The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

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International Atomic Energy Agency

1866-10

School on Pulsed Neutrons: Characterization of Materials

15 - 26 October 2007

Materials and Life Sciences at Spallation Neutron Sources (1)

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PAUL SCHERRER INSTITUT

Materials and Life Sciences at Spallation Neutron Sources (1)

PAUL SCHERRER INSTITUT PSI

Outline

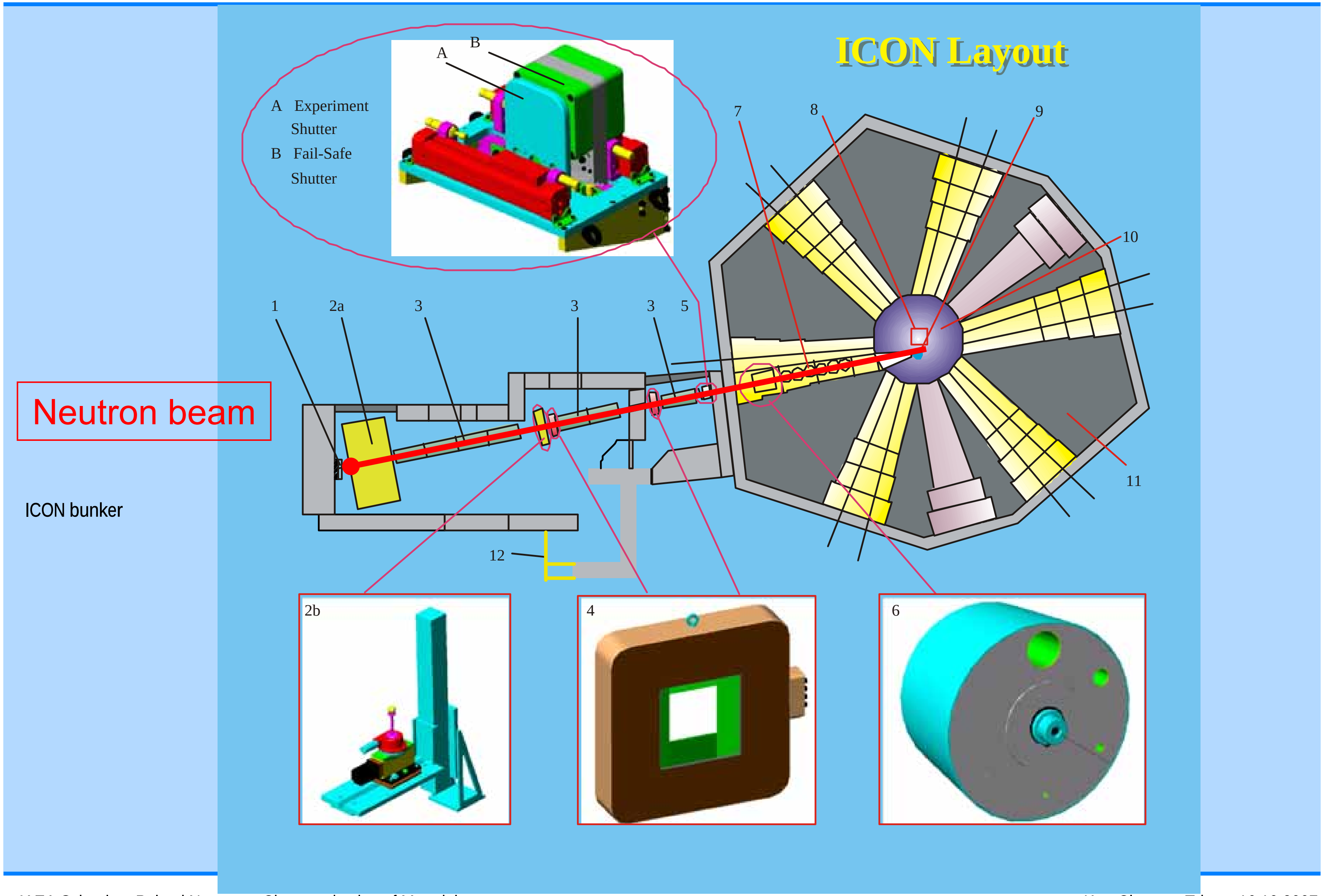
Radiography/tomography

- Layout of instrument – detector systems
- Strain mapping
- “Nuclear” applications
- Complementarity with X-ray’s tomography (example from wood research)

