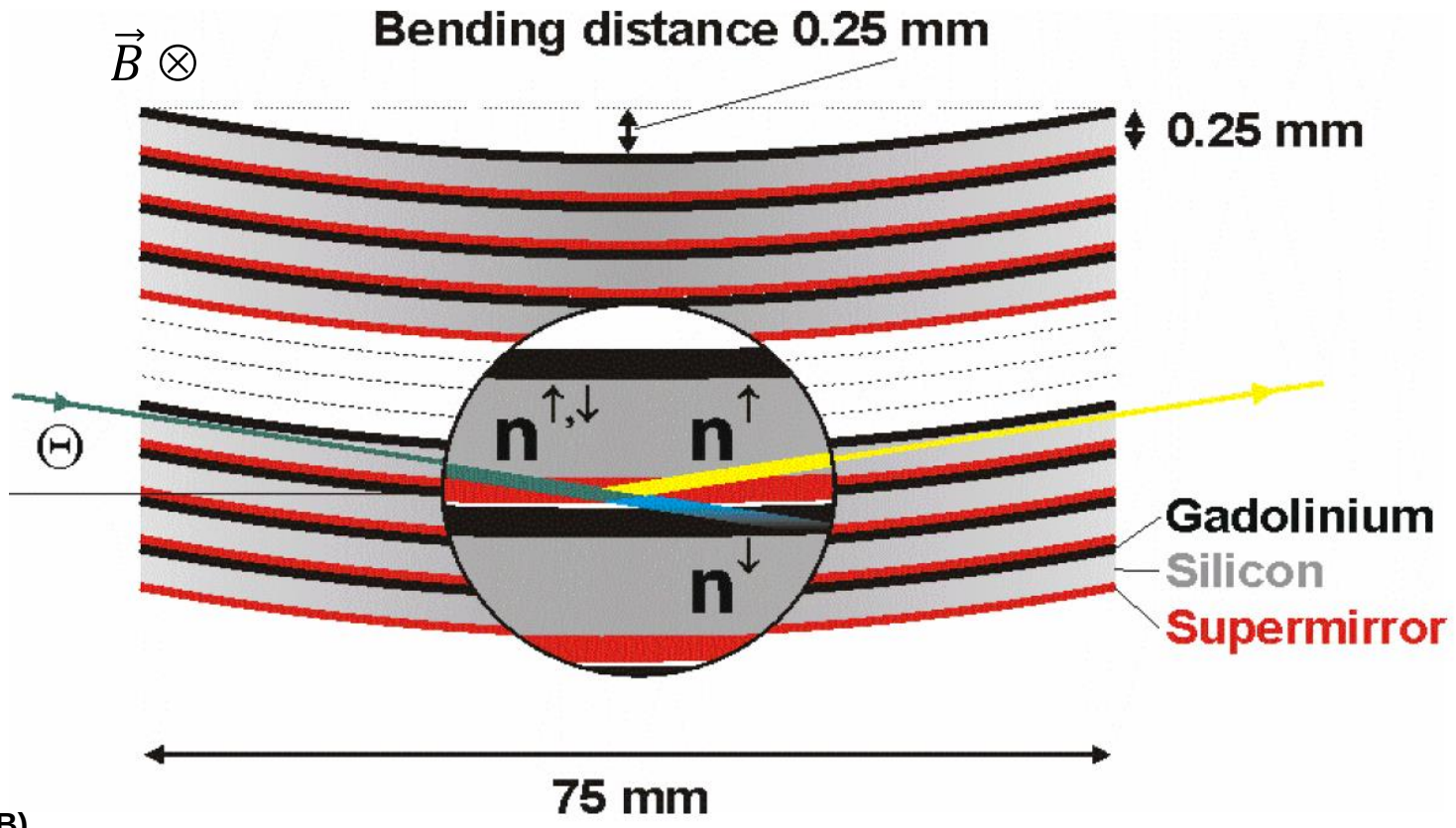
N. Kardjilov, et al, Nature Physics 4, 399-403, (2008)

Experimental setup

Solid state polariser
Wavelength optimum λ = 3.5 Å

Refractive index: $n = \mathbf{1} - \lambda^2 \left(\frac{N \cdot b_c}{2\pi} \pm \frac{\mu m B}{h^2} \right)$





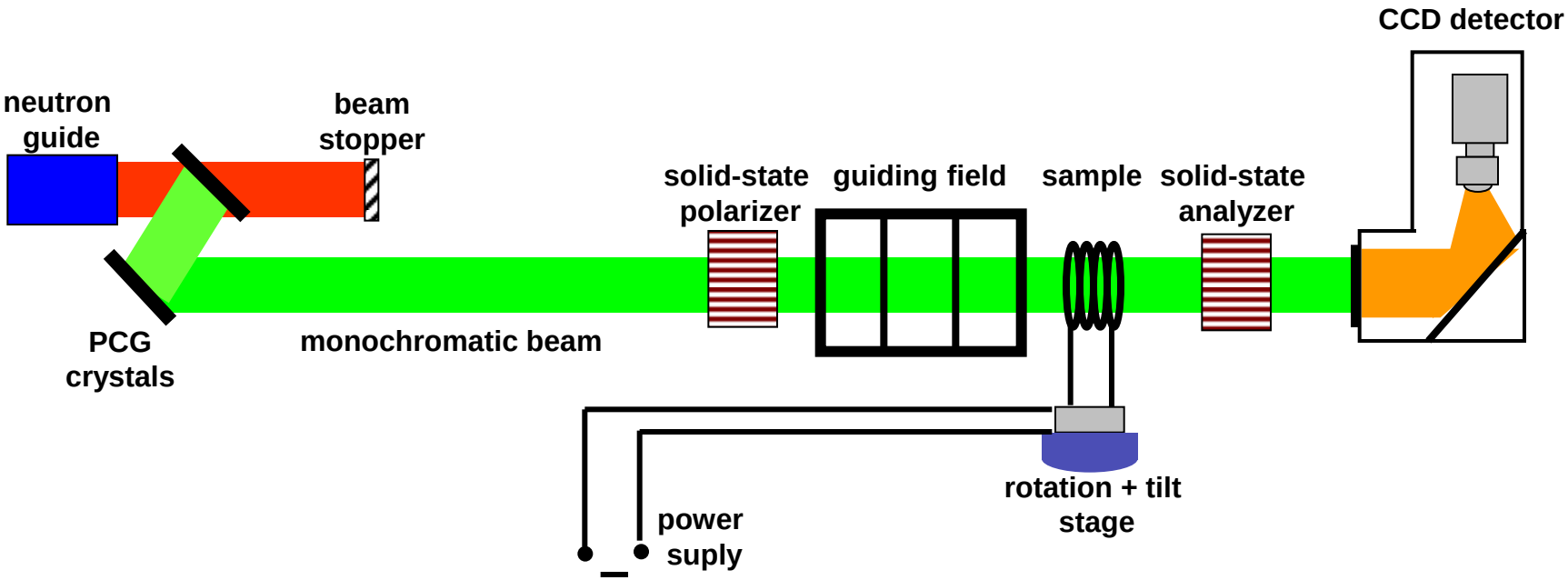
Source: Dr. Krist (HZB)

Experimental setup

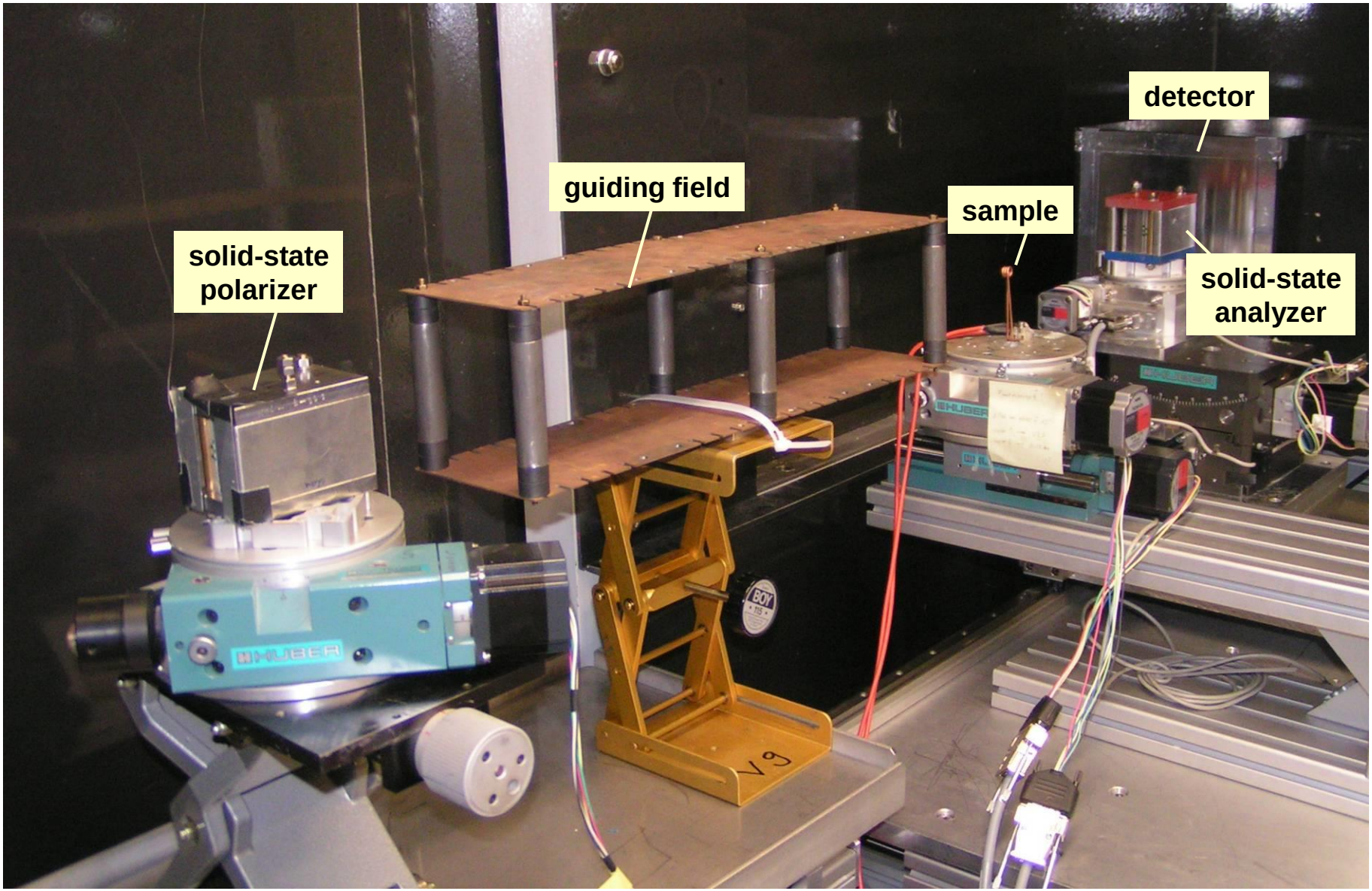
Option with polarized neutrons

Instrument: V7 (CONRAD) at HMI
Date: 11-15 July 2006
Options: Monochromatic option: 4.2 Å
Detector mode: CCD, low-resolution mode (0.2 mm/pixel)

Experimental sketch:



