IAEA International Atomic Energy Agency

CCMX Competence Centre for Materials Science and Technology

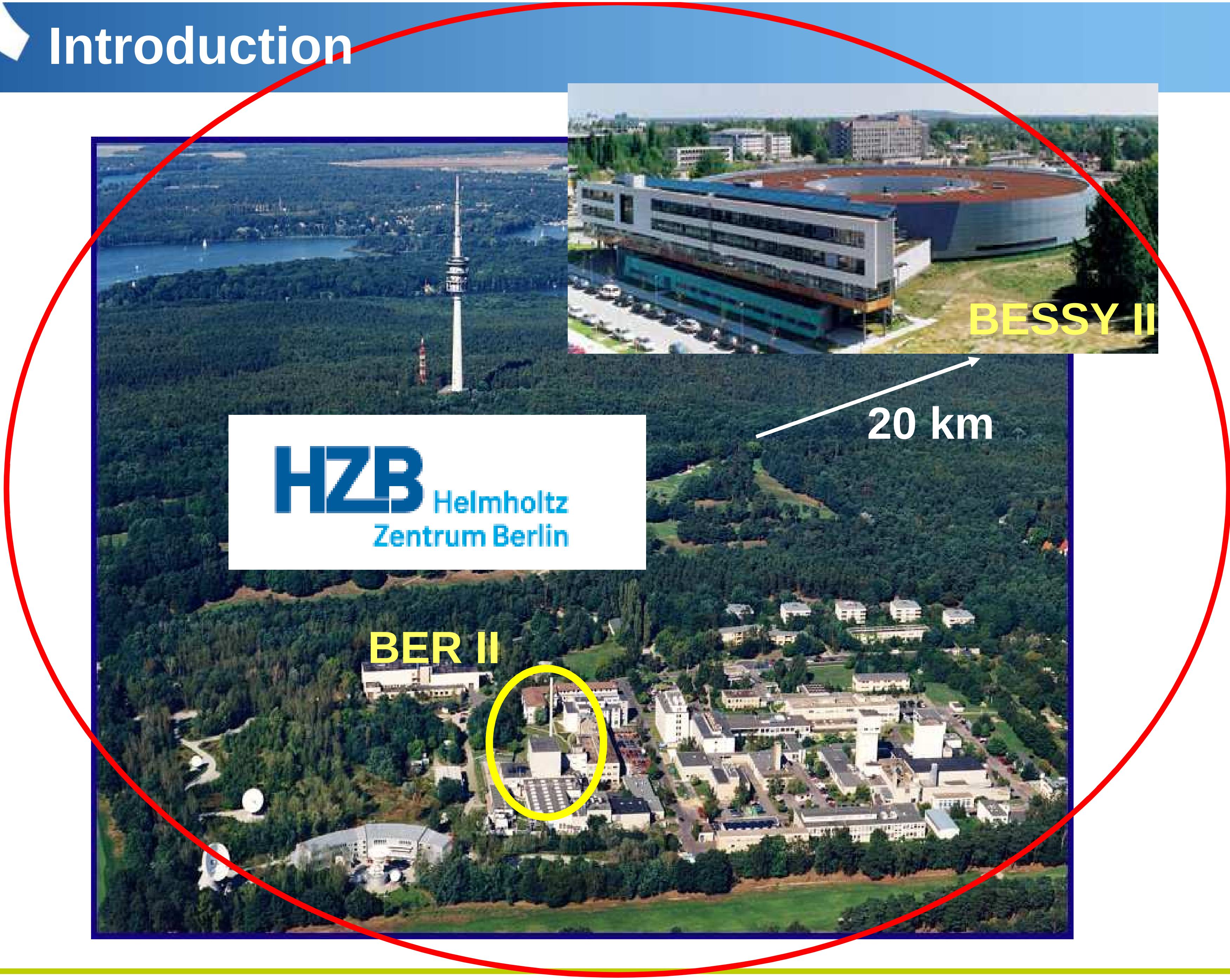
HZB Helmholtz Zentrum Berlin

Summer School AUNIRA 2015

Imaging with Polarized Neutrons

Nikolay Kardjilov, Ingo Manke, André Hilger,
John Banhart

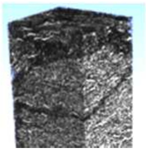
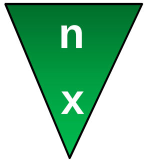
Introduction



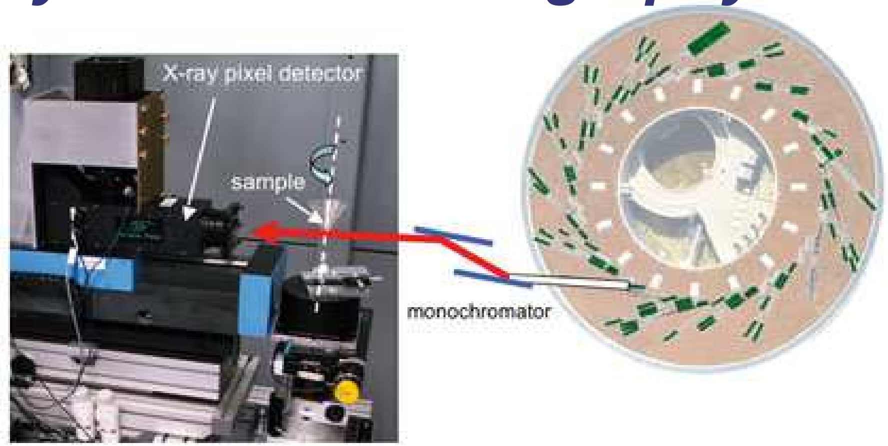
Introduction

Institute of Applied Materials

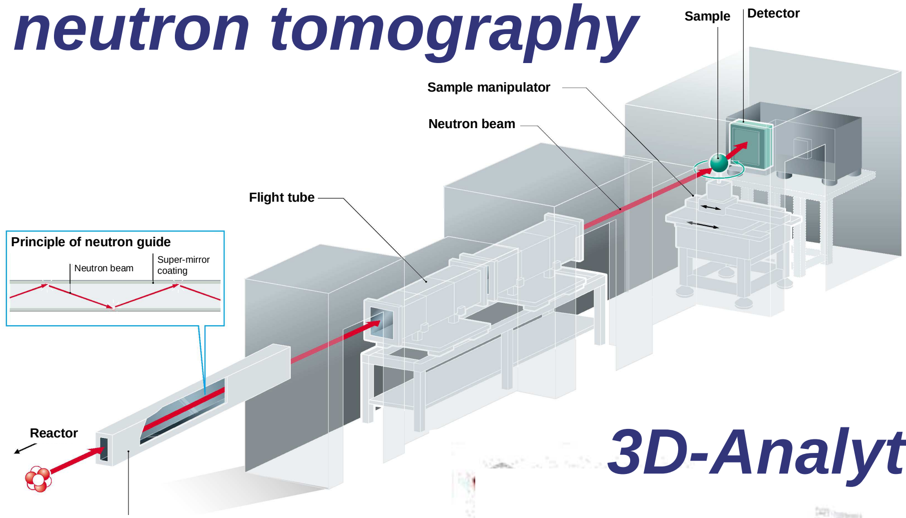
Neutron ***Imaging*** *Micro CT* *Synchrotron*


BAM-Line @ BESSY
Synchrotron tomography

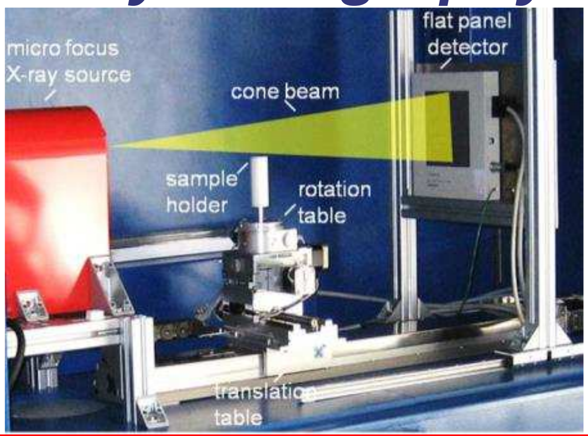


CONRAD-2
neutron tomography



3D-Analytics Lab

MicroCT Lab
X-ray tomography



Summer School on Advanced Imaging for Industrial Applications

26-30 August, 2013
HZB, Berlin

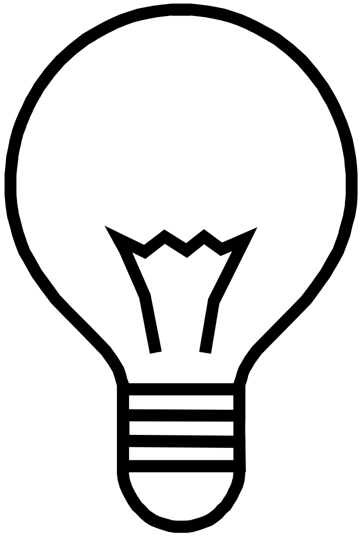
30 Participants

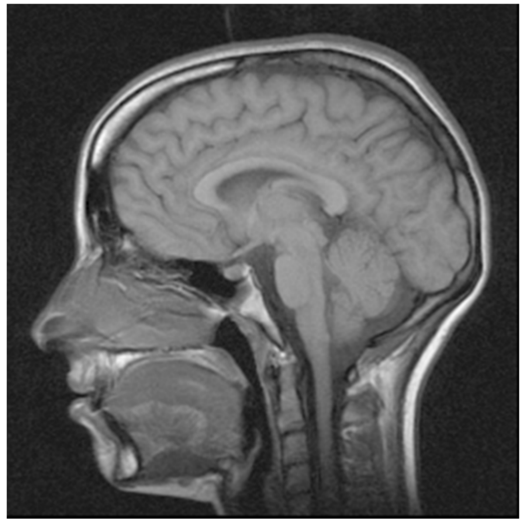
26 Countries:

China, Israel, South Africa, Morocco, Egypt, Argentina, France, Germany, Turkey, Algeria, Indonesia, India, Russia, Switzerland, Kazakhstan, UK, Vietnam, Brazil, Romania, Poland, Malaysia, Australia, Slovenia, Canada, Ireland, Denmark.

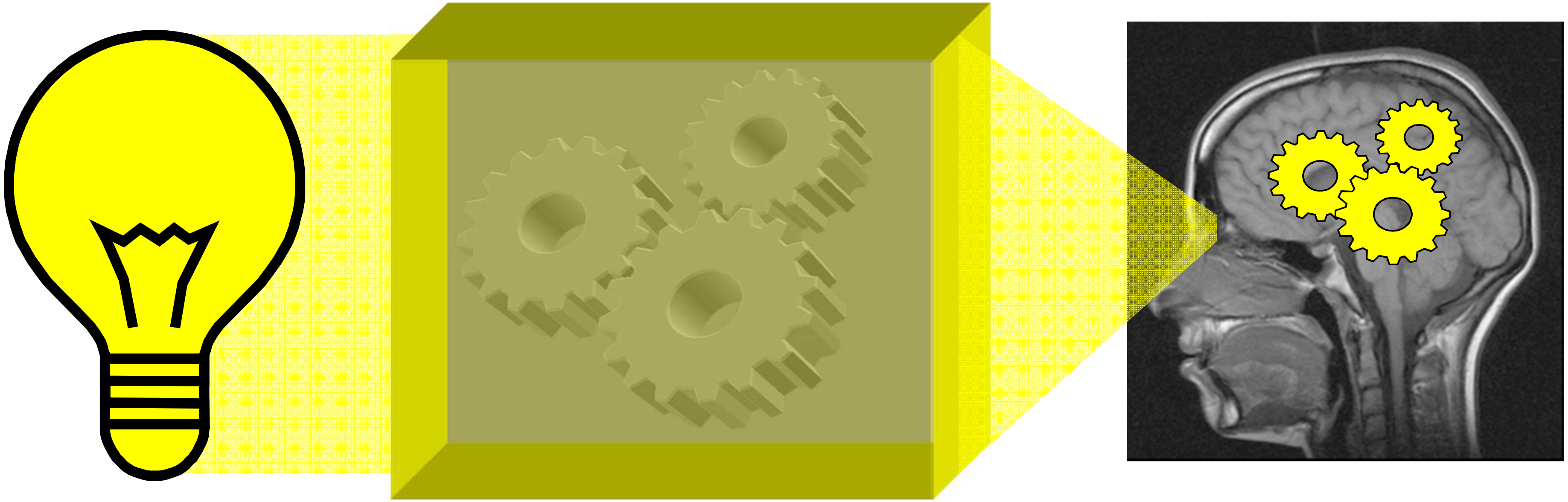
1. Introduction
2. Instrumentation for polarization of neutrons
3. Setup for imaging with polarized neutrons
4. Interpretation of the image contrast
5. Depolarization analysis. Curie temperature
6. Simulation of images with polarized neutrons
7. Procedures for quantification of magnetic fields
8. Vector tomography
9. Application fields
10. Conclusion