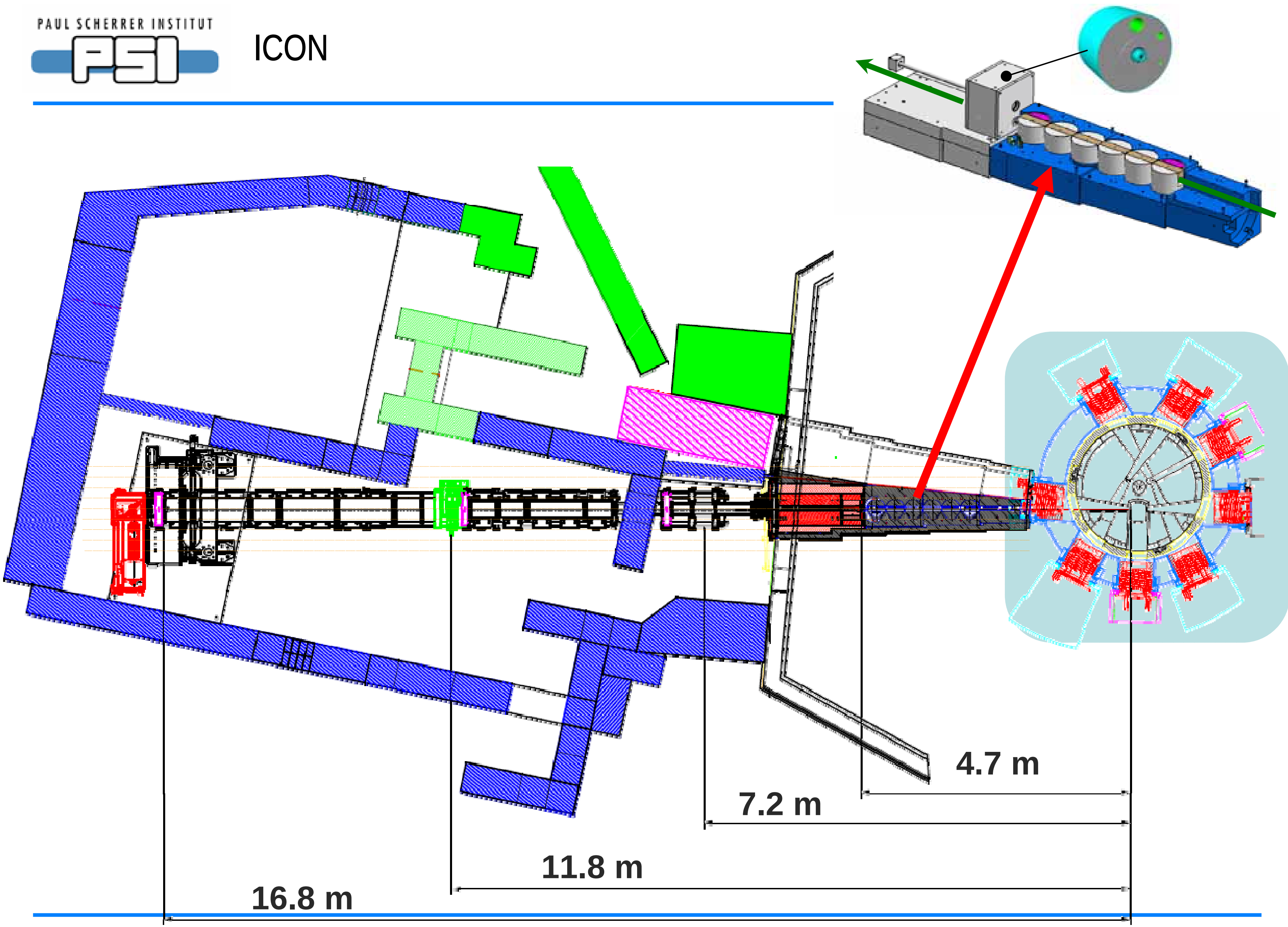
Muon spectroscopy

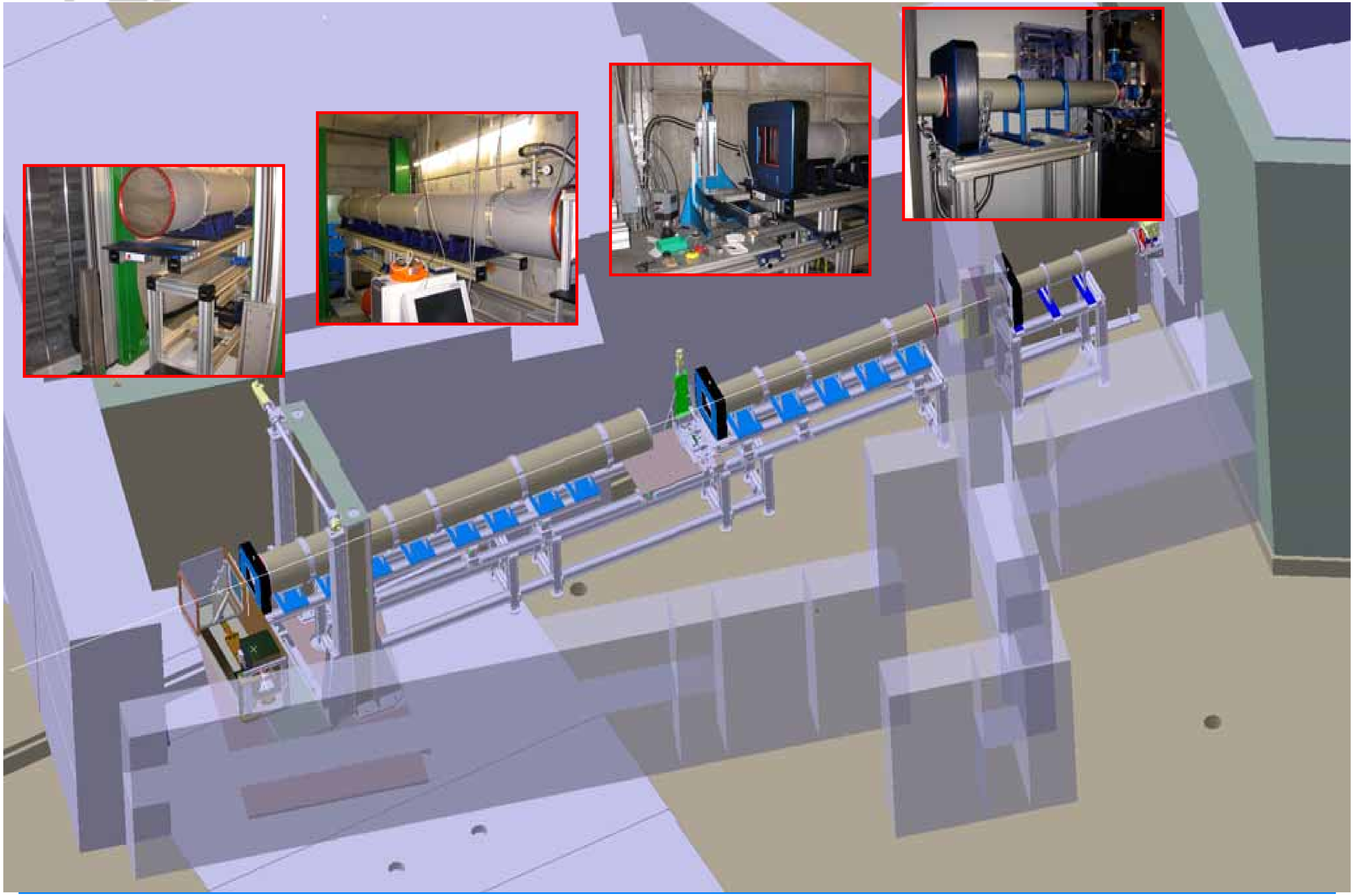
- Layout of instrument
- A Muon experiment – how you measure and what you see
- An example – a thin film (300 nm) of an electron doped SC: $La_{1.9}Ce_{0.1}CuO_4$
- Complementarity with neutron scattering