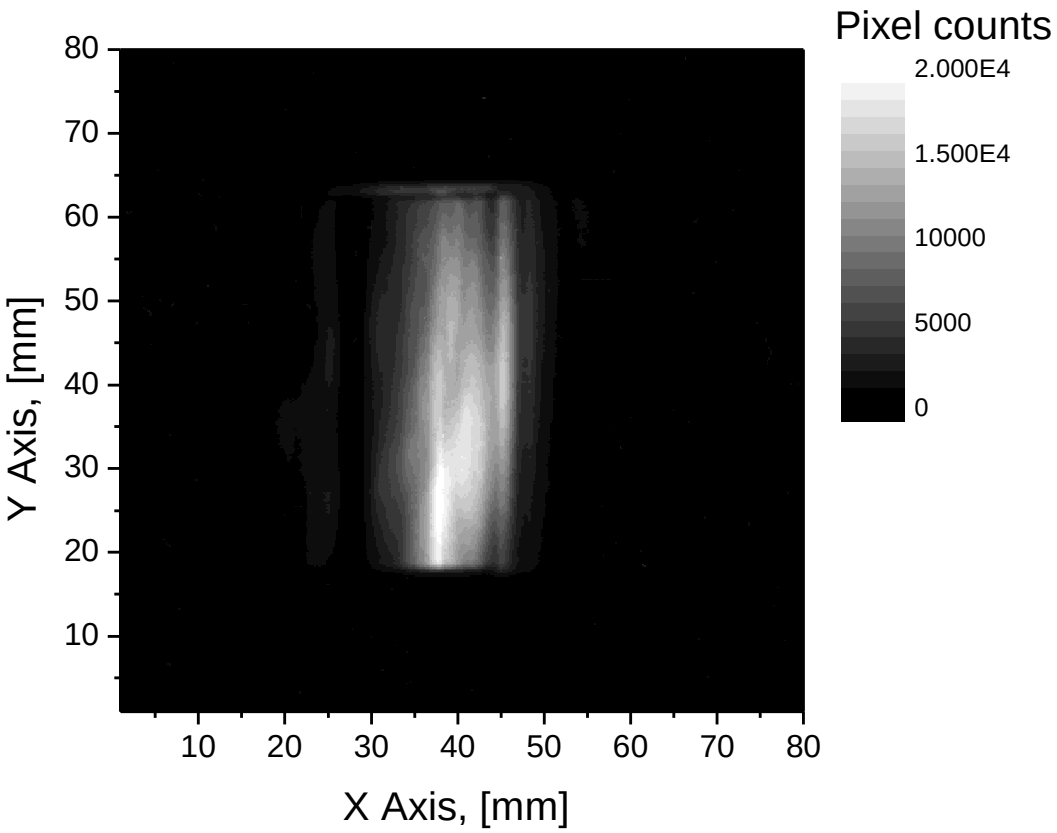
Experimental setup



Experimental setup - results

Experimental parameters

Open beam



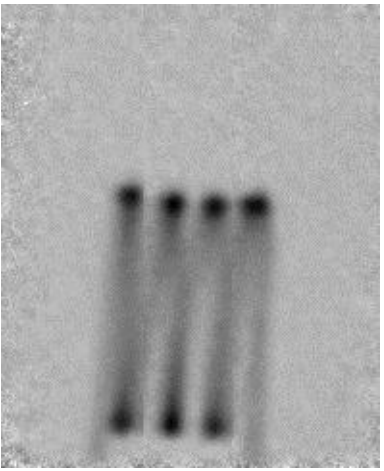
Exposure time: 300 s
Binning: 2x2

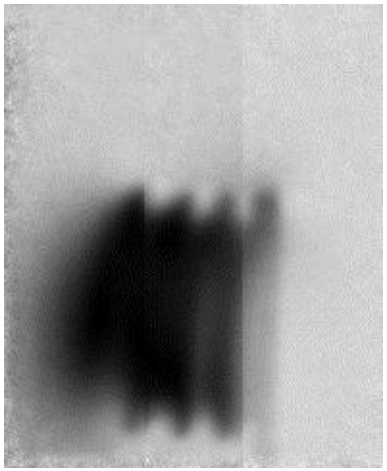
Sample

Copper coil
Wire thickness: 2 mm

Experimental setup - results

Results


current: 0 A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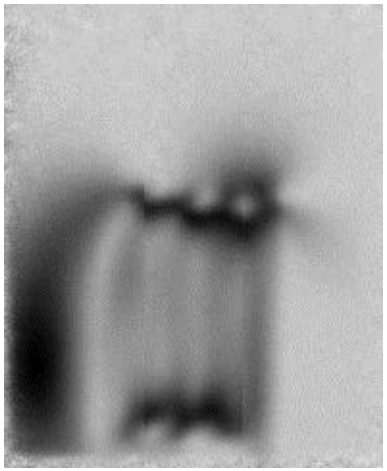
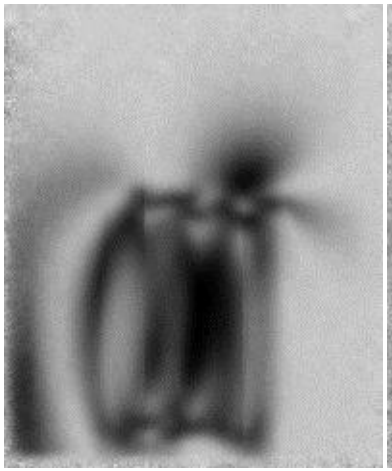

8A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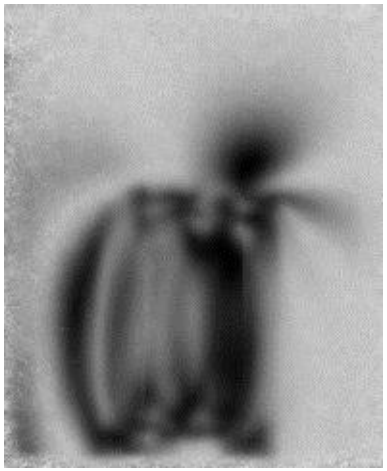
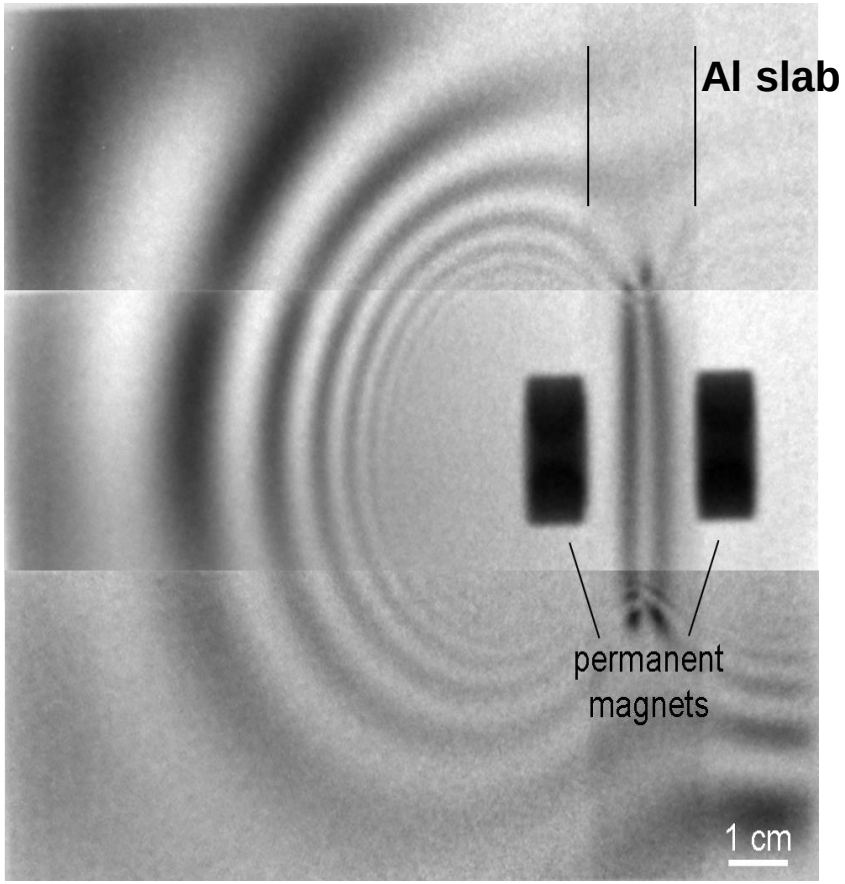
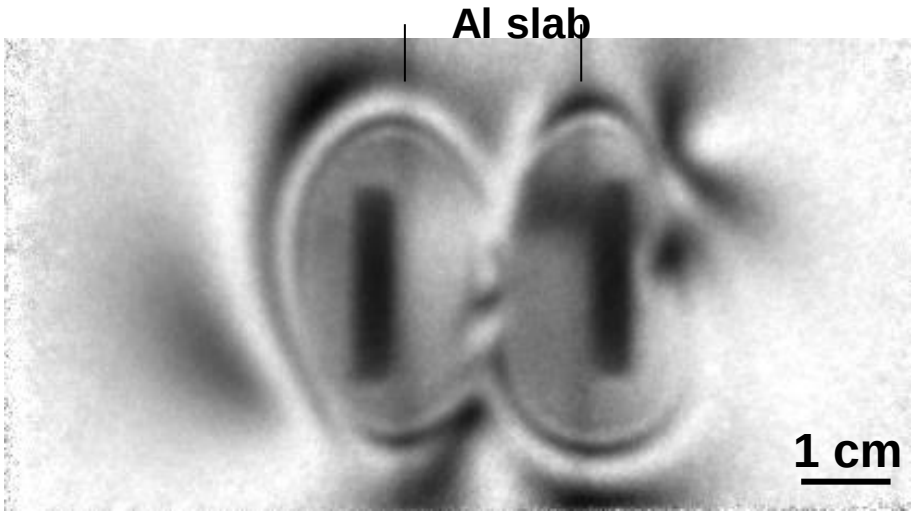