Neutron imaging

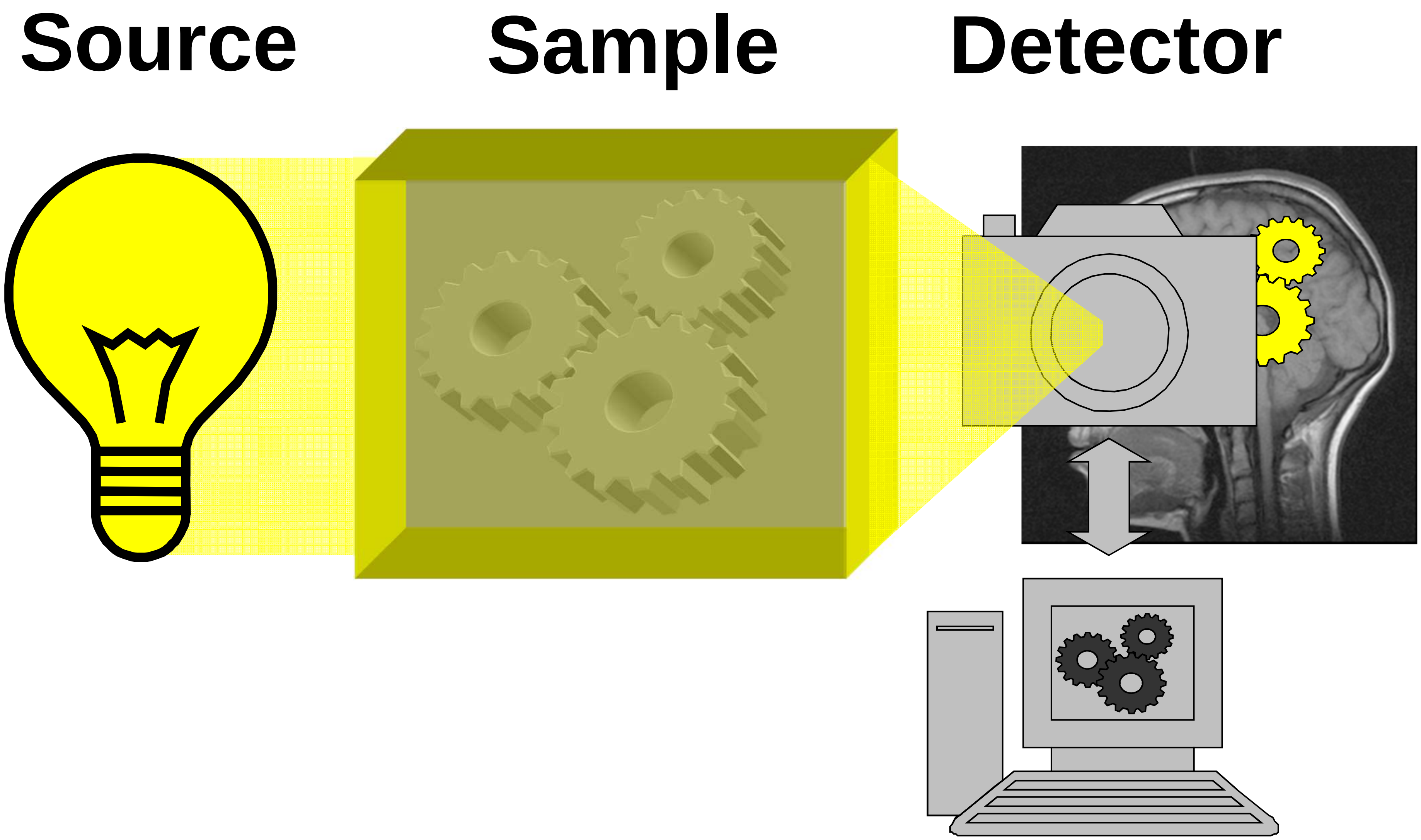




Neutron imaging



Neutron imaging



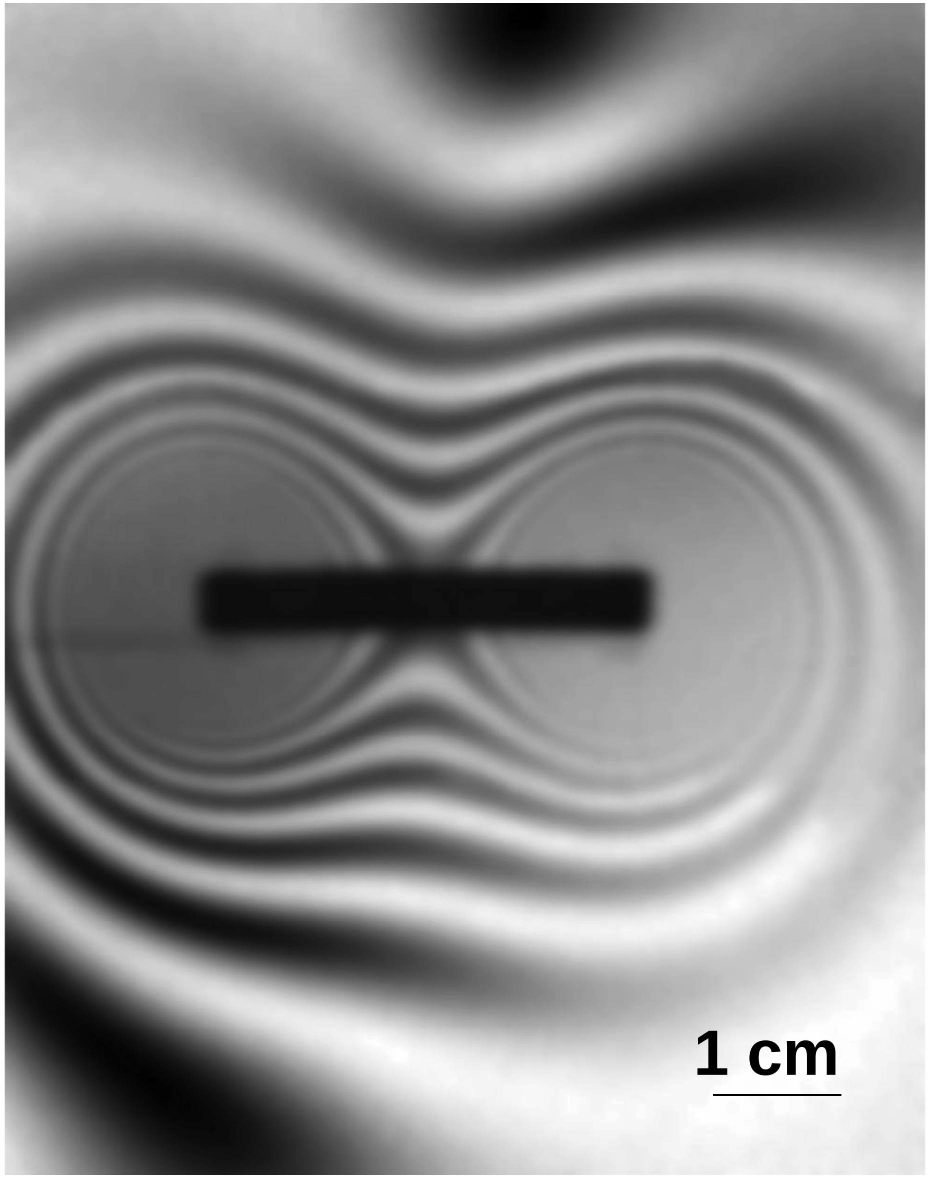
Introduction

Contrast

Resolution

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

Magnetic Contrast

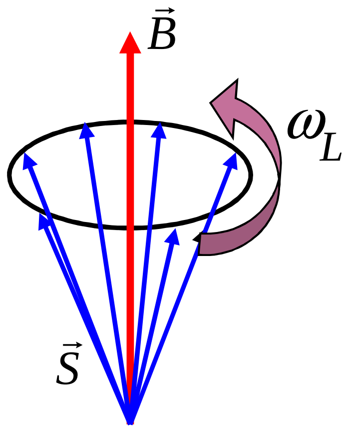


Introduction

Why we used polarised Neutron?

- magnetic moment $\mu = -1.913\ \mu_r$
- Interacts with magnetic fields
- Larmor precession was used as signal for imaging
- Visualisation of magnetic fields in bulk materials

Spin precession



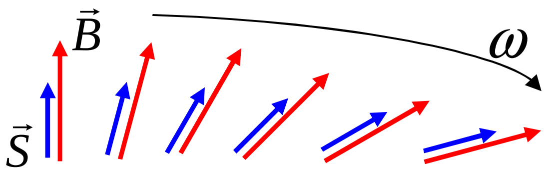
Larmor frequency:

$$\omega_L = \gamma B$$

Gyromagnetic ratio:

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

Adiabatic spin rotation



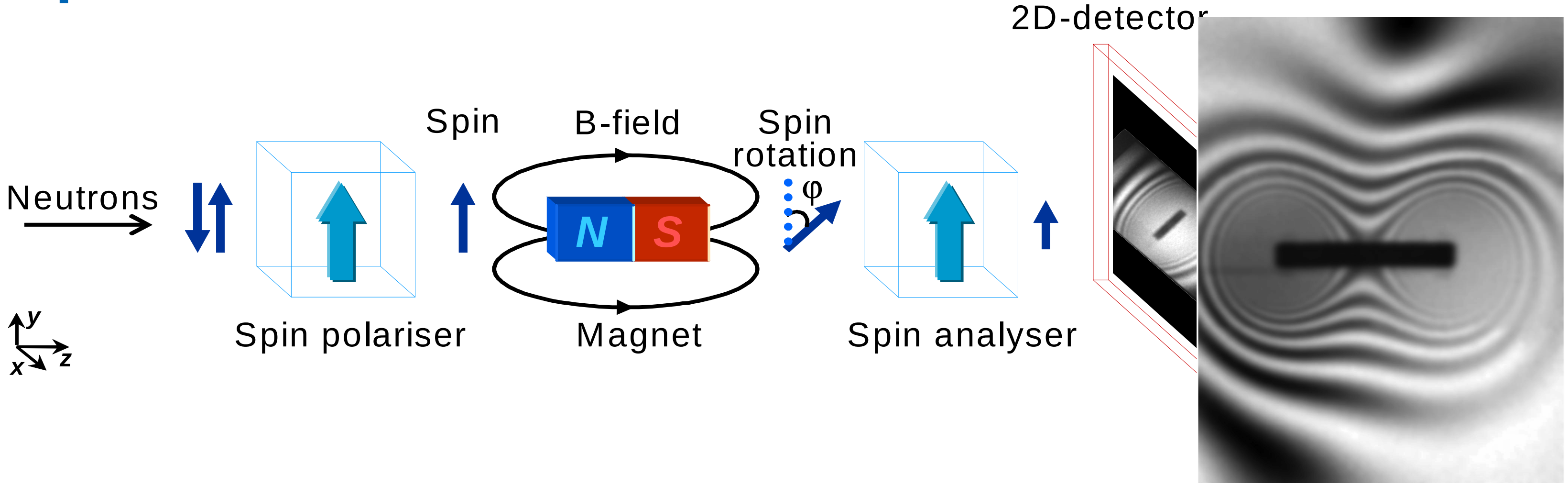
$\vec{B}$ **= magnetic flux density**

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

$$\omega << \omega_L$$

Magnetic Contrast

Principle



Experimental parameters

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

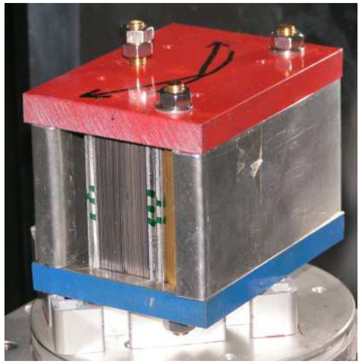
$$\varphi = \omega_L t = \frac{\gamma_L}{v} \int_{path} H ds$$