Radiography/Tomography station



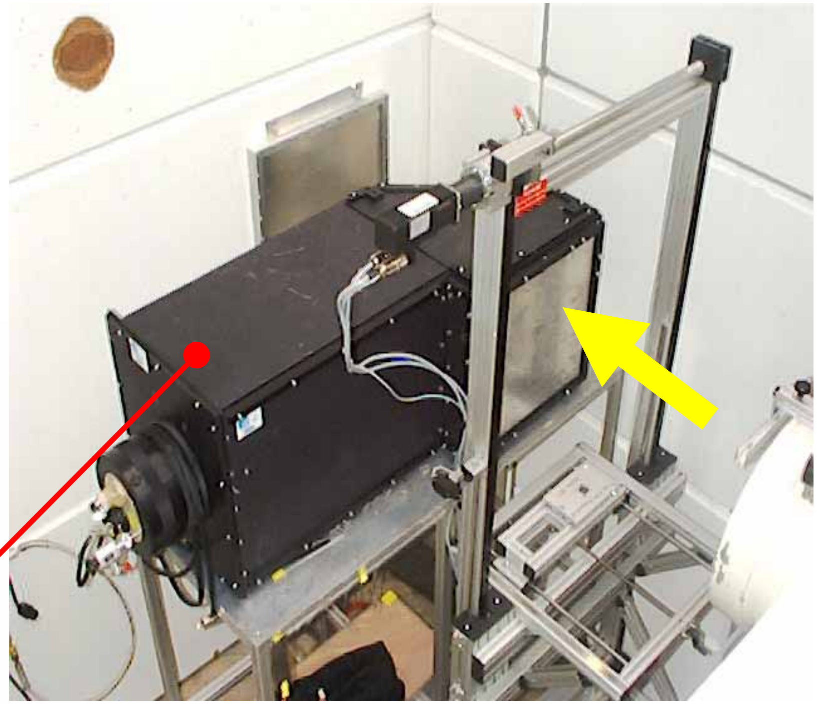
ICON

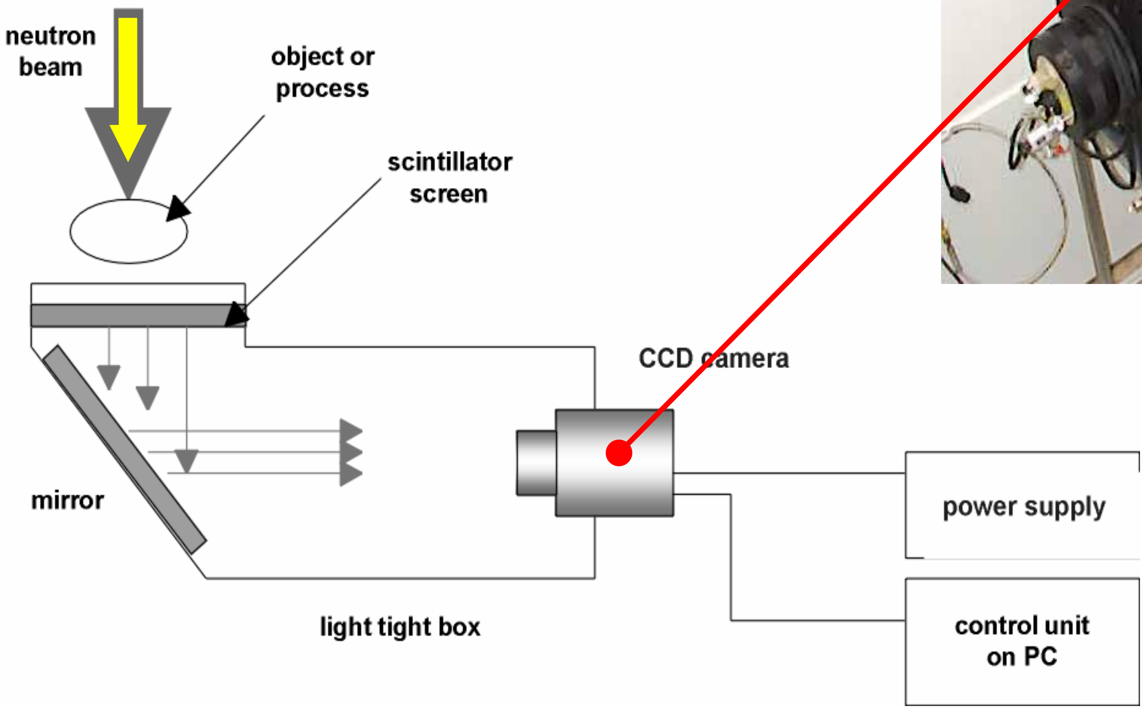




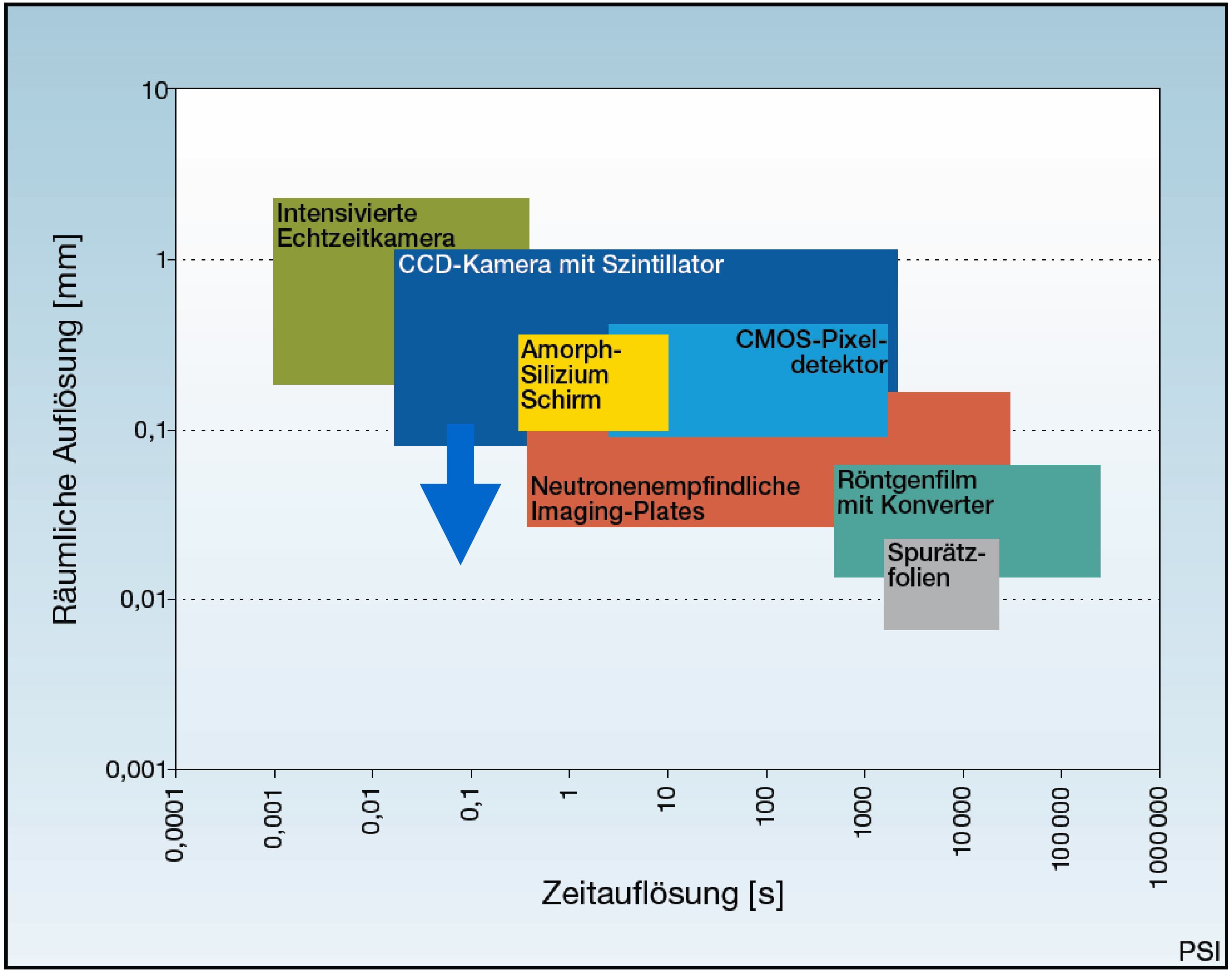
Neutron Imaging

The neutron beam transmitted through the object is converted to light at the scintilator – this light is observed by a CCD camera through a Mirror.