15 A

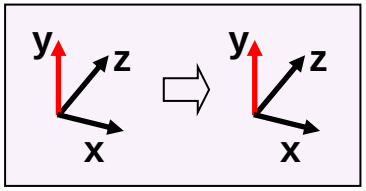
Experimental setup - results



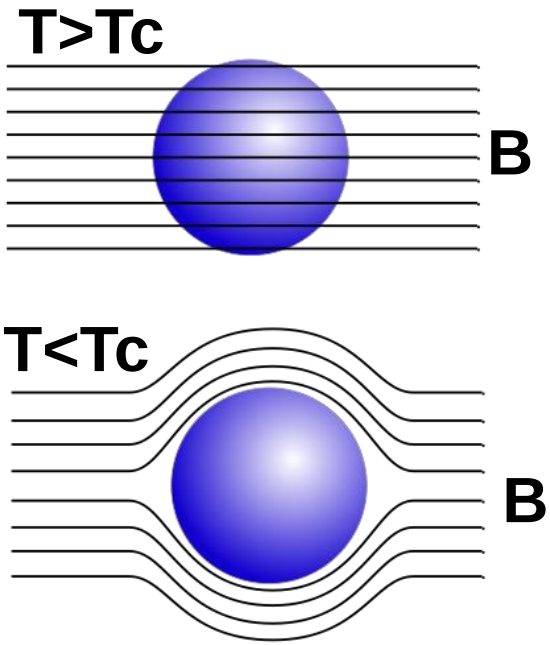
dipole magnets

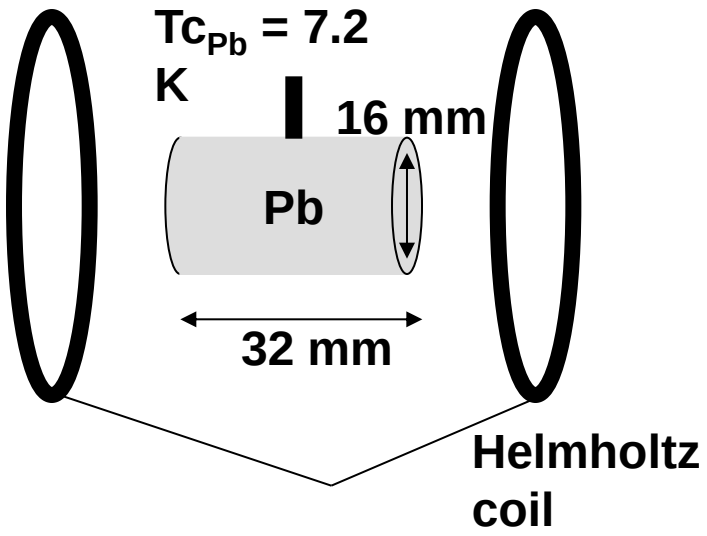


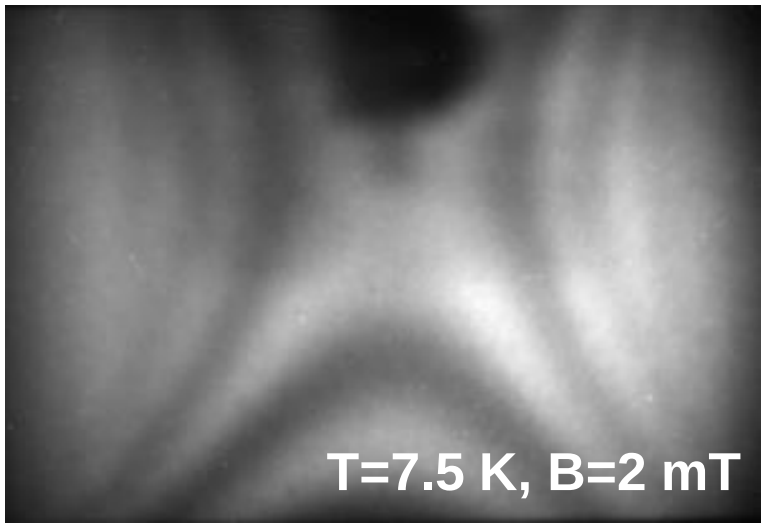
non-dipole magnets

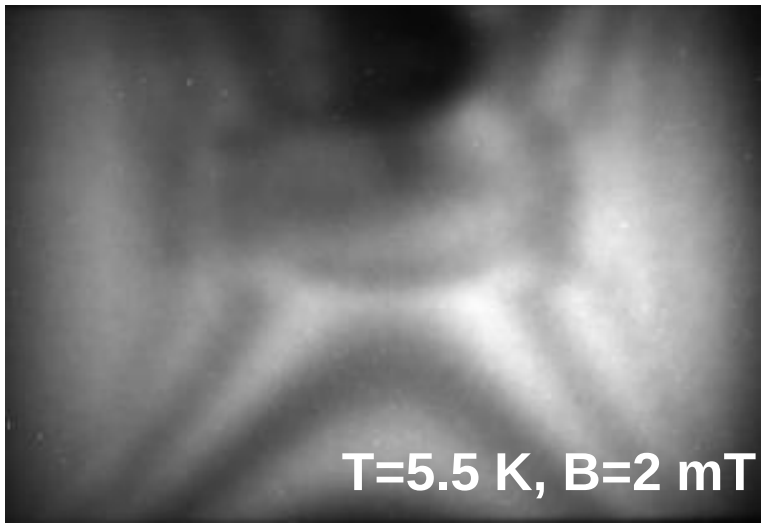


Application: Meissner-Effect



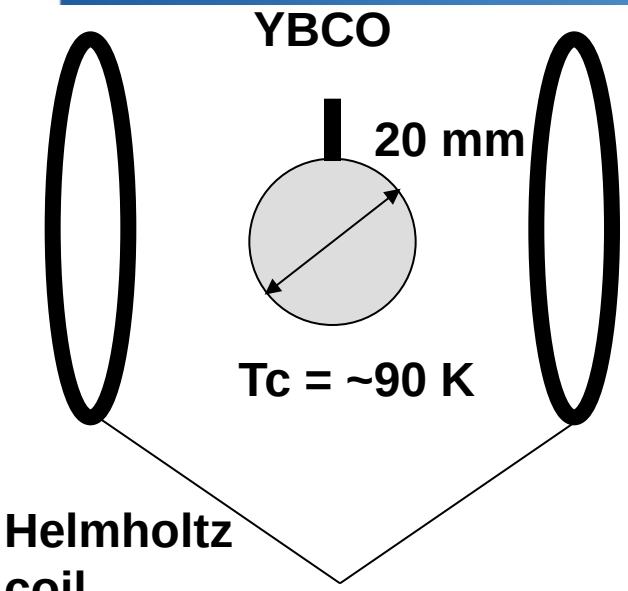






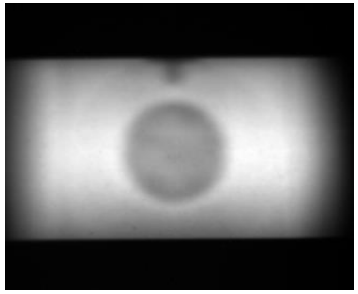
1 cm

Application: Meissner-Effect



Sample photo

Radiography image (polarized neutrons)



100 K@0.0mT

Observation of „Meissner effect“:

100K@0.0mT

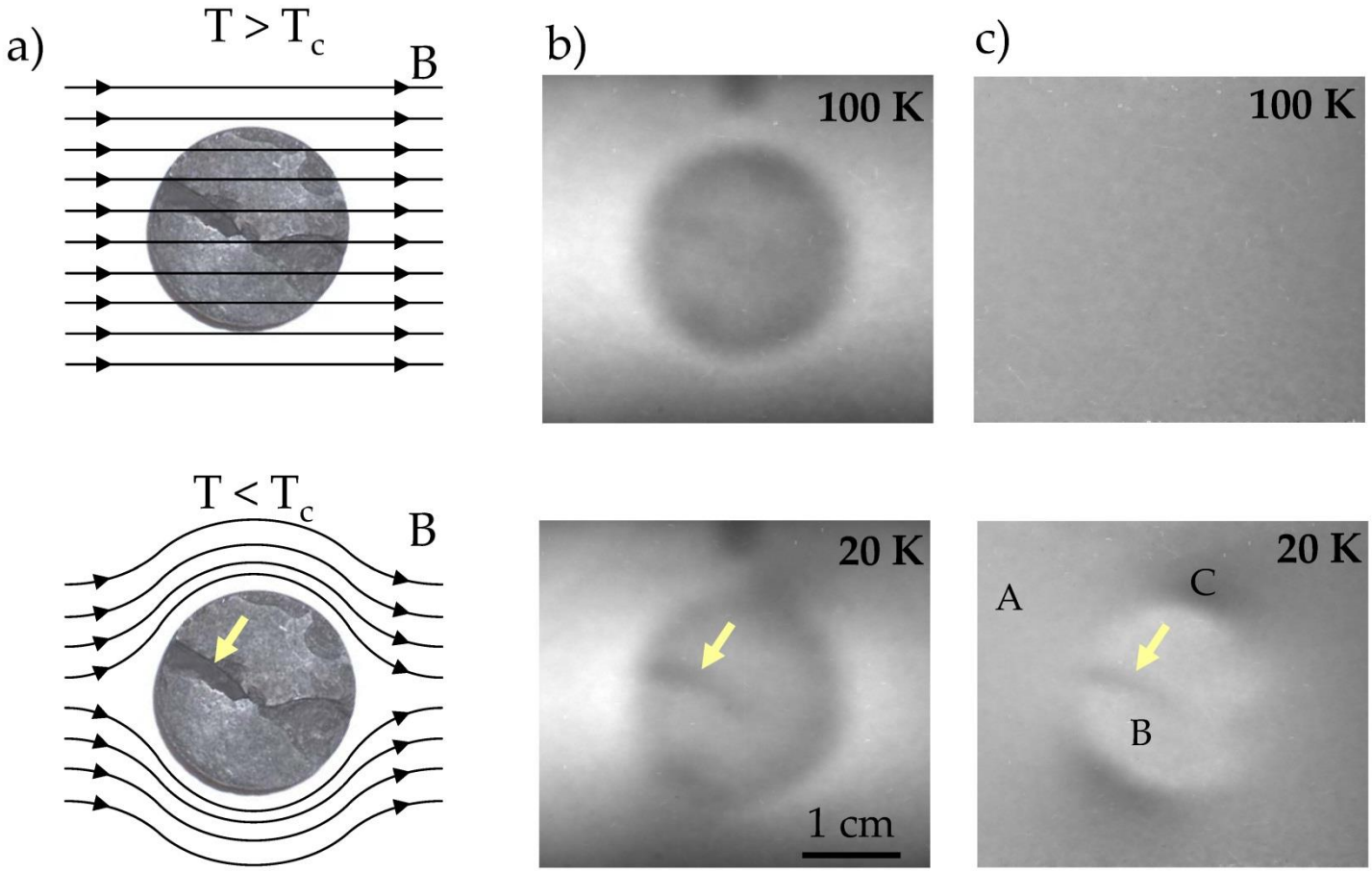
20K@0.0mT

20K@0.1mT

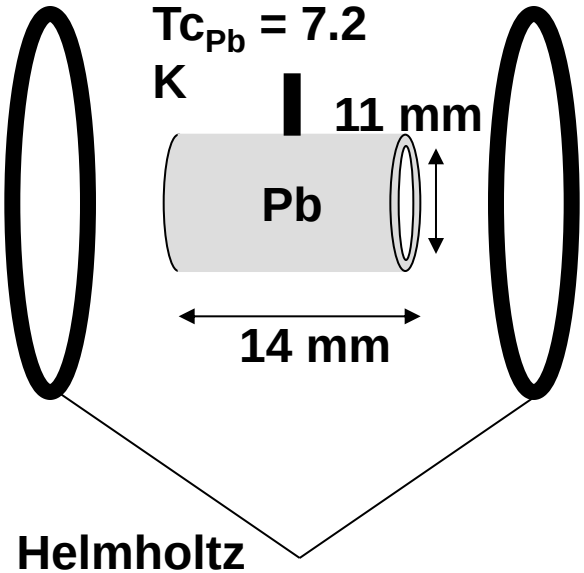
Images normalized by the initial image at 100K@0.0mT

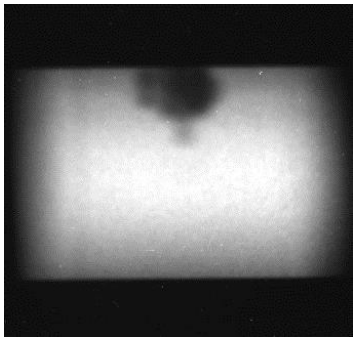
20 K@0.1mT | 50 K@0.1mT | 60 K@0.1mT | 73 K@0.1mT | 100 K@0.1mT