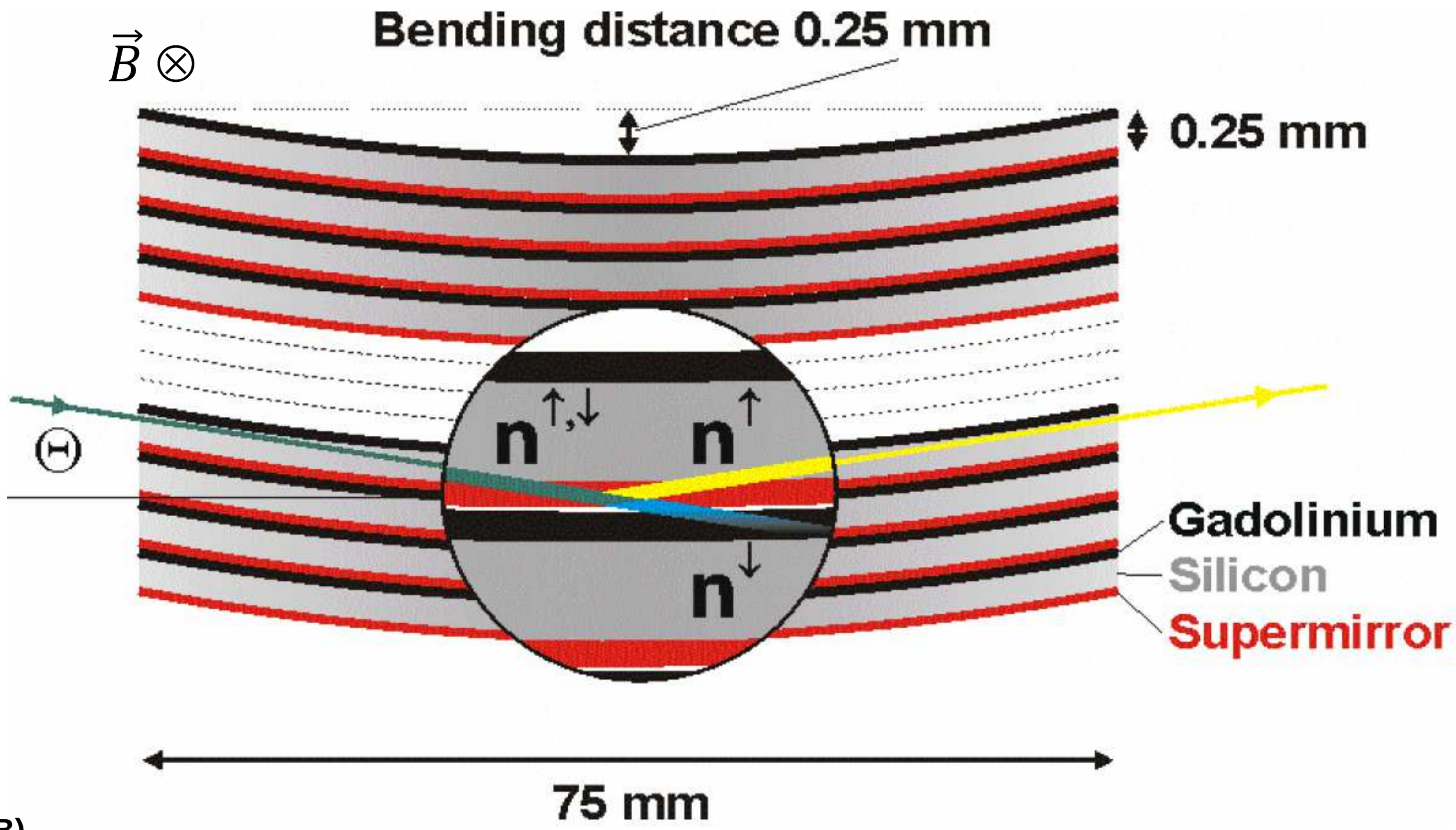
N. Kardjilov, et al, Nature Physics 4, 399-403, (2008)

Experimental setup

Solid state polariser
Wavelength optimum λ = 3.5 Å

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





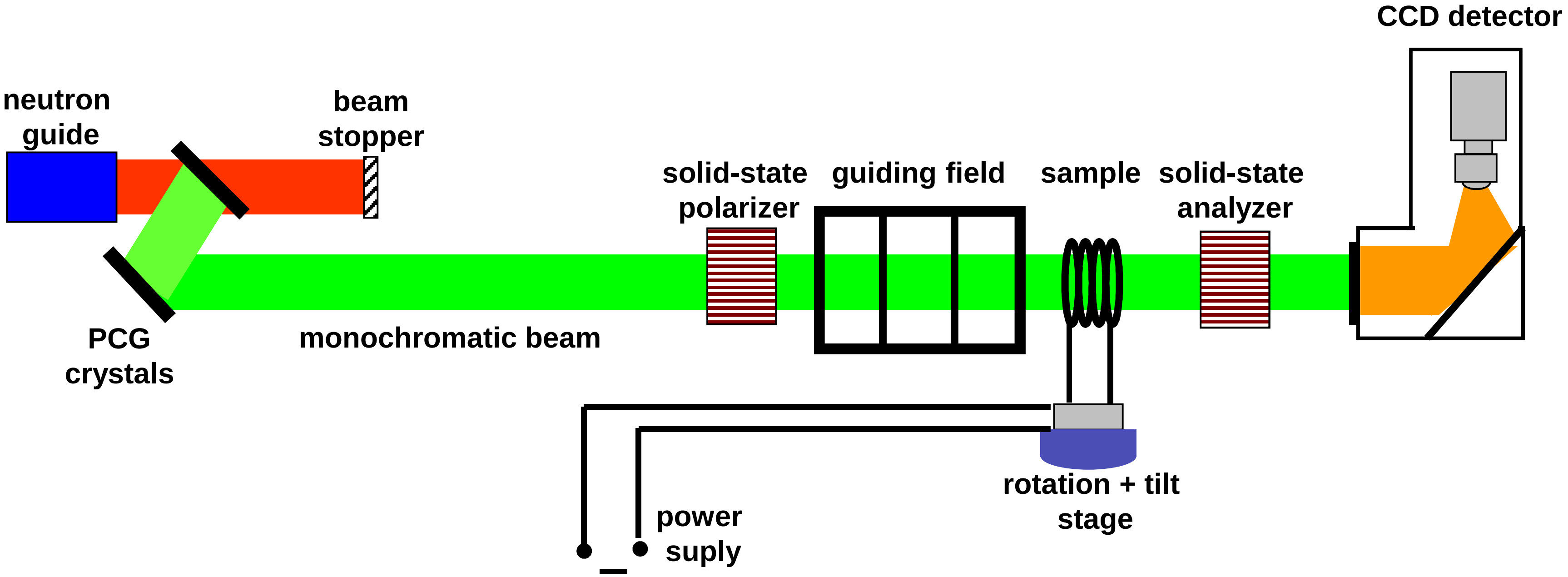
Source: Dr. Krist (HZB)

Experimental setup

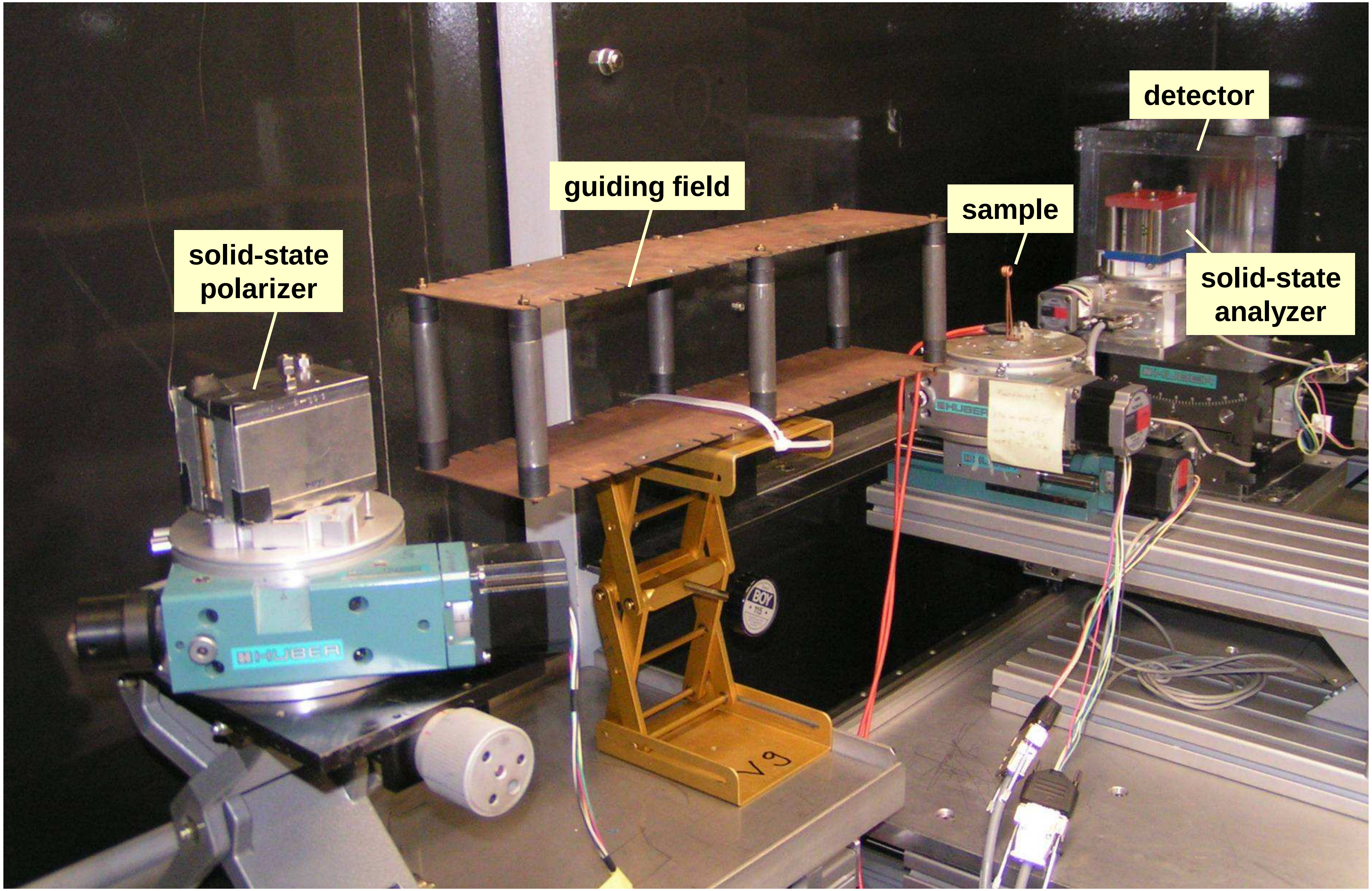
Option with polarized neutrons

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:



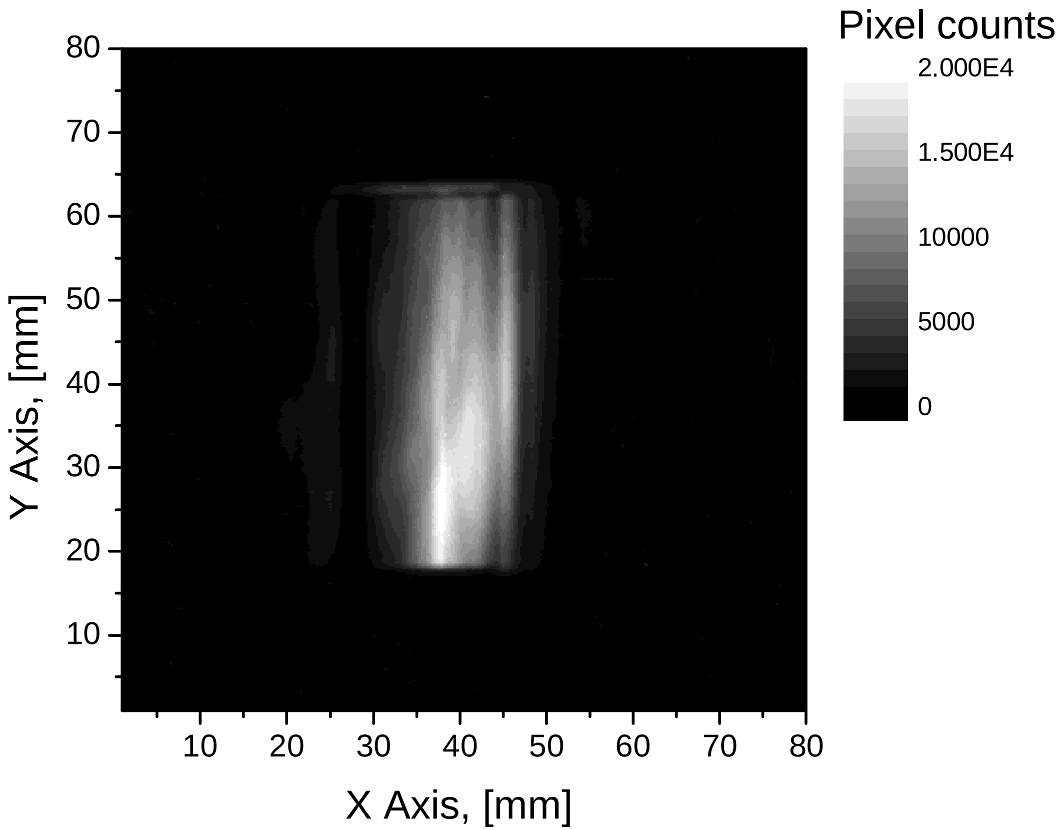
Experimental setup



Experimental setup - results

Experimental parameters

Open beam



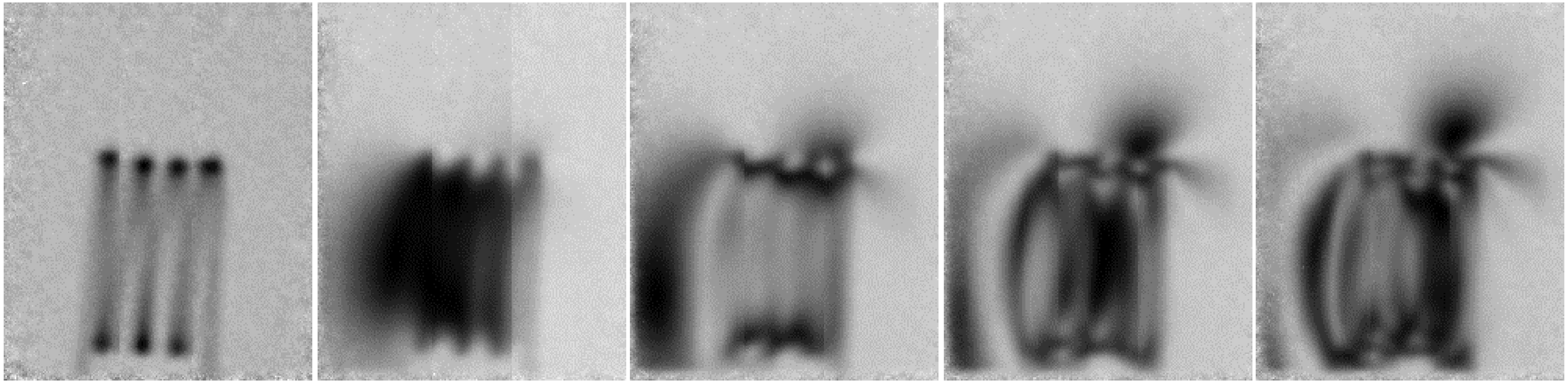
Exposure time: 300 s
Binning: 2x2

Sample

Copper coil
Wire thickness: 2 mm

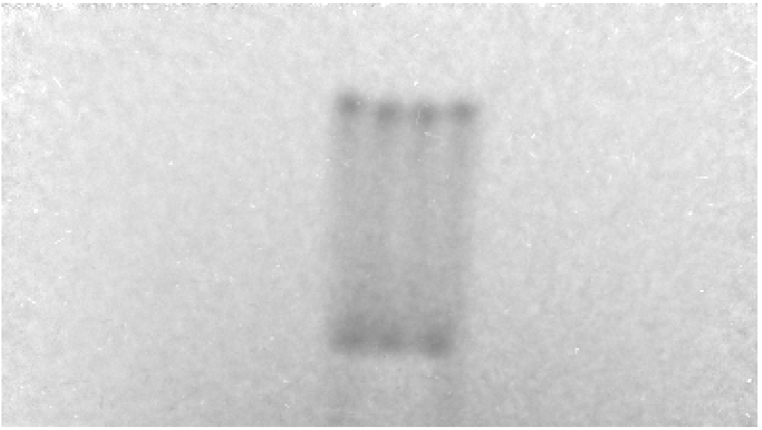
Experimental setup - results

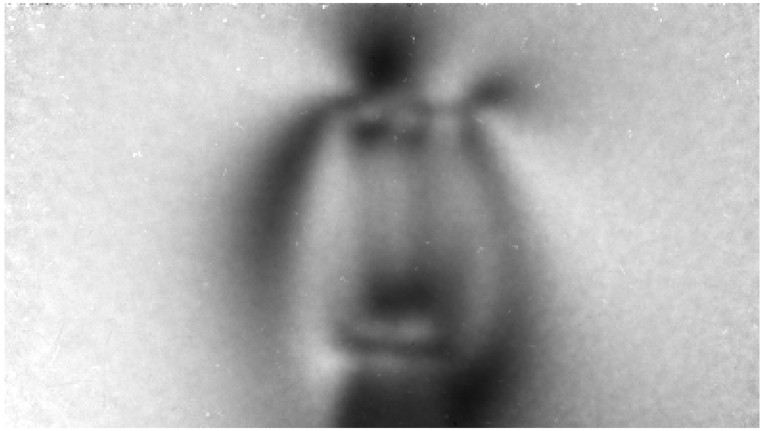
Results



current: 0 A **4 A** **8A** **12 A** **15 A**

Scan option

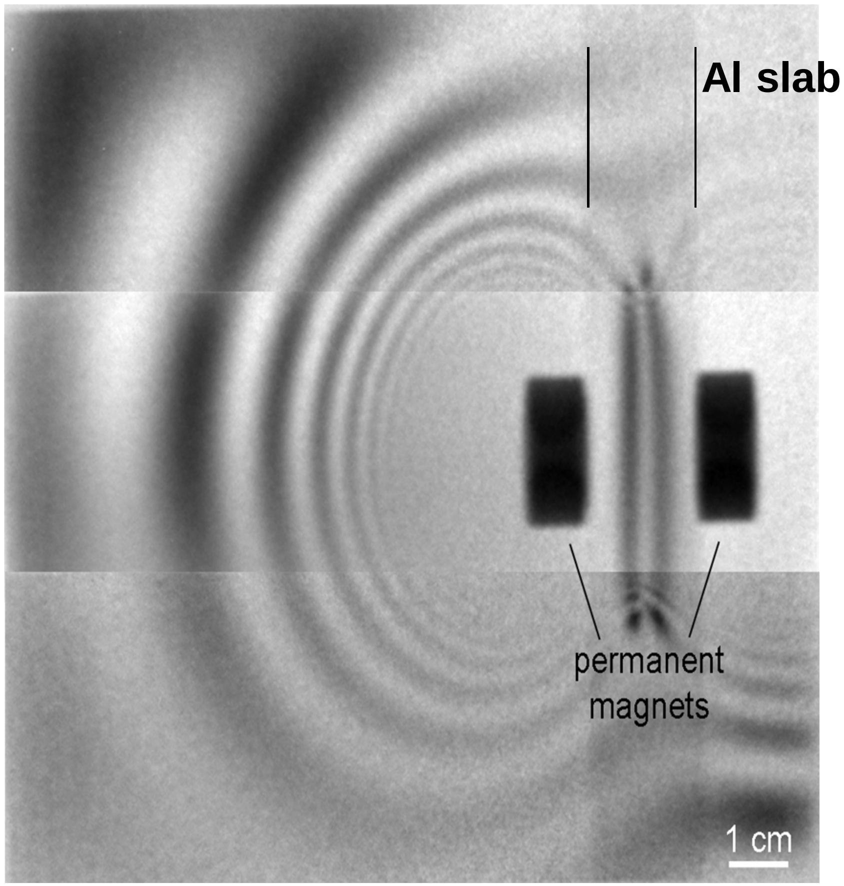




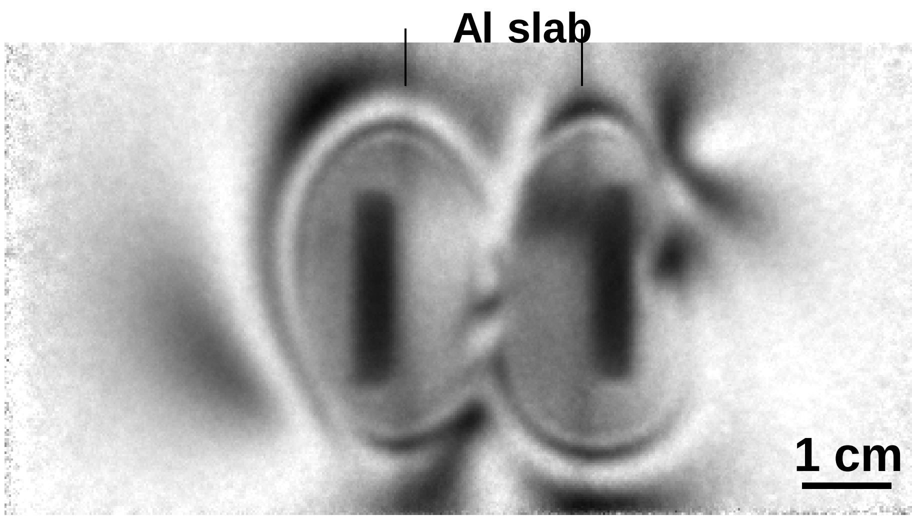
1 cm

Exposure time: 1440 s (24 min)
Binning: 2x2

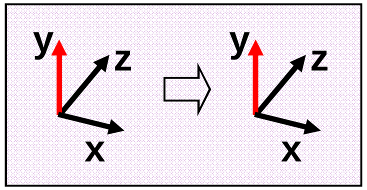
Experimental setup - results



dipole magnets



non-dipole magnets

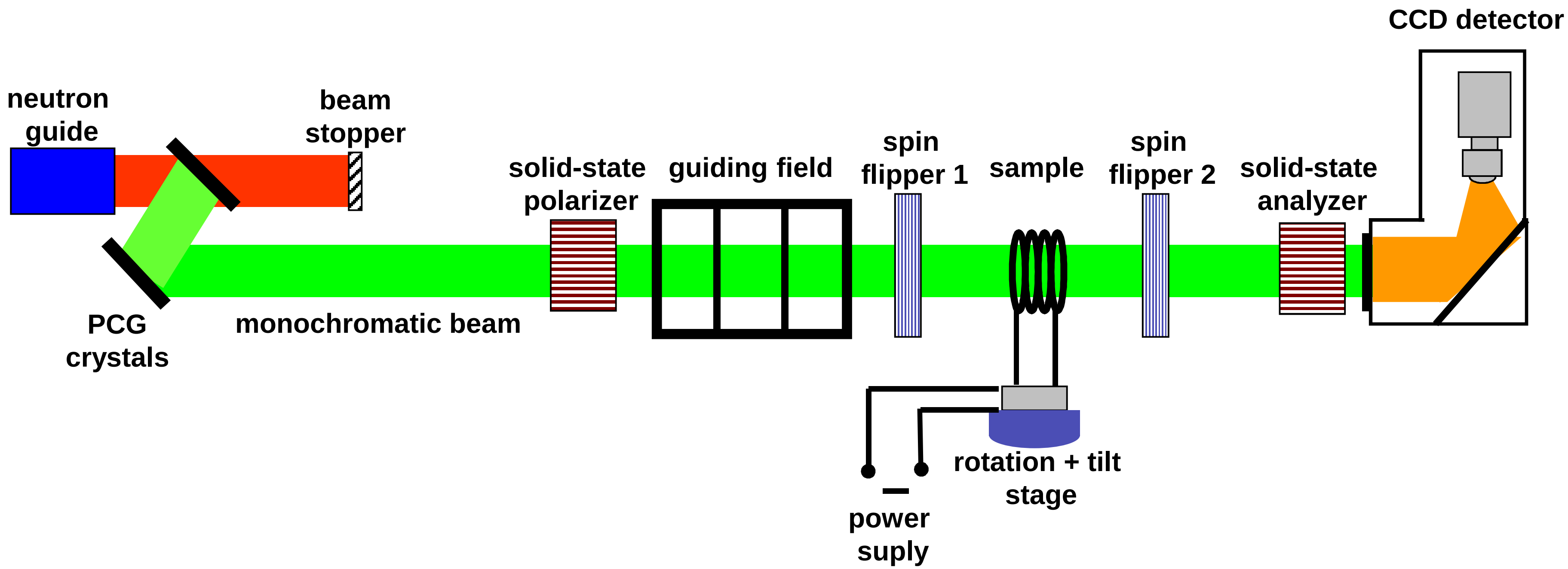


Experimental setup - results