Detector systems



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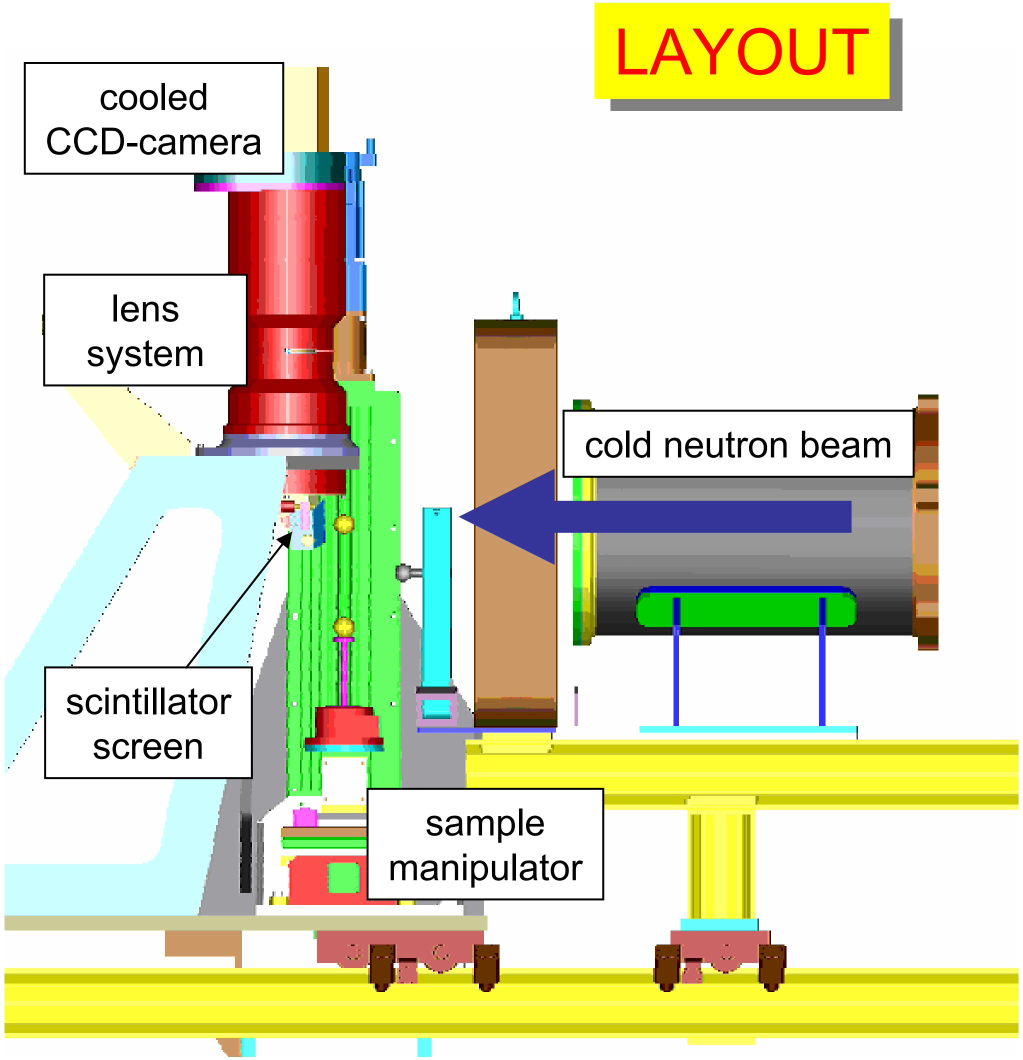