Application: Meissner-Effect

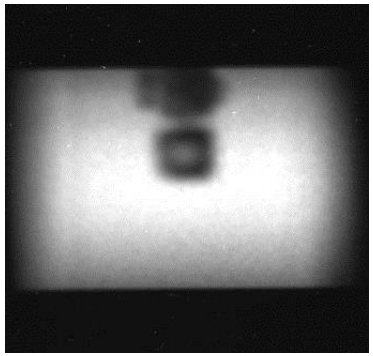


Application: Flux-Trapping

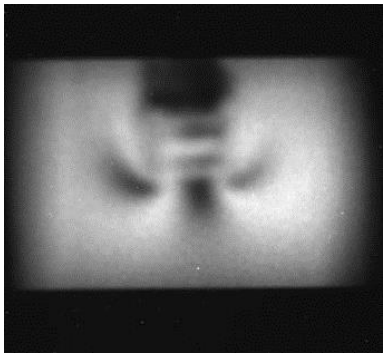




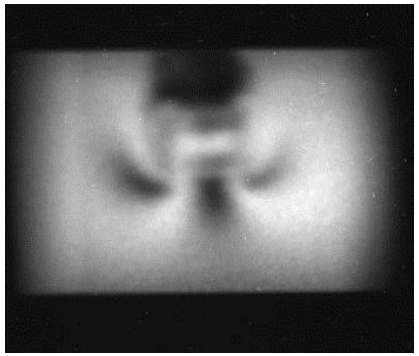
7.5 K@0.0A



5.5 K@1.0A

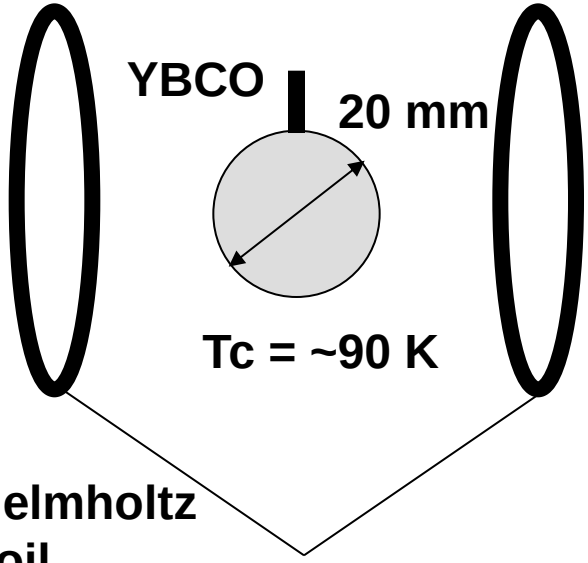


5.5 K@4.5A



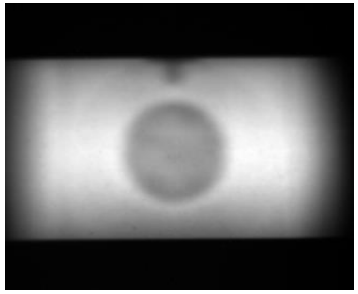
5.5 K@4.8A

Application: Flux-Trapping



Sample photo

Radiography image (polarized neutrons)



100 K@0.0mT

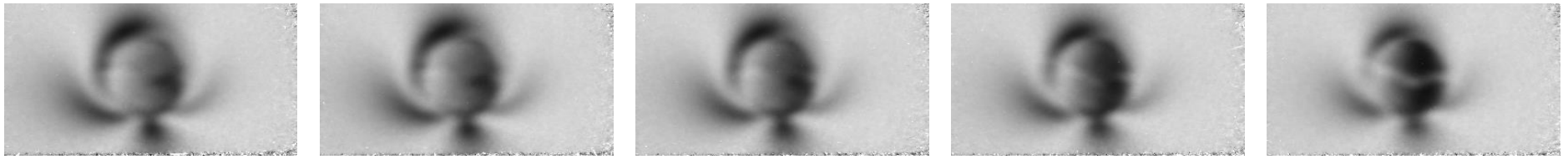
Observation of „flux pinning effect“:

100K@8.0mT

20K@8.0mT

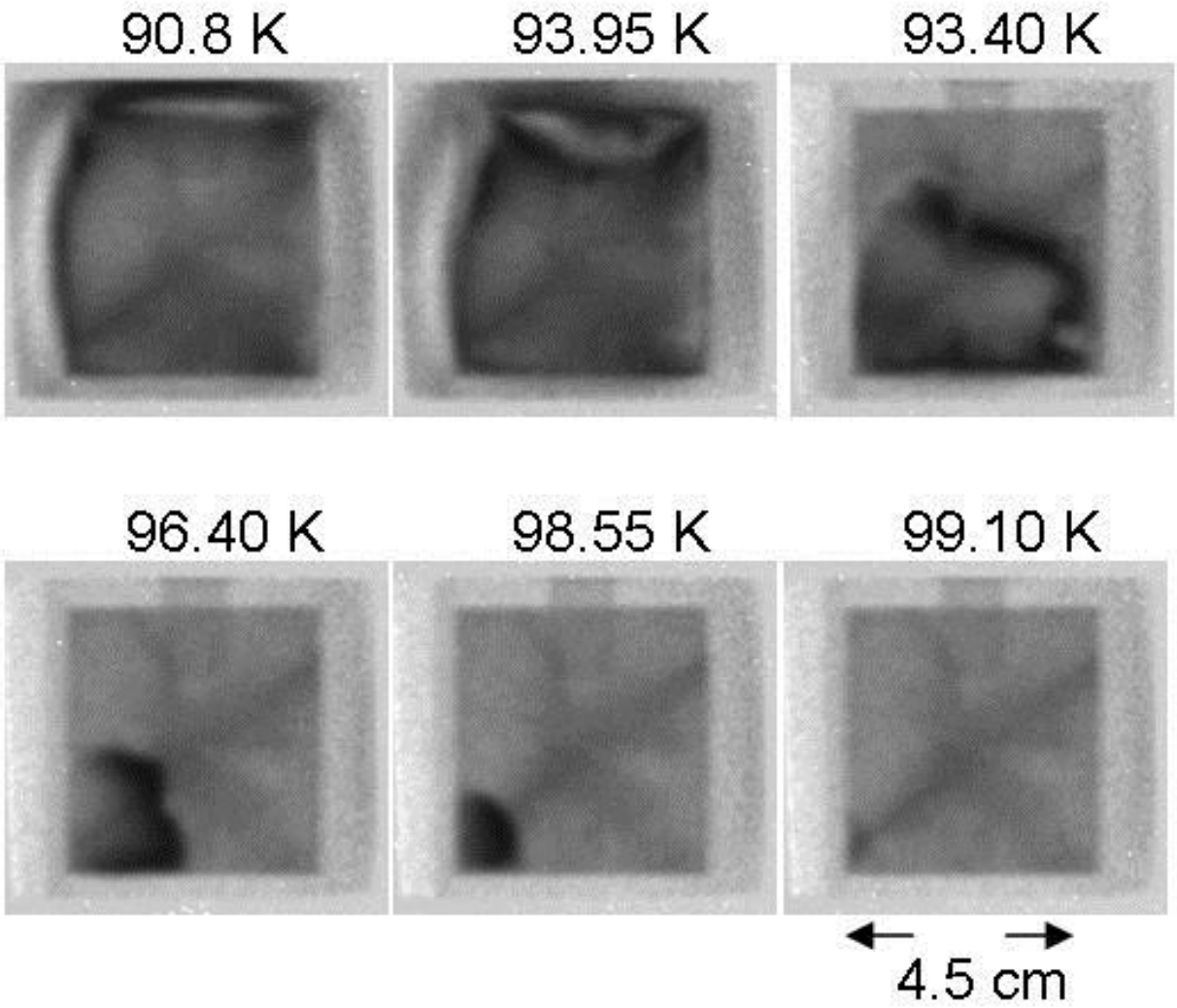
20K@0.0mT

Images normalized by the initial image at 100K@0.0mT



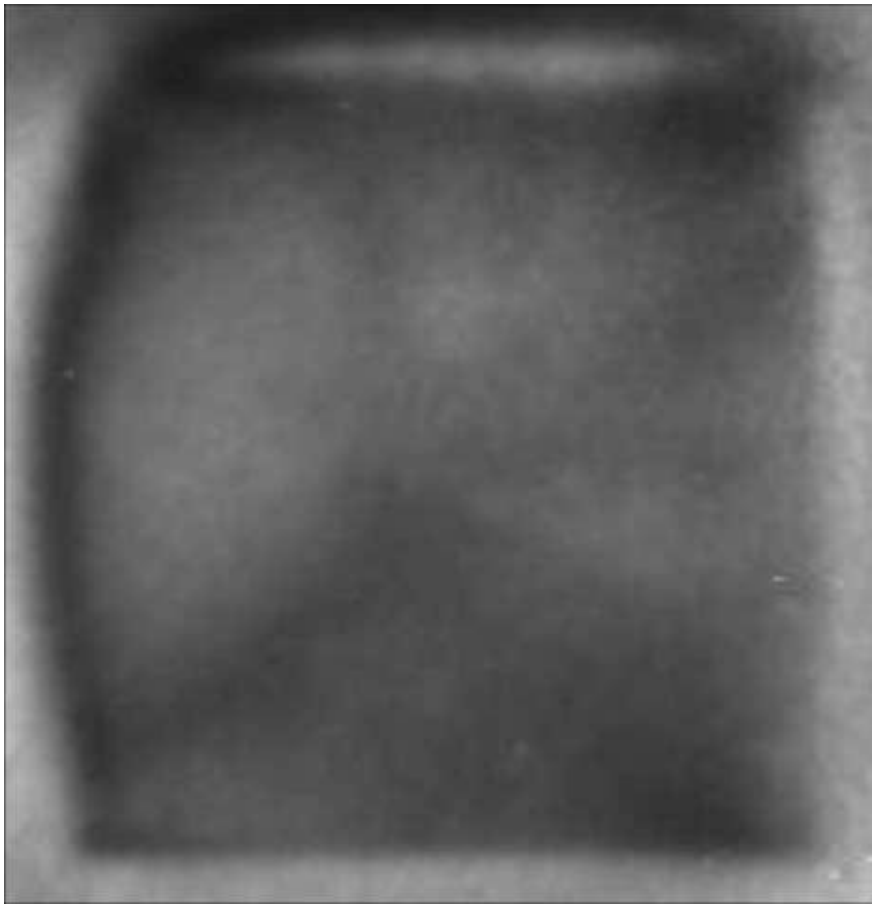
20 K | 30 K | 40 K | 50 K | 60 K

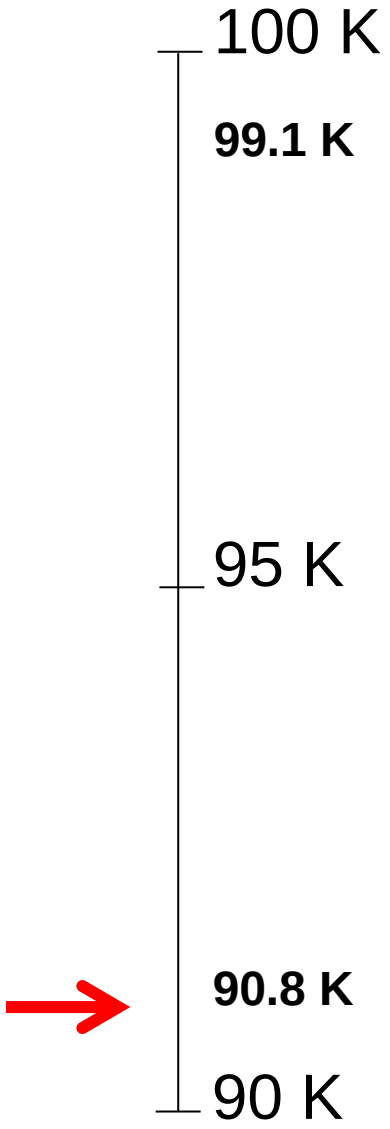
Magnetic Contrast



Flux trapping in a 45x45x12 mm^2 bulk YBCO sample.