Using of spin-flippers

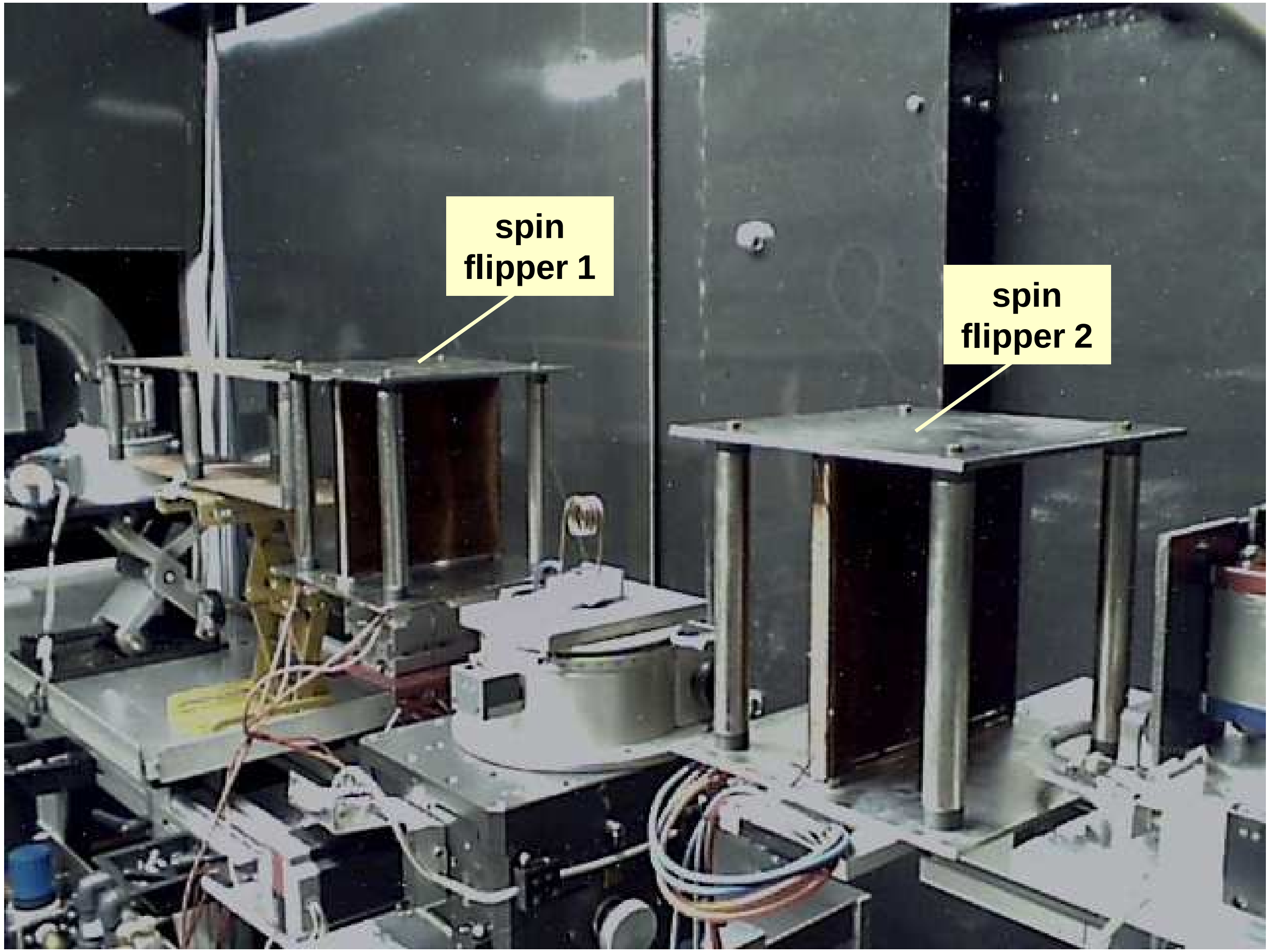
Instrument: V7 (CONRAD) at HMI
Date: 11-15 July 2006
Options: Monochromatic option: 4.2 Å
Detector mode: CCD, low-resolution mode (0.2 mm/pixel)

Experimental sketch:



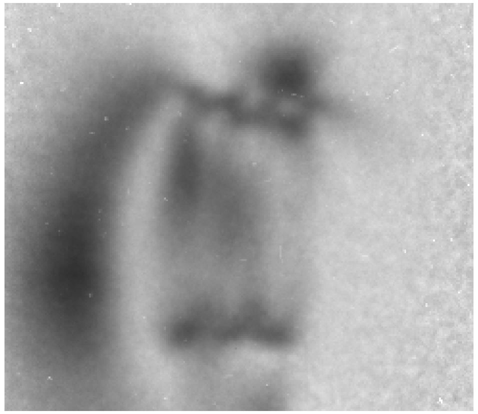
Experimental setup - results

Using of spin-flippers

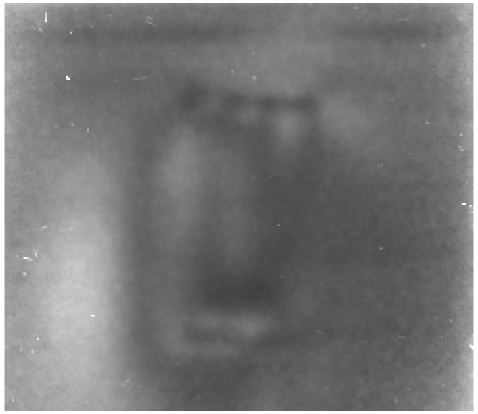


Experimental setup - results

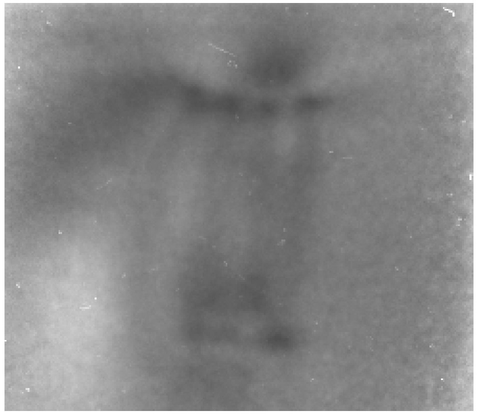
Using of spin-flippers



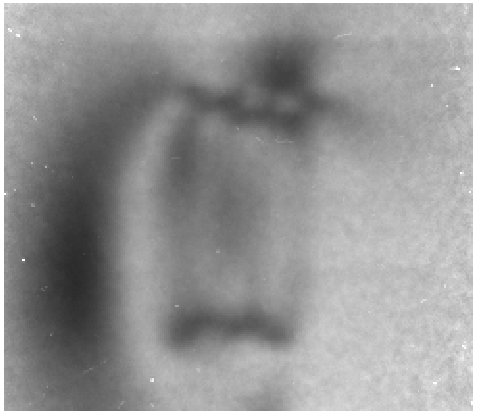
Spin Flipper1: 0.0 A
Spin Flipper2: 0.0 A



Spin Flipper1: 0.2 A
Spin Flipper2: 0.6 A

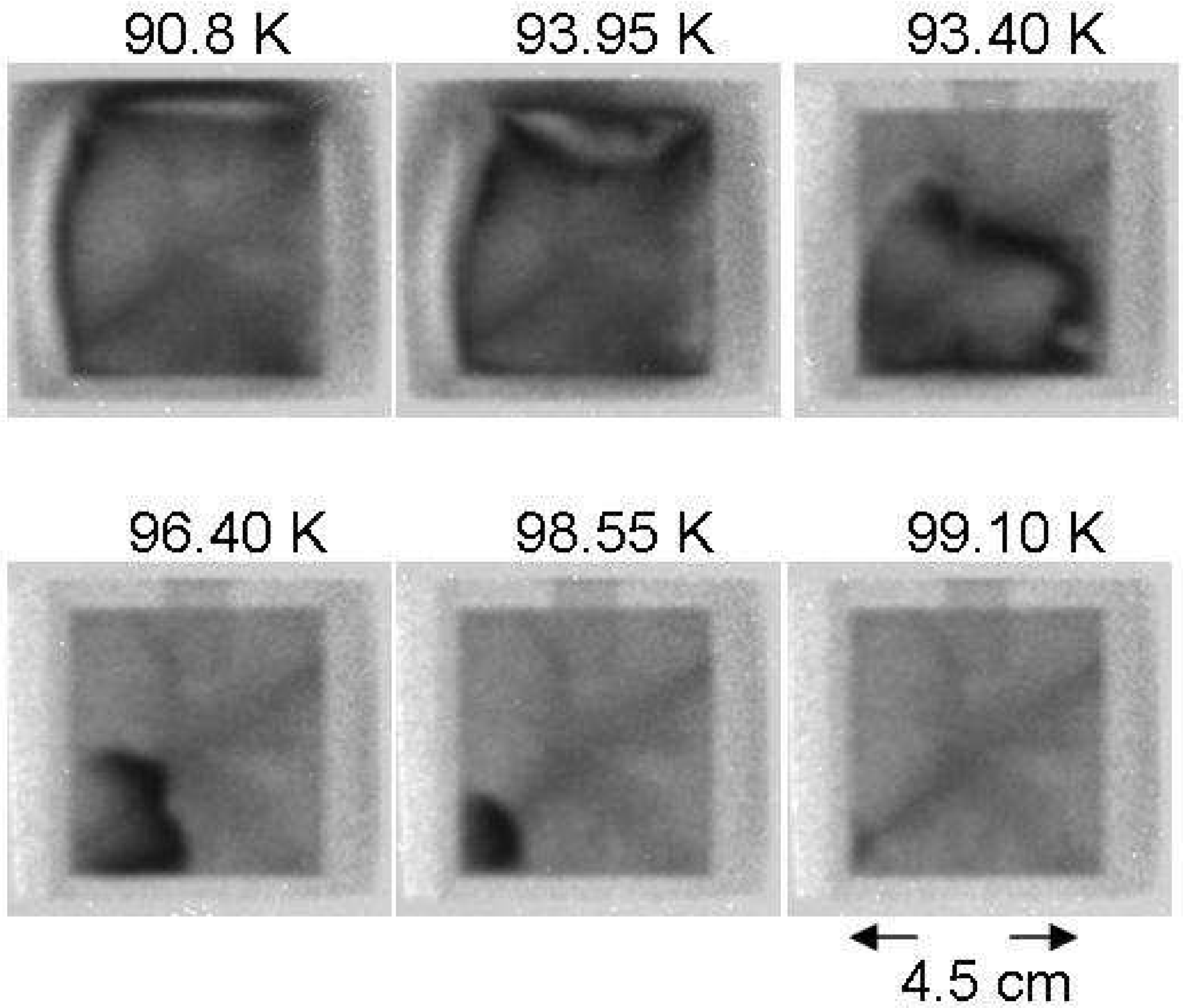


Spin Flipper1: 0.4 A
Spin Flipper2: 0.4 A



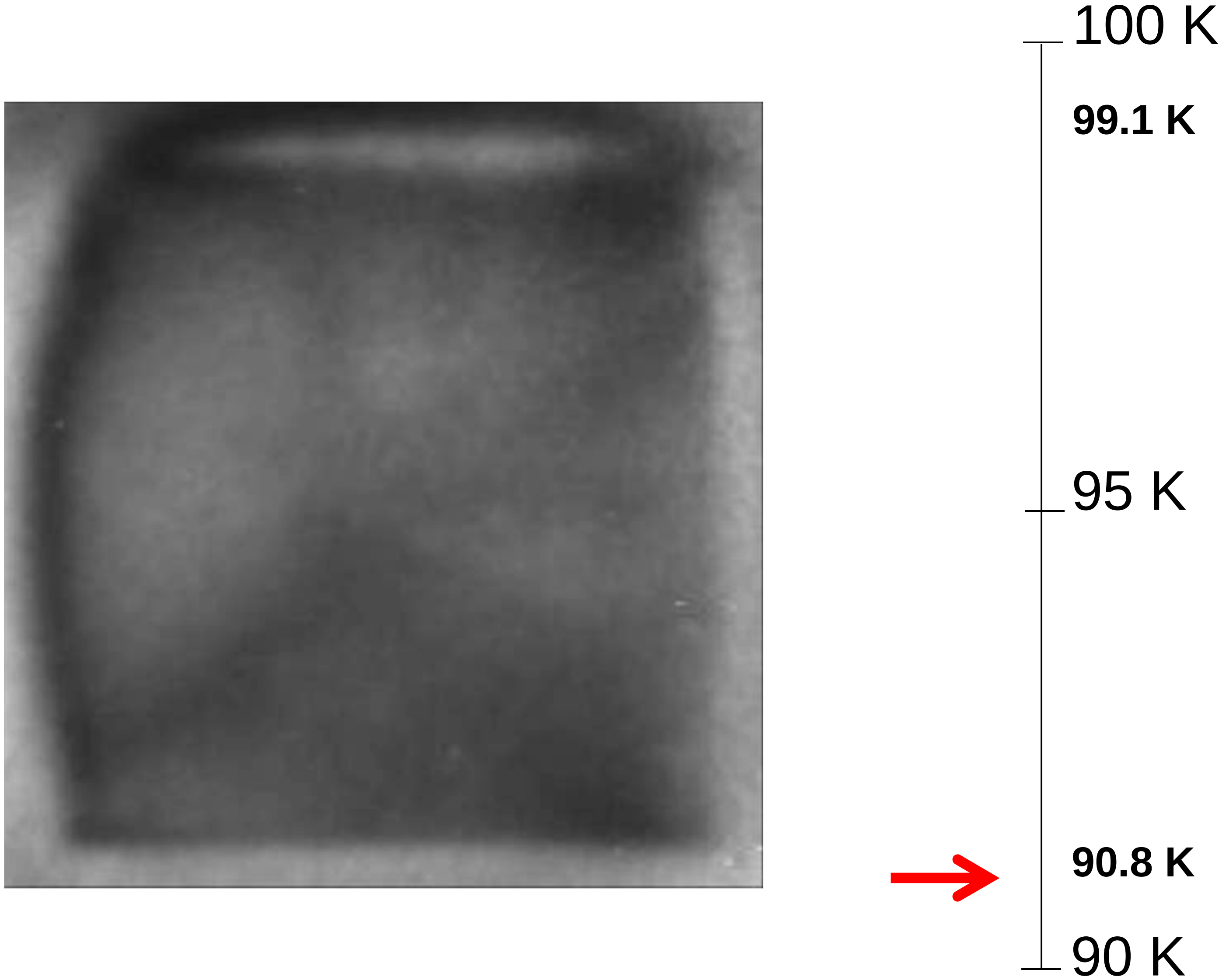
Spin Flipper1: 0.8 A
Spin Flipper2: 0.8 A