Magnetic Contrast



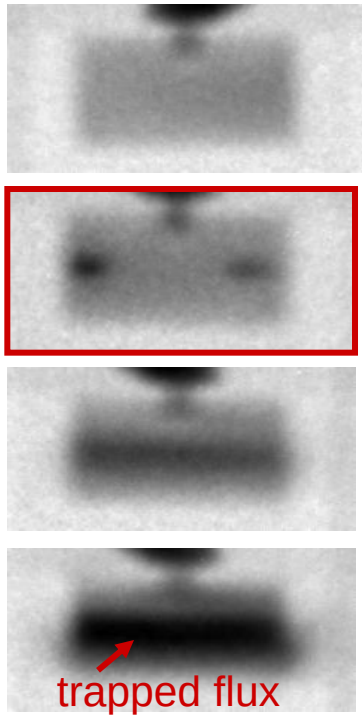


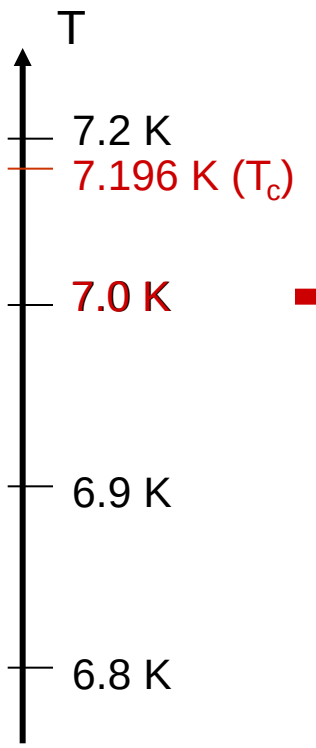
Flux trapping in a 45x45x12 mm² bulk YBCO sample.

Magnetic Contrast

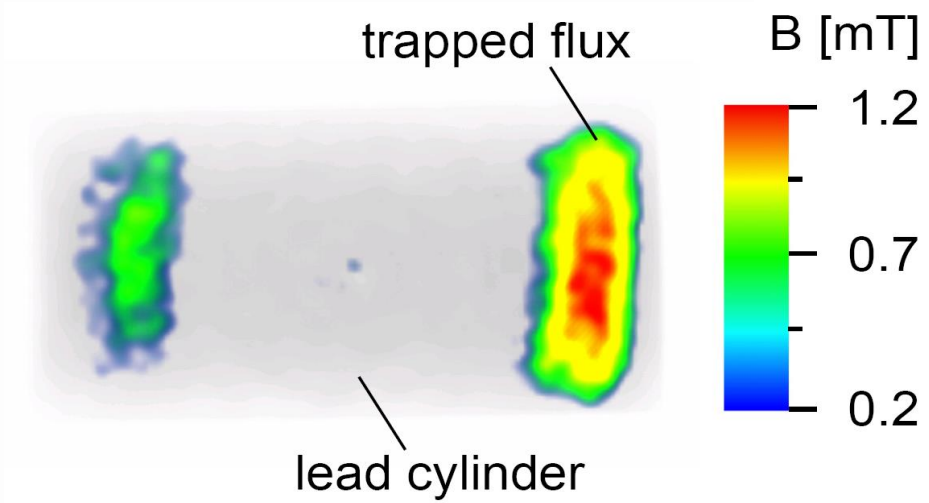
Flux pinning in superconductors

Pb cylinder
(polycrystalline)





Tomography

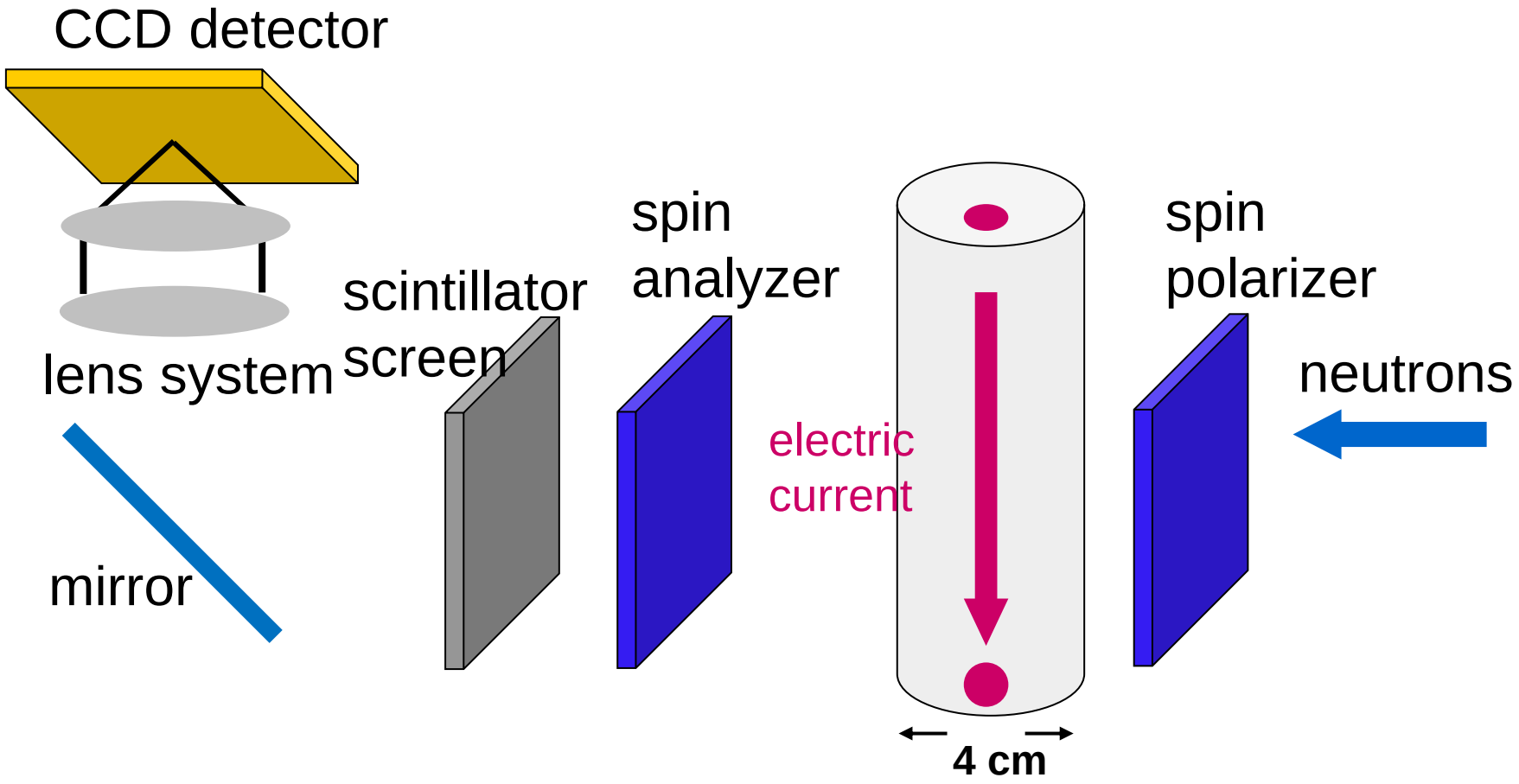


Flux pinning at cooling down below Tc while applying a homogenous magnetic field of 10 mT perpendicular to the beam.

The images were recorded after switching off the magnetic field.

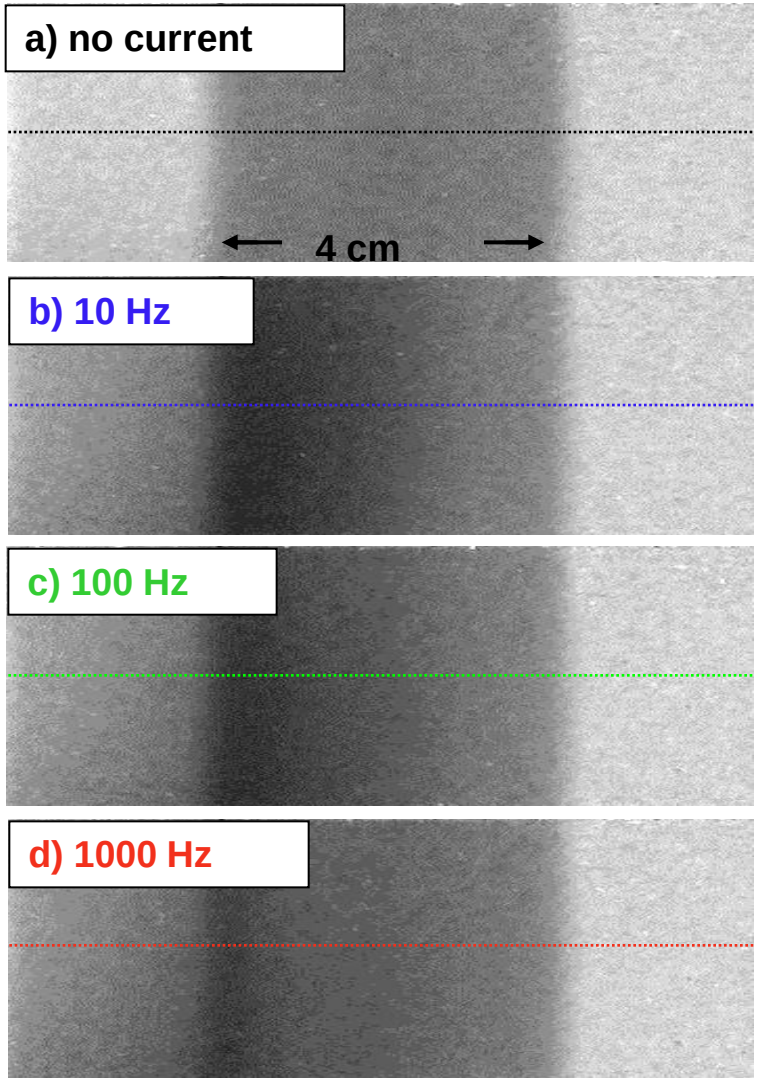
N. Kardjilov, et al, Nature Physics 4, 399-403, (2008)

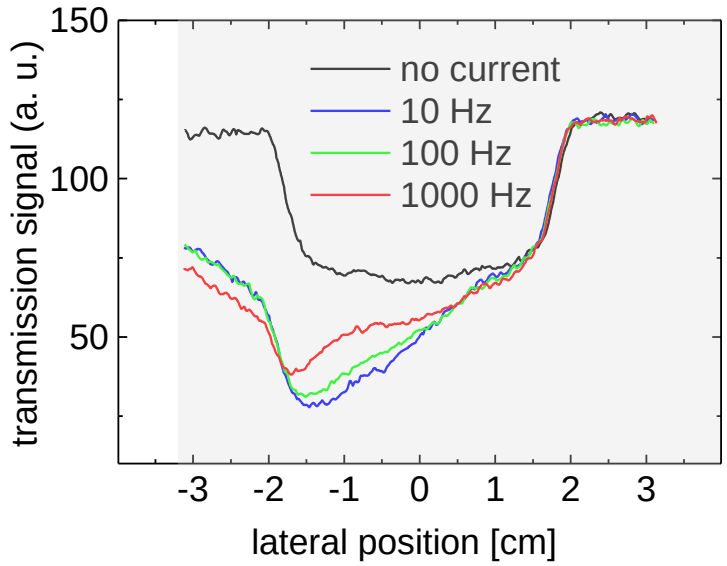
Application: Skin-Effect

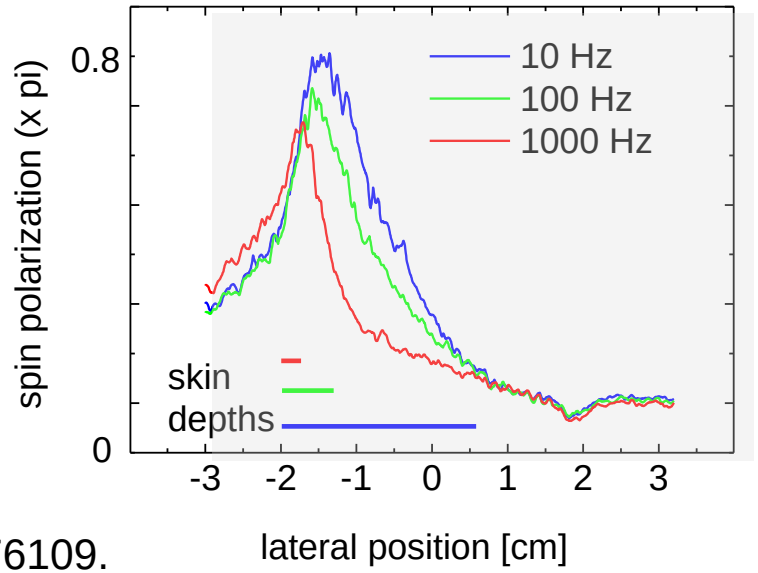


Manke, I., et al. "Investigation of the skin effect in the bulk of electrical conductors with spin-polarized neutron radiography.“Journal of Applied Physics (2008): 076109.

Application: Skin-Effect





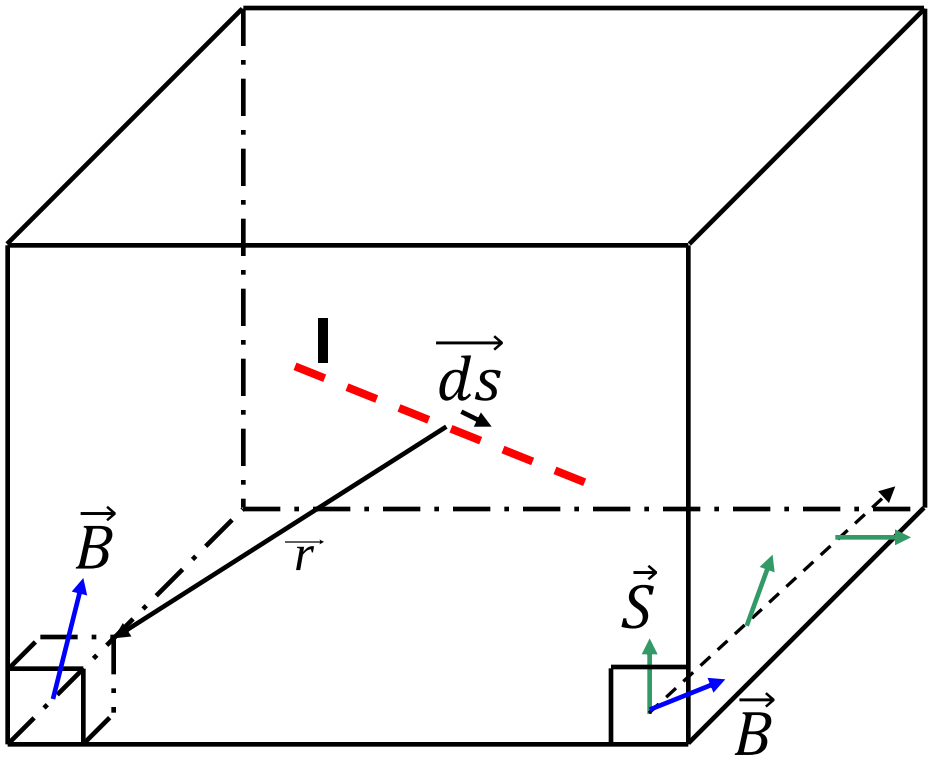


Manke, I., et al. Journal of Applied Physics (2008): 076109.

Simulation process

- Aim: to describe a real experiment by a simulation
  - the magnetic field of a conductor can be describe by using the Biot-Savart‘s law
  - this is the precondition for the calculation of the spin rotation during the field penetration

Simulation process



Voxel matrice

Biot-Savart's law:

$$\vec{B}(\vec{s}) = -\frac{\mu_0}{4\pi} \cdot I \cdot \frac{\overrightarrow{ds} \times \vec{r}}{r^3}$$

Larmor precession

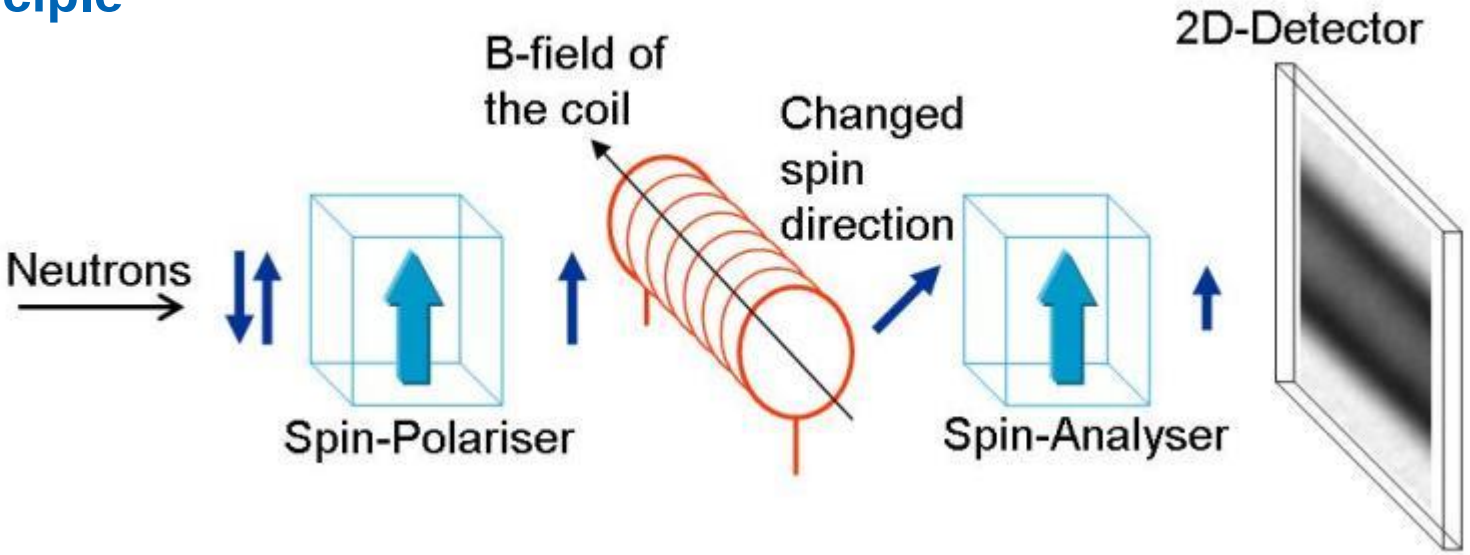
$$\varphi = \gamma \cdot t \cdot B$$

$$\gamma = 1.832 \cdot 10^8 \ \frac{rad}{s \cdot T}$$

$$t \sim \lambda$$

Neutron imaging

Principle

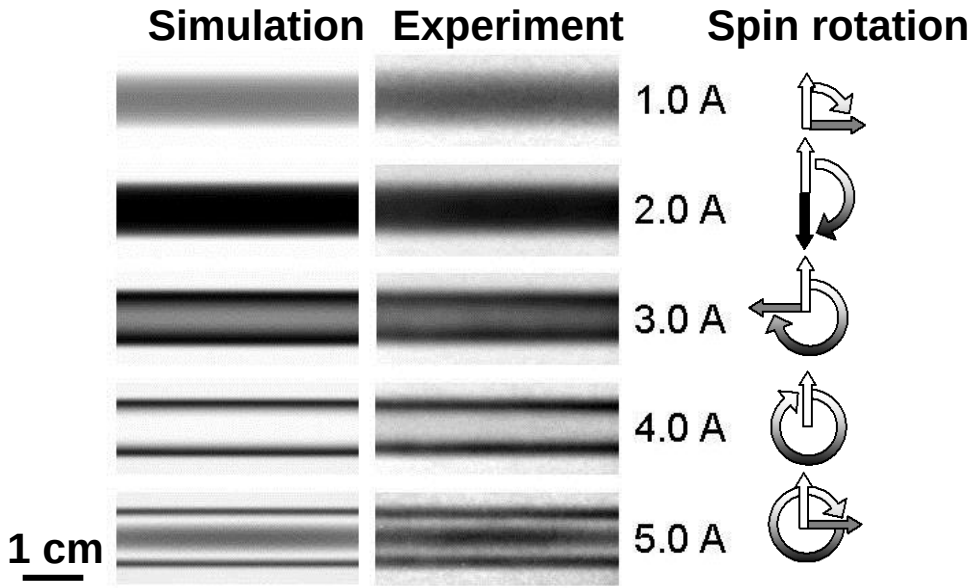


Biot-Savart law

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{Id\vec{l} \times \hat{r}}{r^2}$$

Spin rotation

$$\varphi = \frac{\gamma_L}{v} \int_{path} Bds$$

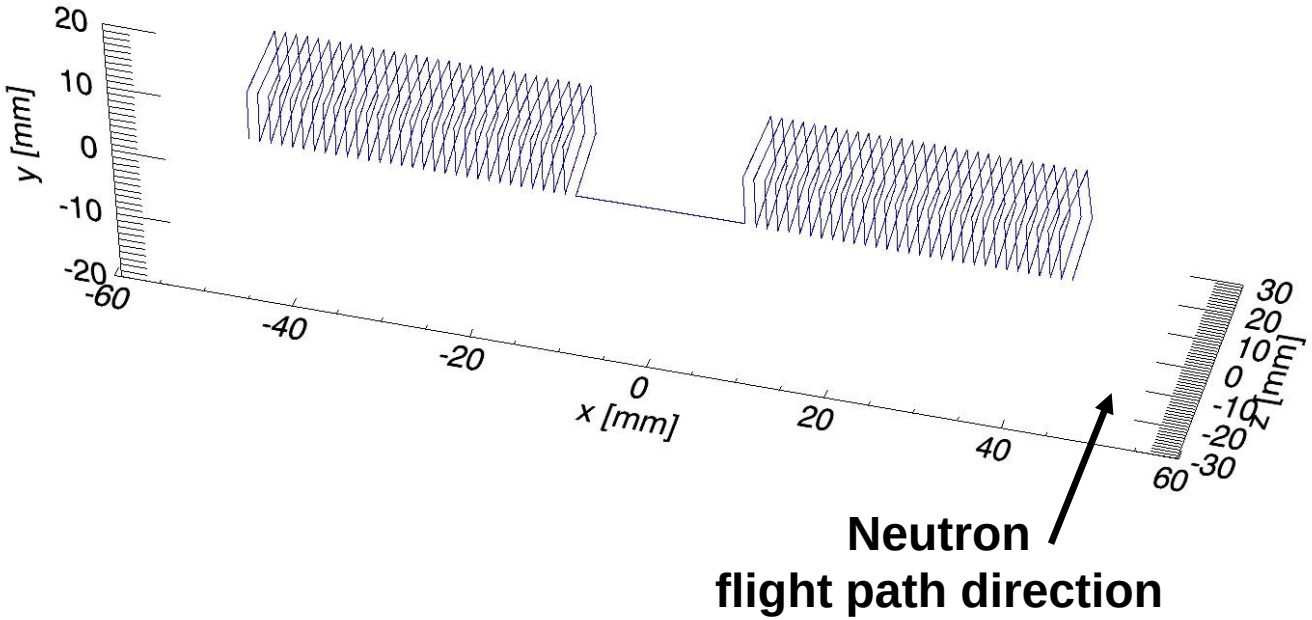


Simulation process - results

Double rectangle coil

- length = 36 mm
- width = 7 mm
- height = 21 mm
- windings = 30

- distance between the coils = 20 mm
- applied currents = 0.0 – 9.0 A
- field strength B = 1.05 mT @ I=1A