Magnetic Contrast



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

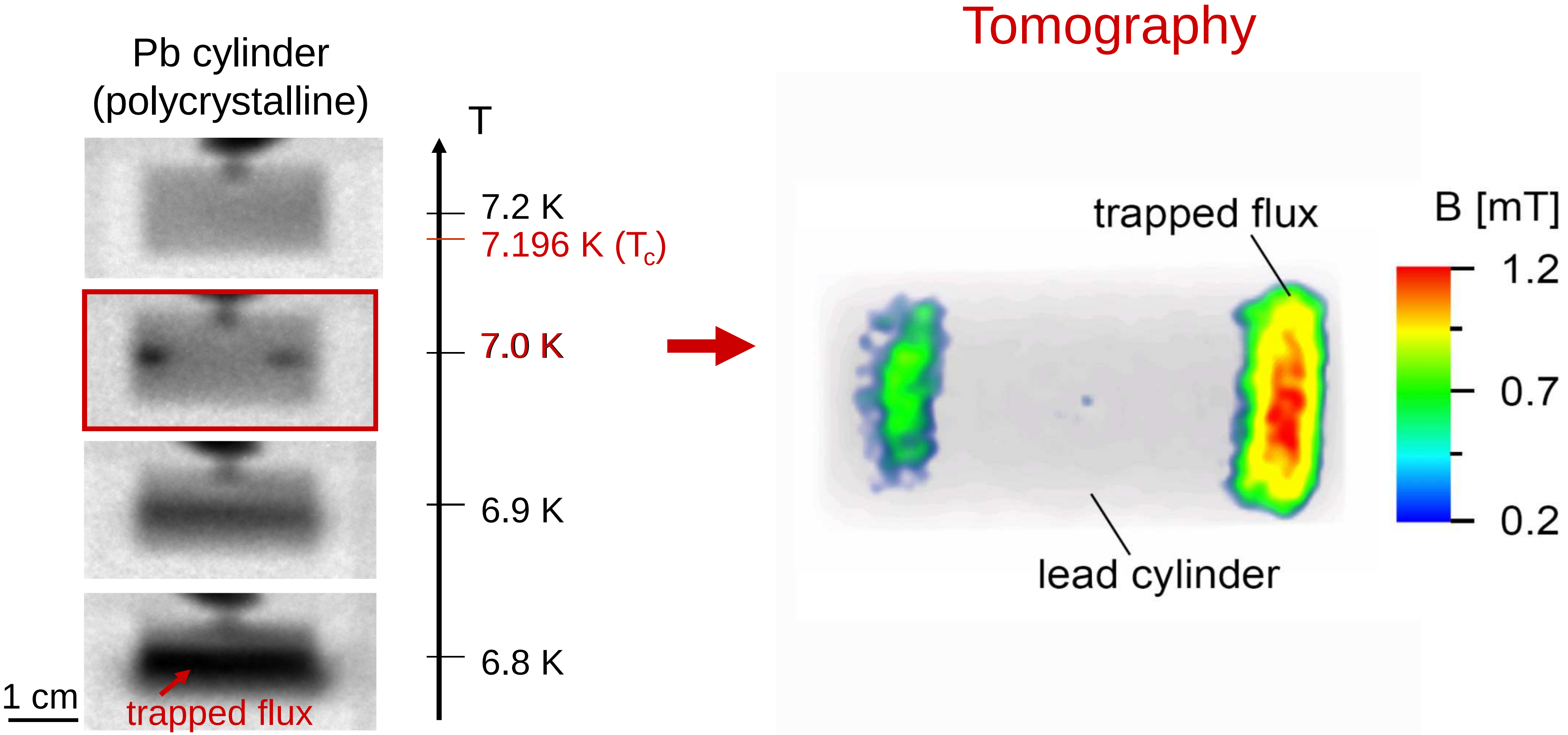
Magnetic Contrast



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

Magnetic Contrast

Flux pinning in superconductors



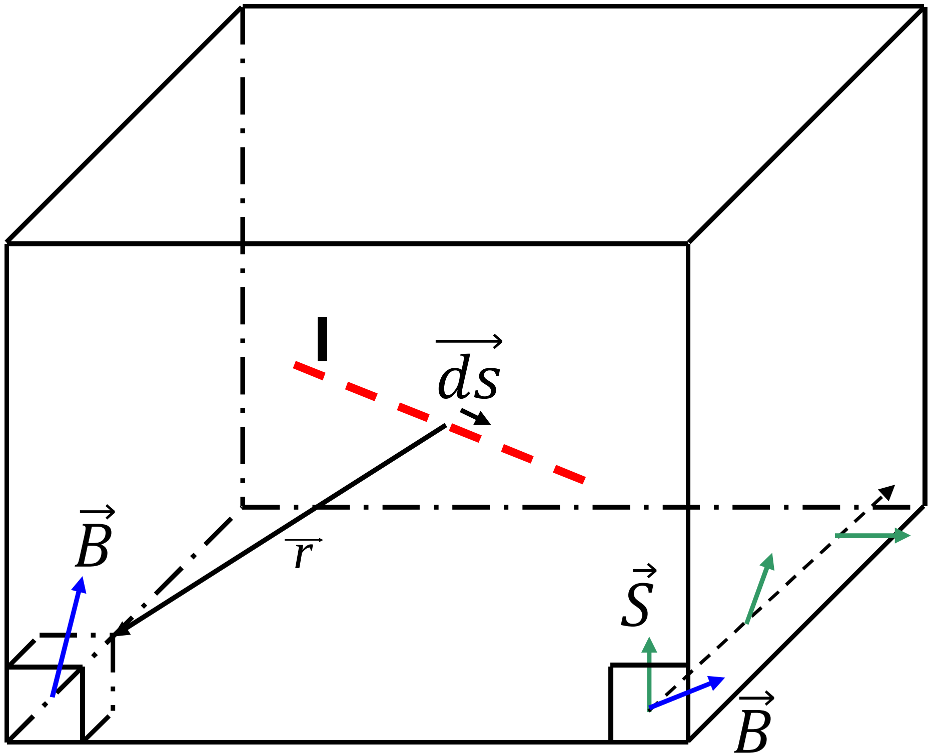
Flux pinning at cooling down below Tc while applying a homogenous magnetic field of 10 mT perpendicular to the beam.

The images were recorded after switching off the magnetic field.