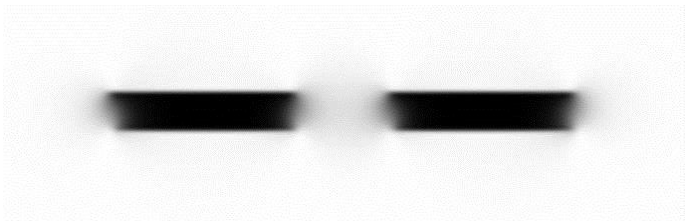


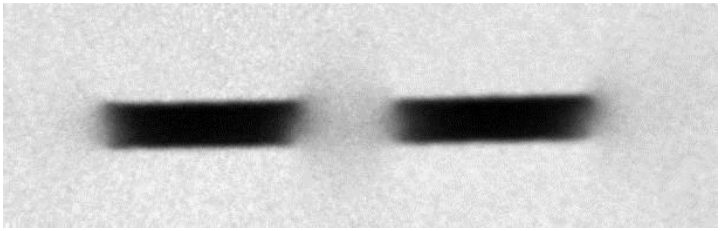
Simulation process - results

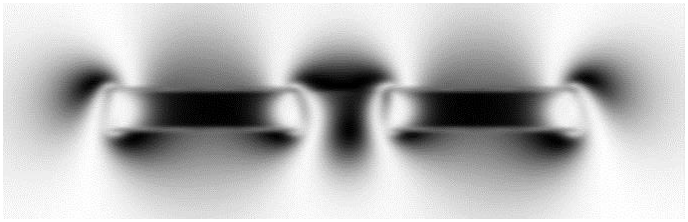
1.0 A

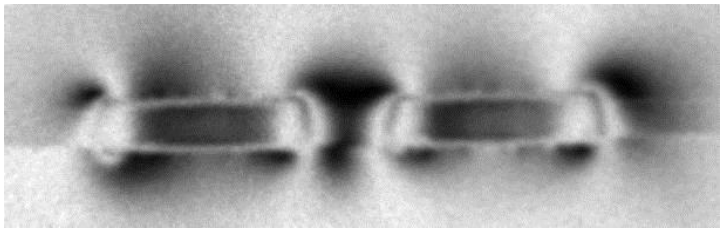
5.0 A

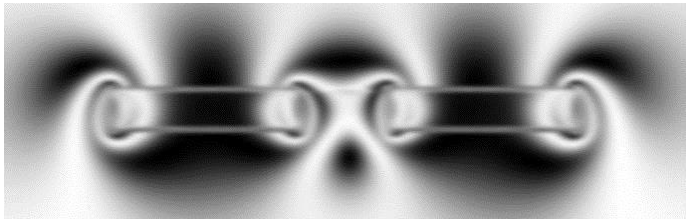
9.0 A

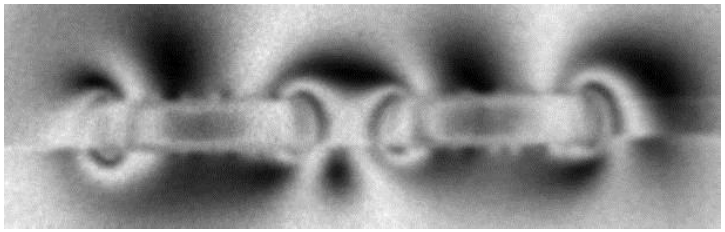


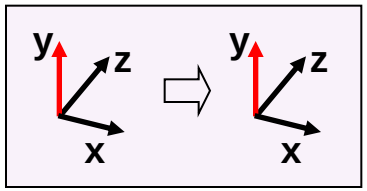












Simulated radiograms

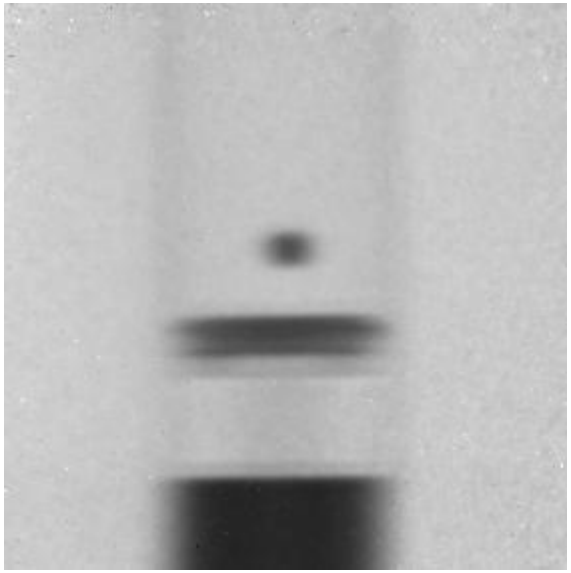
Measurements

Simulation process - results

Levitating dipole over a superconductor

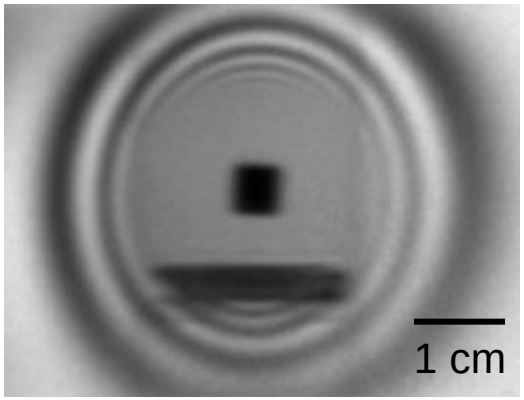
Superconductor: $YBa_2Cu_3O_7$

Critical temperature: 90 K

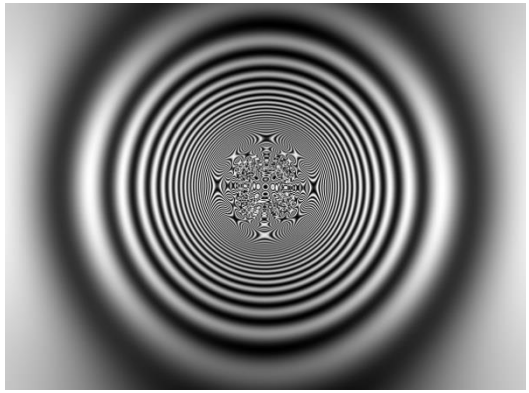


Absorption contrast

Simulation process - results



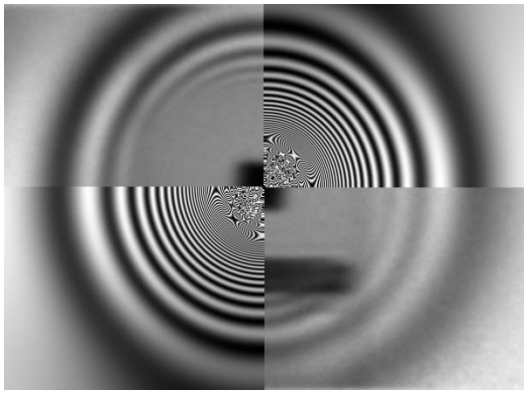
Levitating magnet over YBCO



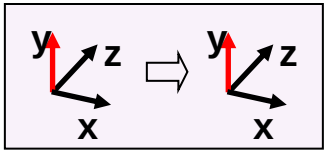
Simulated Radiogram

Simulation parameter:

- wavelength λ=3.5 Å (narrow)
- the dipole was described by a ring current

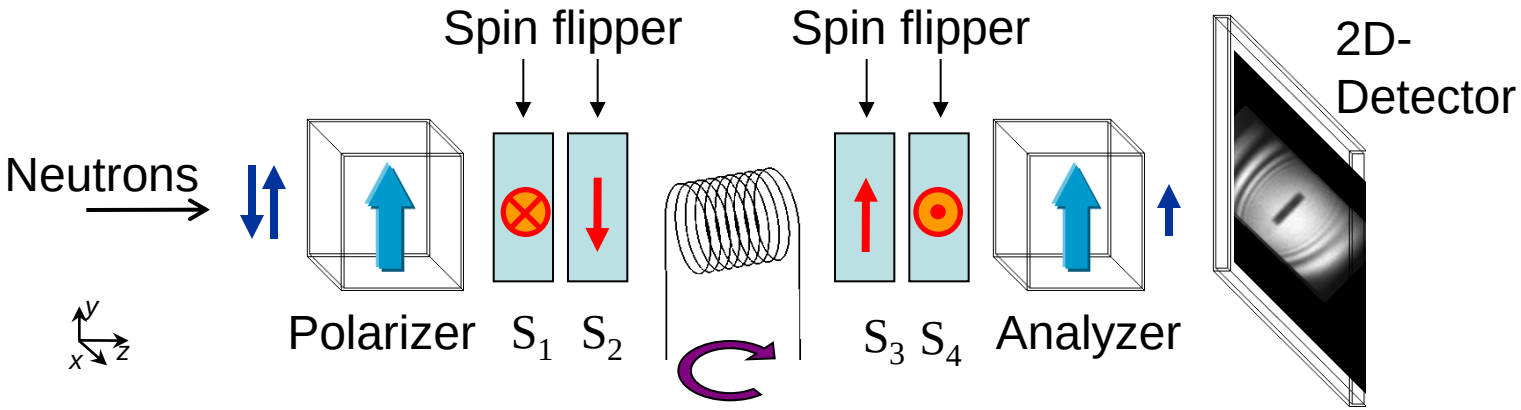


Comparison between measured and simulated data

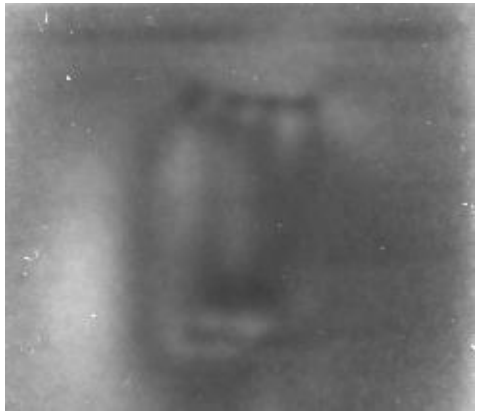


Experimental setup - results

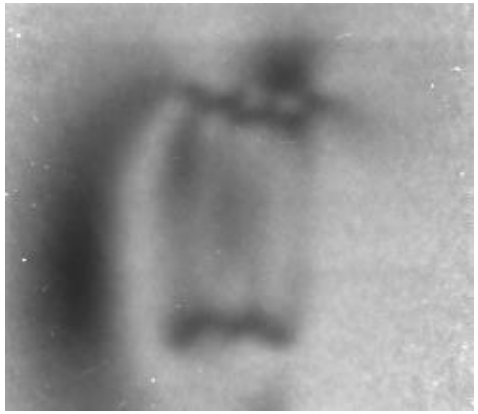
Using of spin-flippers



Spin Flipper1: 0.0 A
Spin Flipper4: 0.0 A



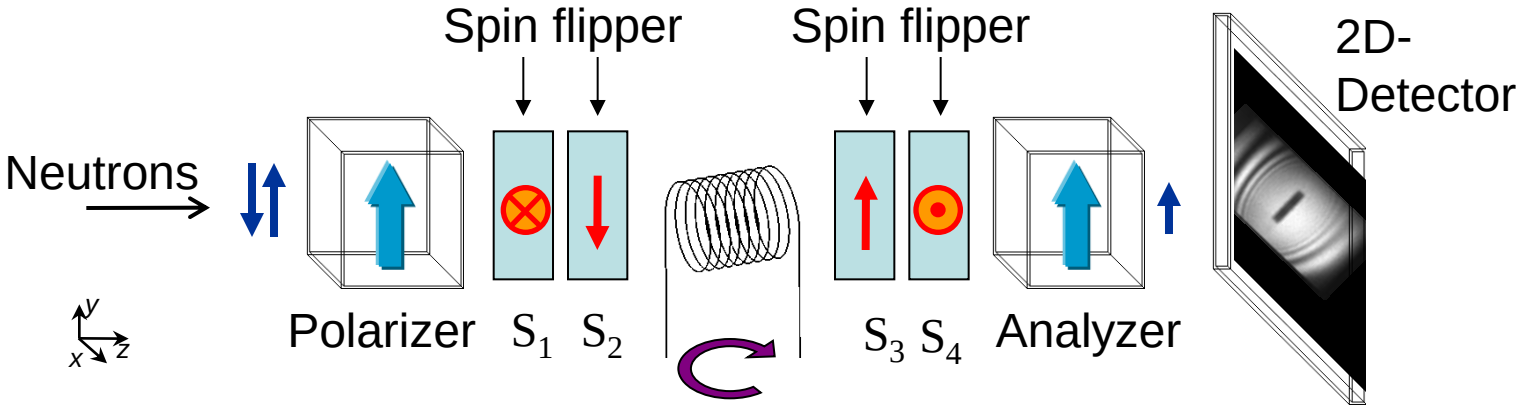
Spin Flipper1: 0.8 A
Spin Flipper4: 0.0 A

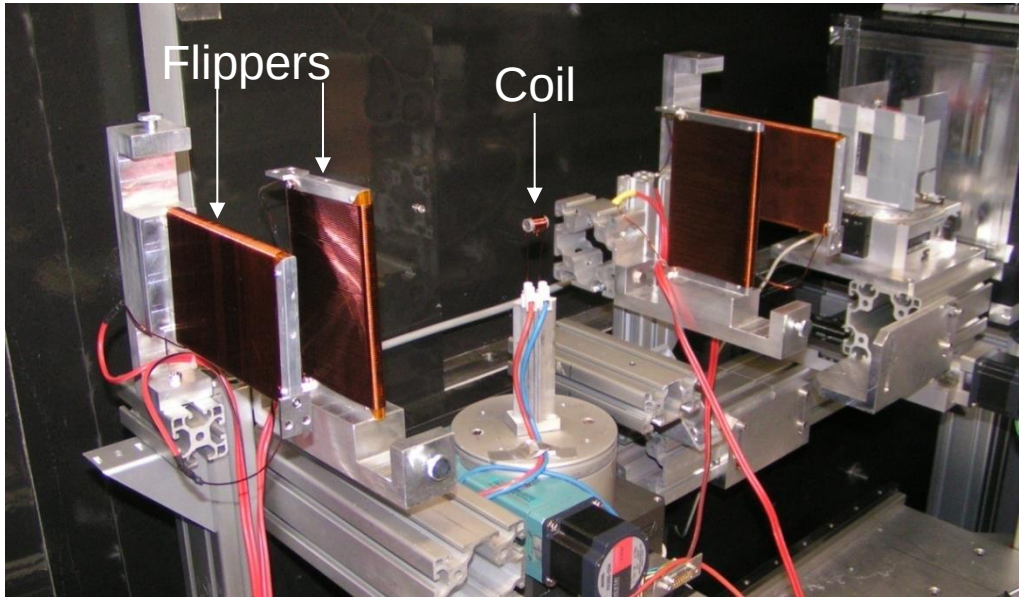


Spin Flipper1: 0.8 A
Spin Flipper4: 0.8 A

Magnetic Contrast

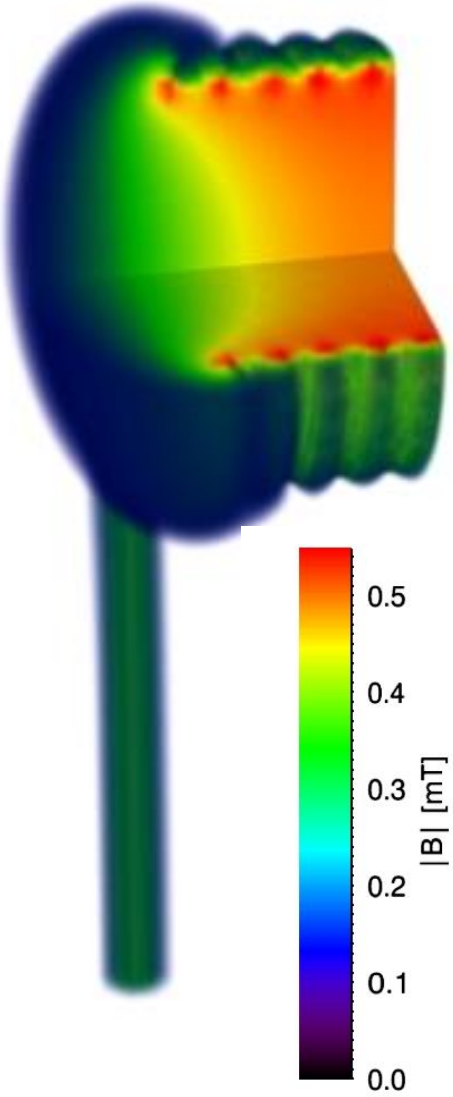
Steps towards quantification





9.5 loops
I = 1.5 A
101 Projections
9+1 Tomographies

Magnetic Contrast



mponent: X Y Z

Simulation Experiment Simulation Experiment Simulation Experiment

0°

72°

144°

216°

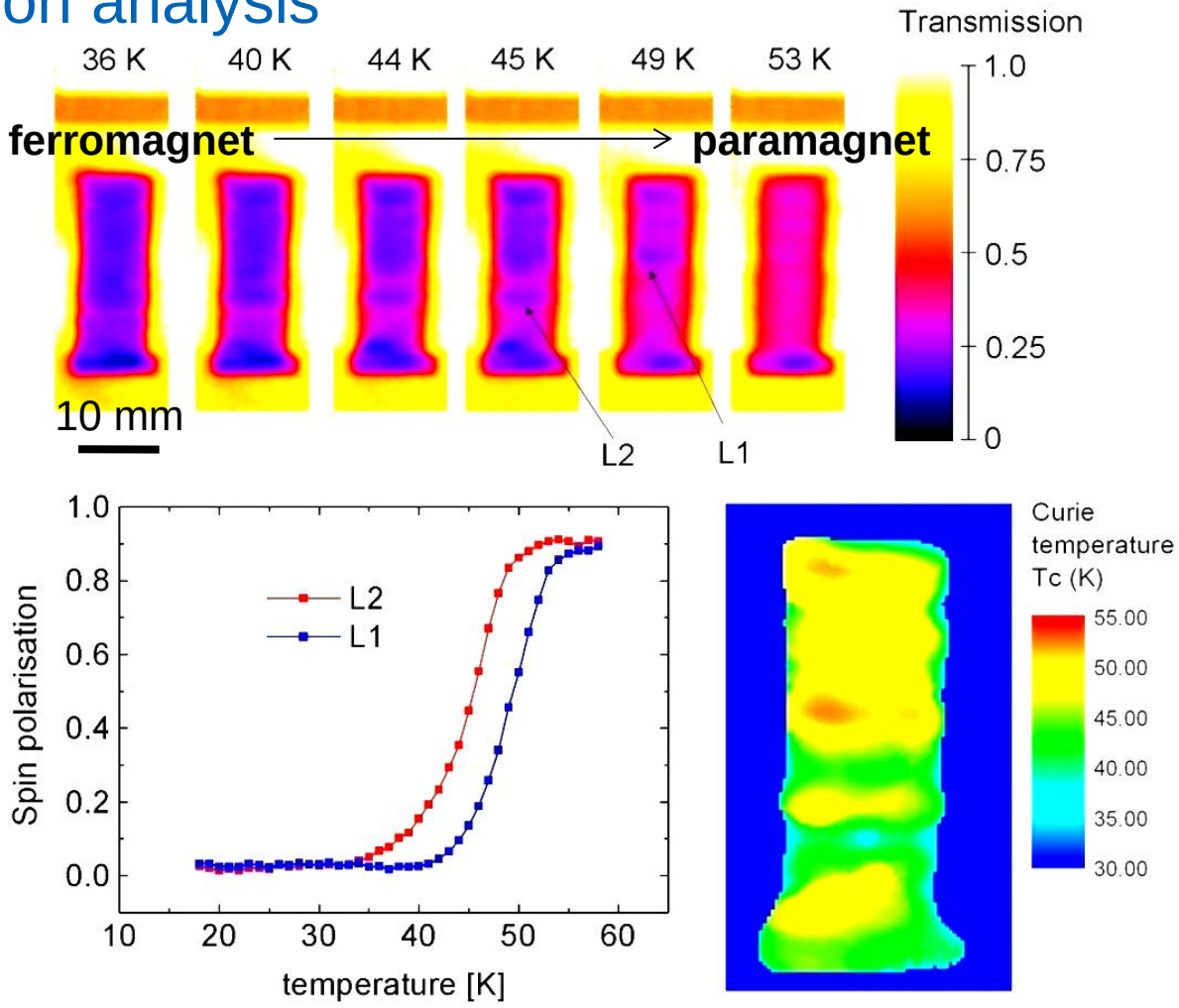
288°

360°

Sales, Morten, et al. *Scientific reports* 8.1 (2018): 2214

Magnetic Contrast

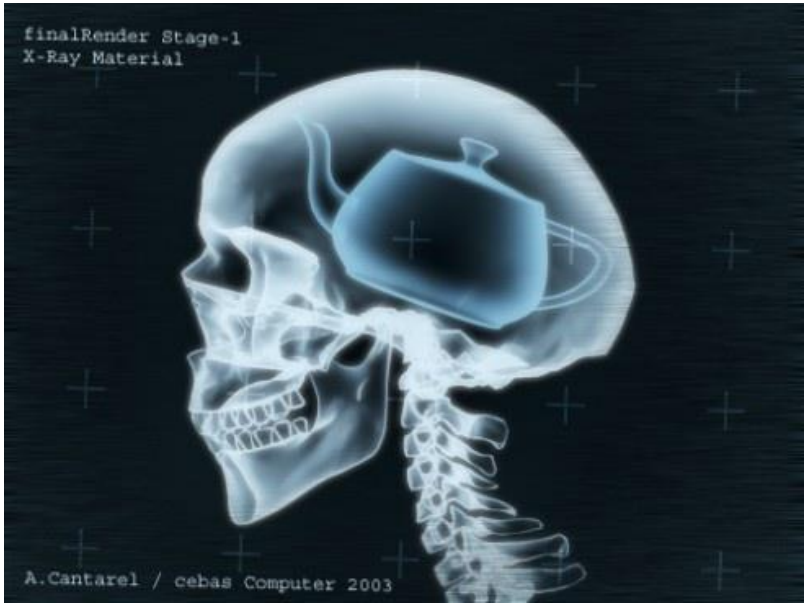
Depolarisation analysis



PdNi crystal (3.24% Ni) imaged by polarised neutrons

Schulz, Michael, et al. "Towards a tomographic reconstruction of neutron depolarization data." *Journal of Physics: Conference Series*. Vol. 211. No. 1. IOP Publishing, 2010.

Thank you !


finalRender Stage-1
X-Ray Material
A.Cantarel / cebas Computer 2003