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

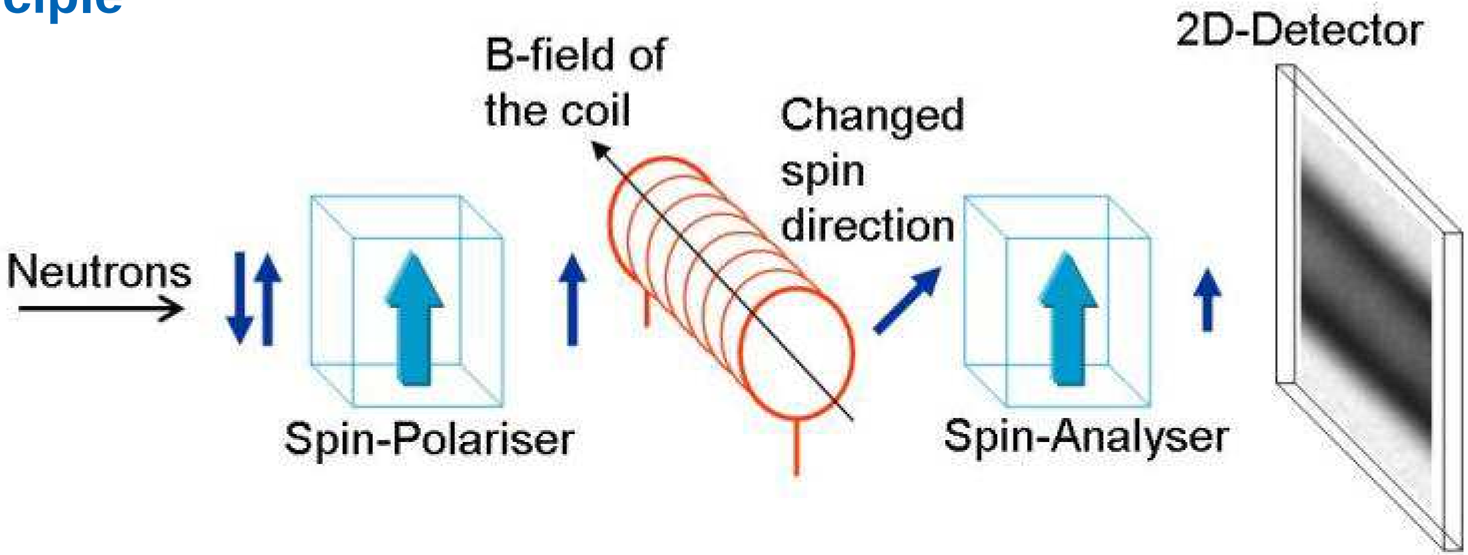
$$\varphi = \gamma \cdot t \cdot B$$

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

$$t \sim \lambda$$

Neutron imaging

Principle

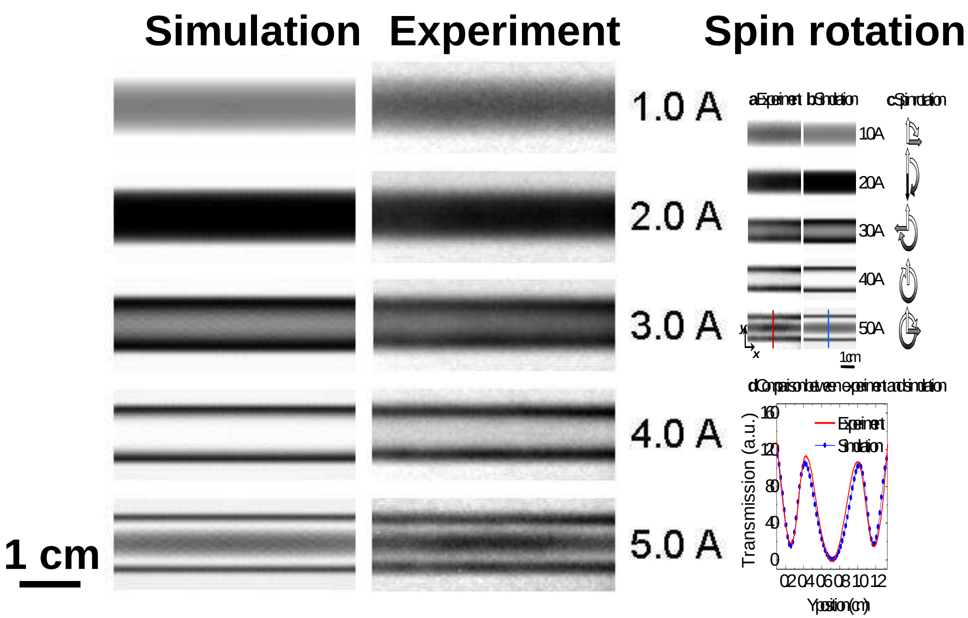


Biot-Savart law

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

Spin rotation

$$\varphi = \frac{\gamma_L}{v}\int_{path} B ds$$

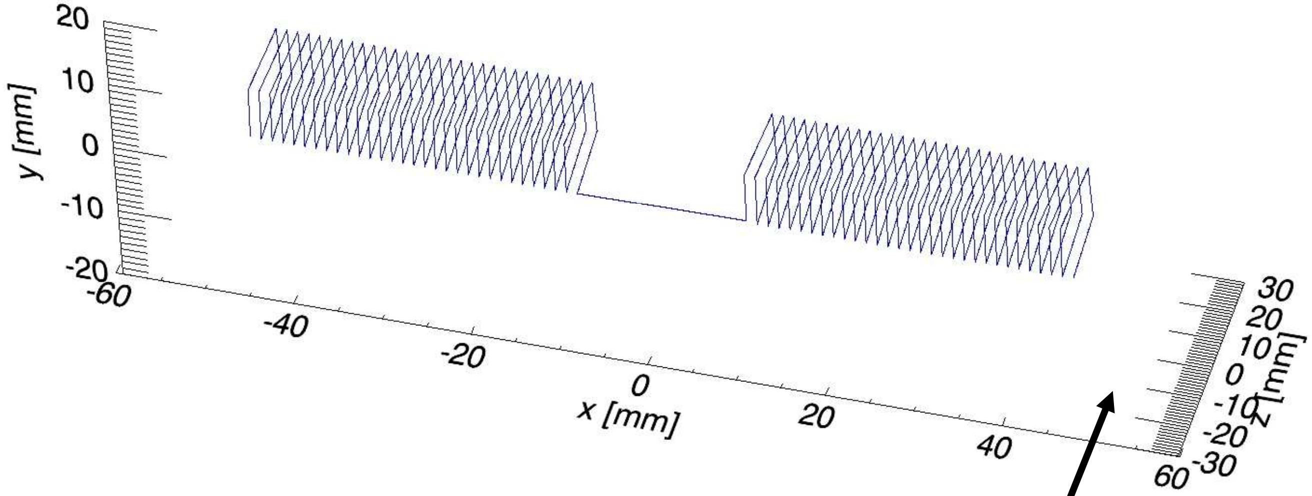


Simulation process - results

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



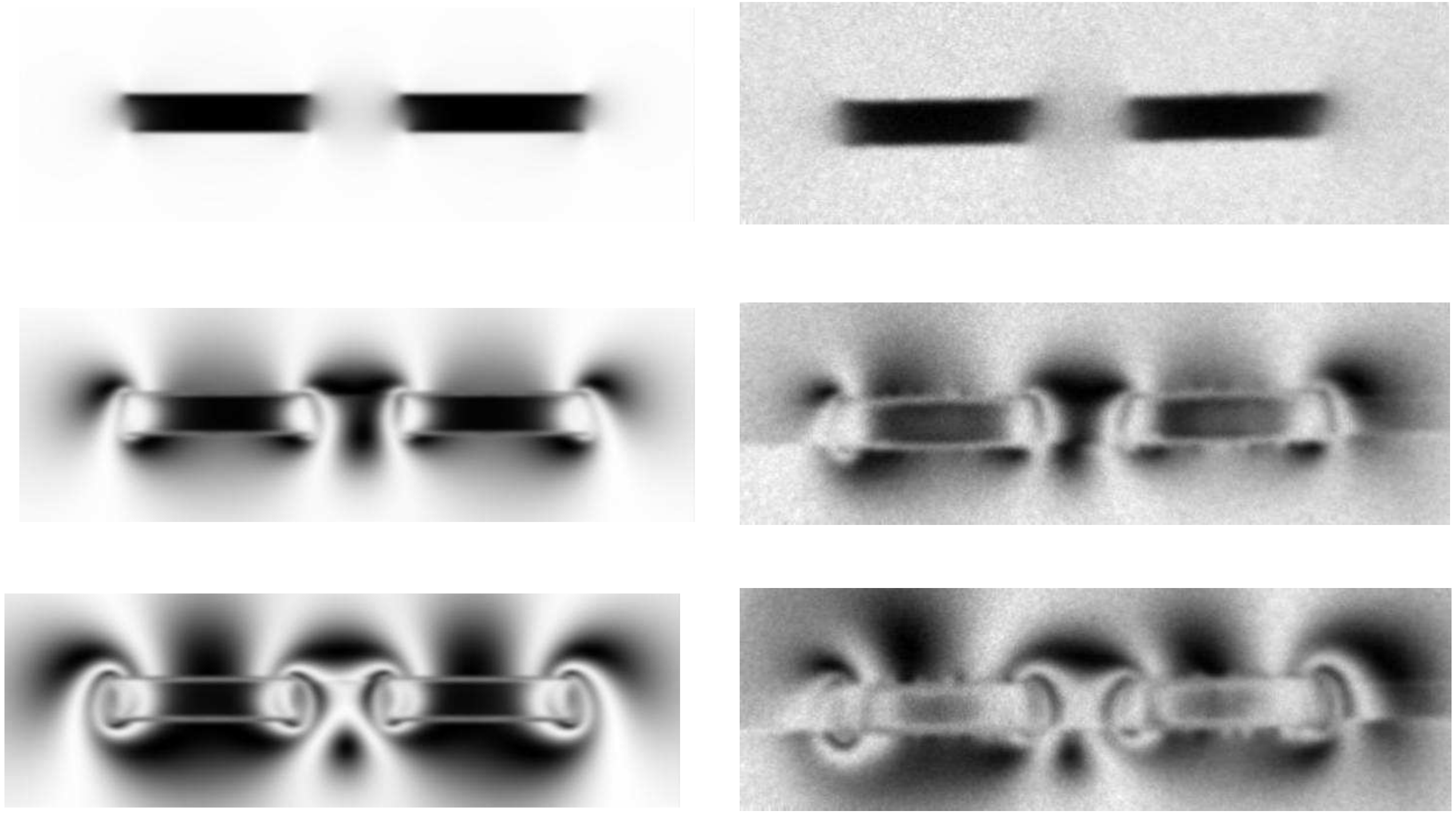
Neutron flight path direction

Simulation process - results

1.0 A

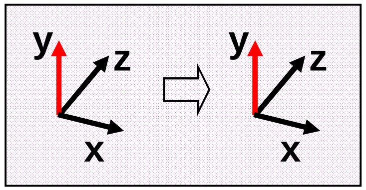
5.0 A

9.0 A



Simulated radiograms

Measurements

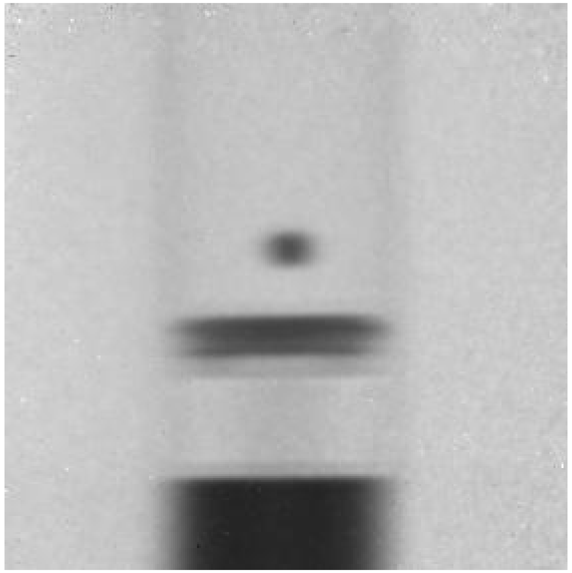


Simulation process - results

Levitating dipole over a superconductor

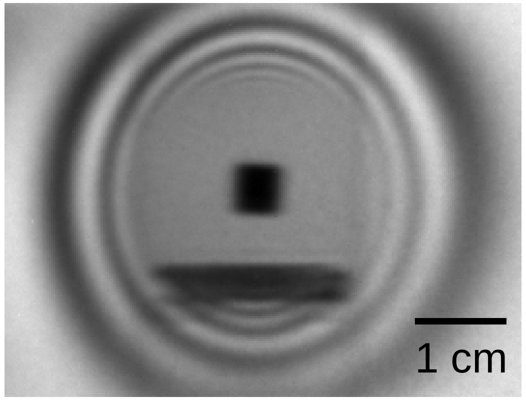
Superconductor:$YBa_2Cu_3O_7$

Critical temperature: 90 K

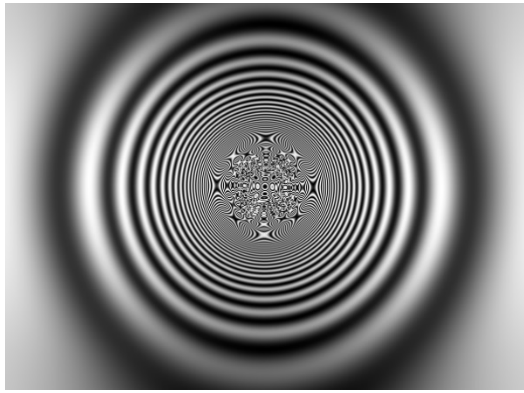


Absorption contrast

Simulation process - results



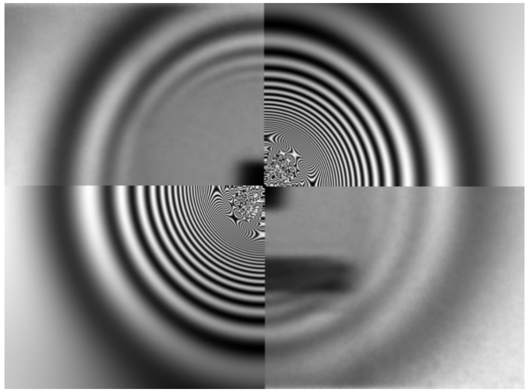
Levitating magnet over YBCO



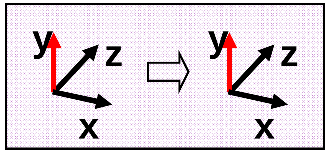
Simulated Radiogram

Simulation parameter:

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

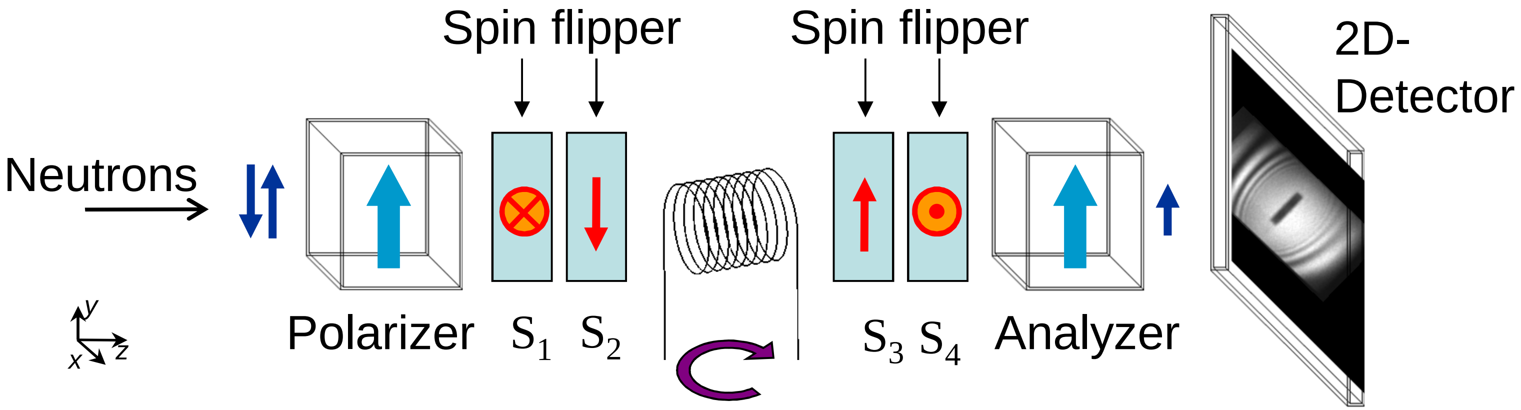


Comparison between measured and simulated data

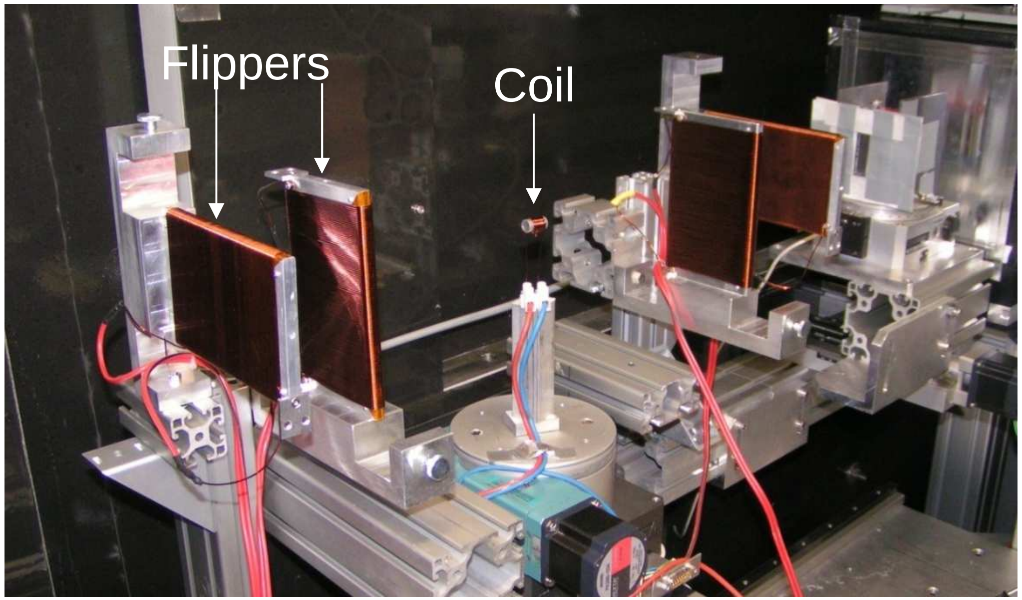


Magnetic Contrast

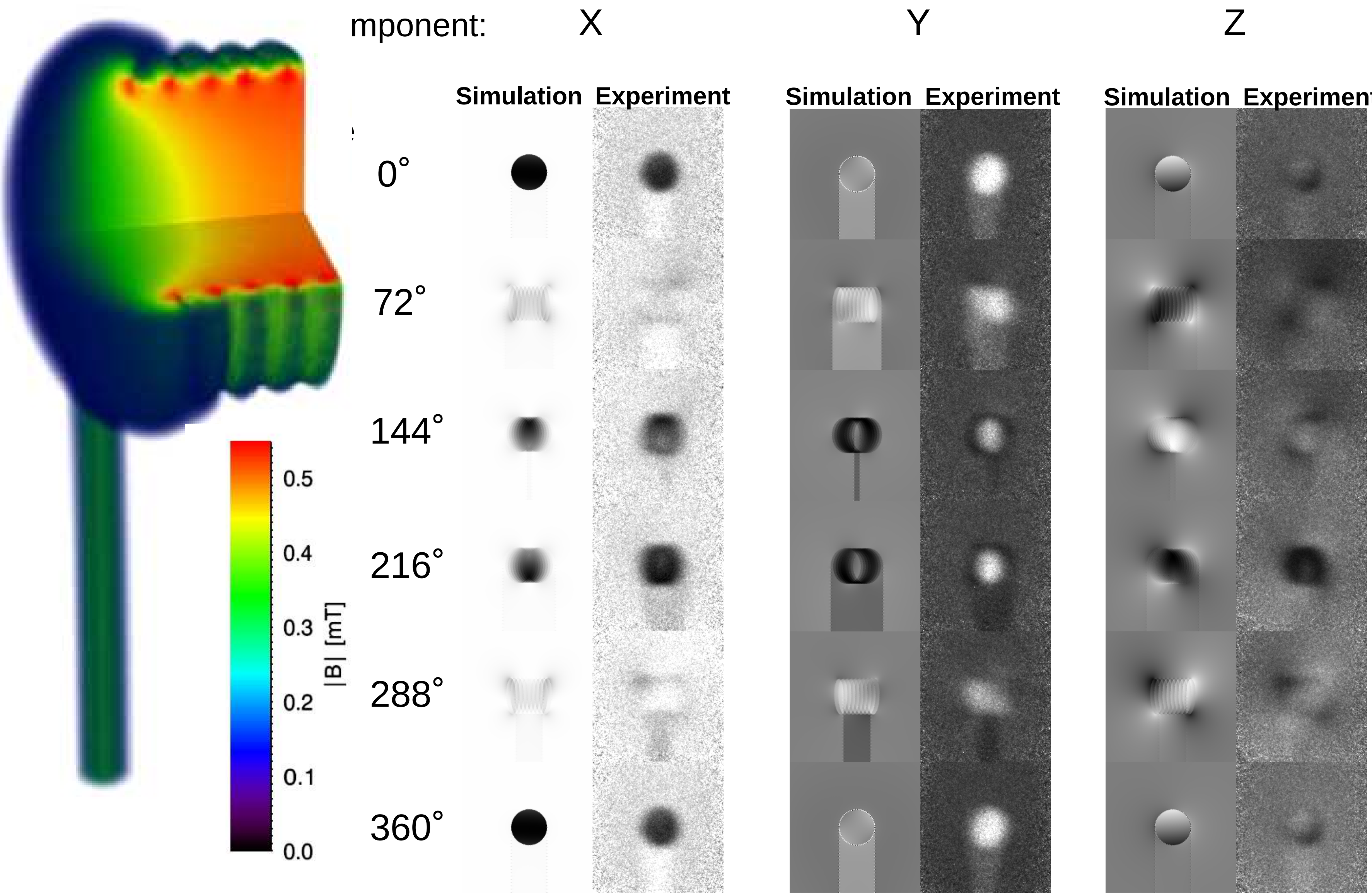
Steps towards quantification



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



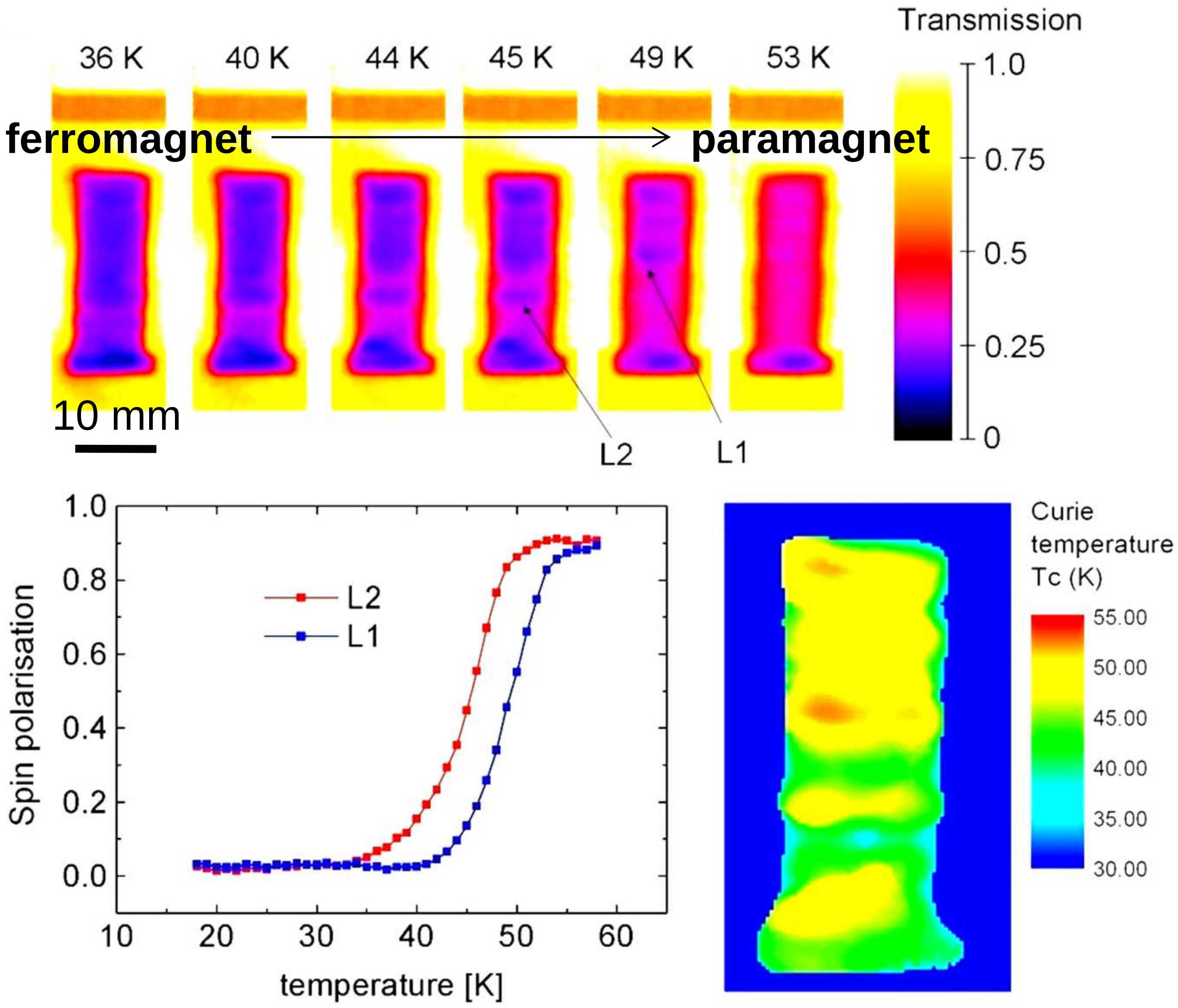
Magnetic Contrast



M. Strobl et al, Phys. B (2009); M. Strobl, NIMA 604 (2009)

Magnetic Contrast

Depolarisation analysis

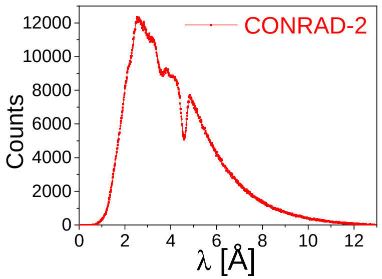


PdNi crystal (3.24% Ni) imaged by polarised neutrons

State-of-the-art neutron imaging instrument

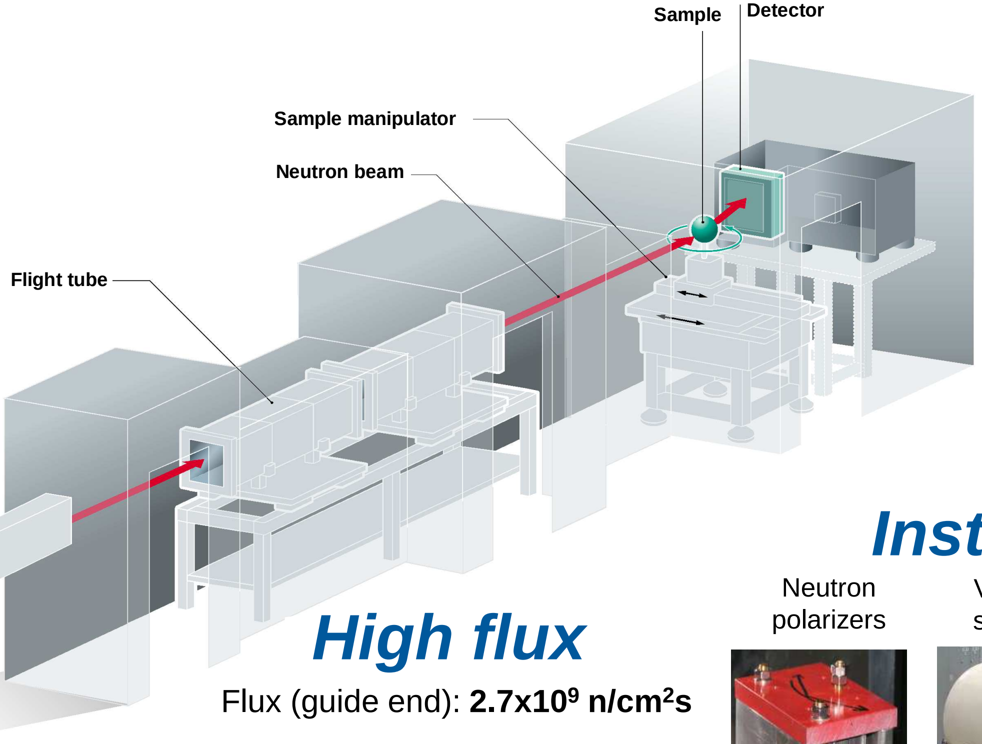
Cold neutrons

Wavelength range: **1.5 Å – 10 Å**



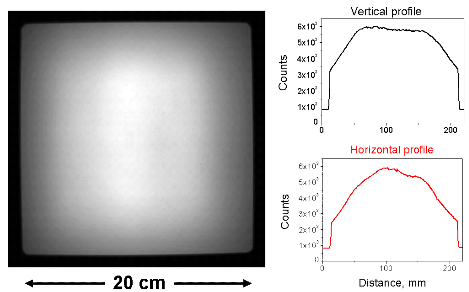
Labs

Micro-CT Lab
3D Data Analytics Lab



Large beam

Beam size: **20 cm x 20 cm**



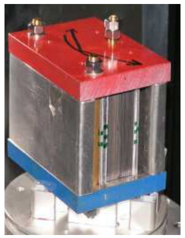
Guide system: super-mirror coated neutron guide (M=3) with a curvature of 750 m and length of 15 m followed by linear guide section (M=2) with a length of 10 m.

High flux

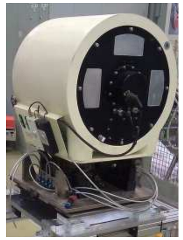
Flux (guide end): **$2.7x10^9$ n/cm^{2}s**

Instrumentation

Neutron polarizers

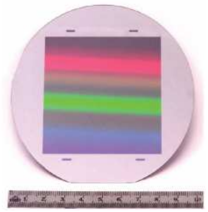


Velocity selector

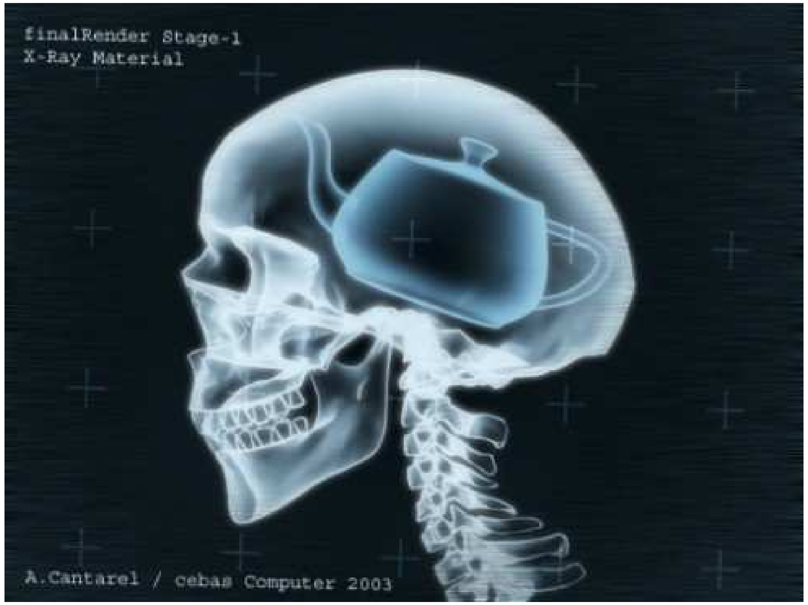


Double-crystal monochromator

Grating interferometry



Thank you !


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