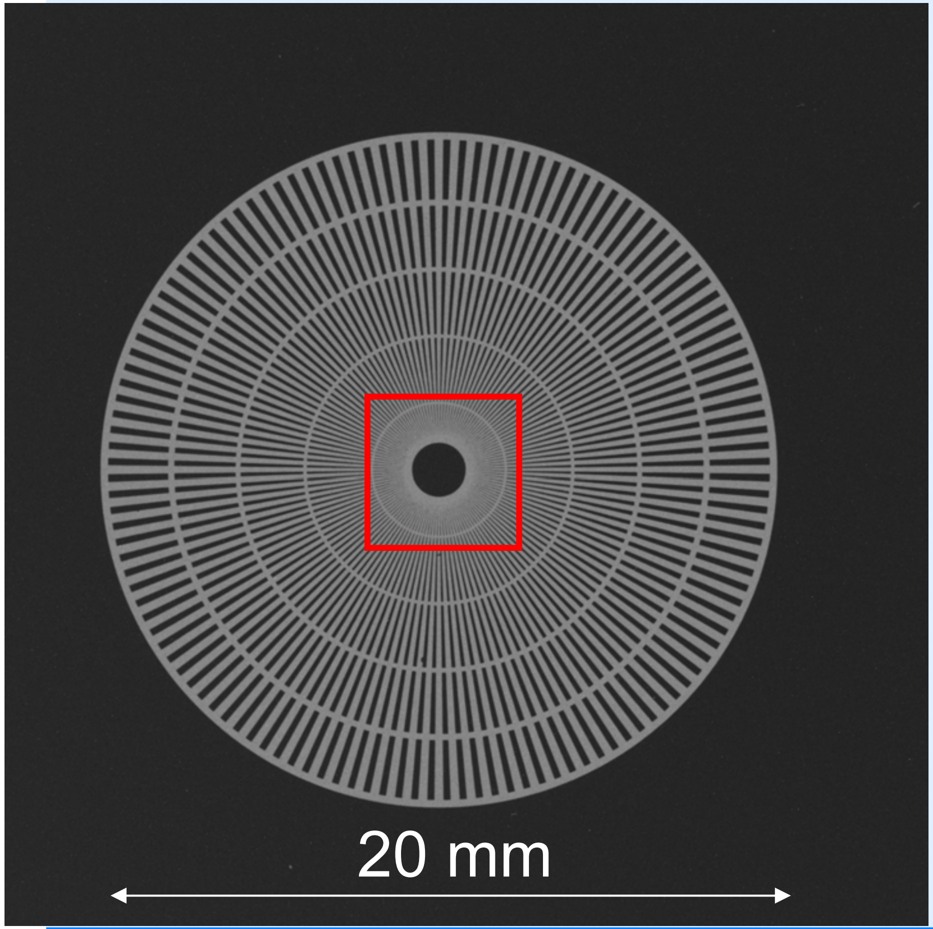
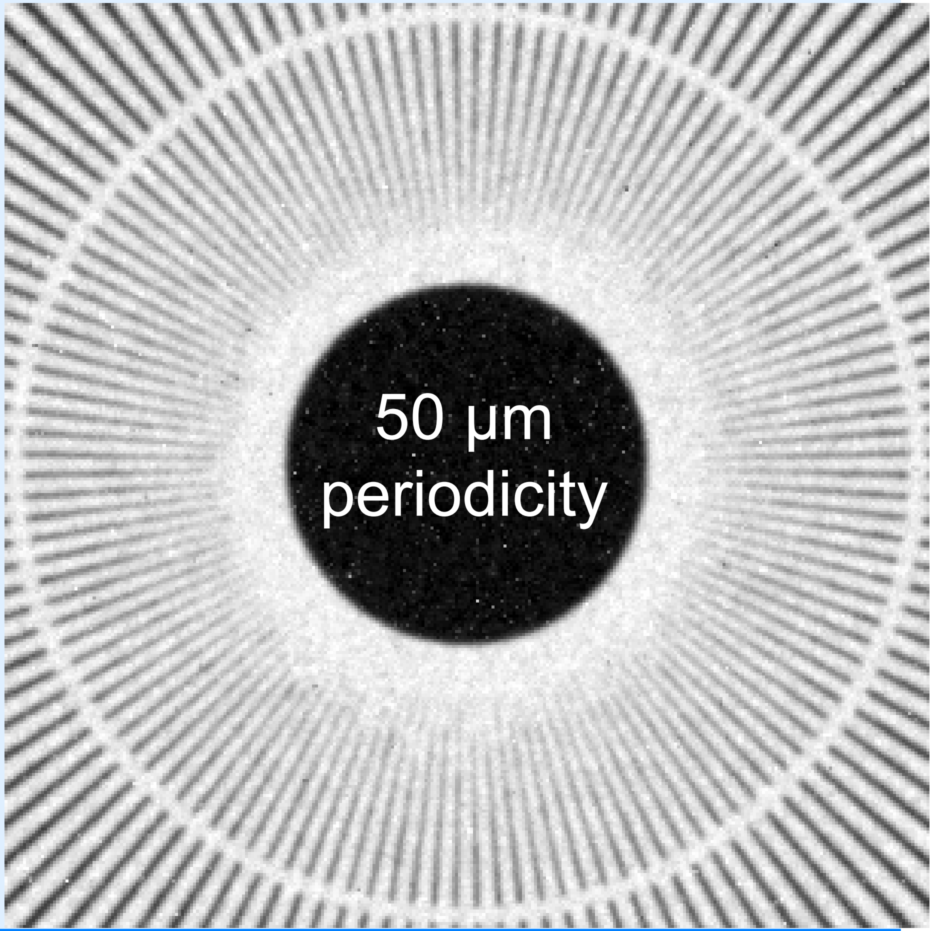
Micro tomography - Experimental Details



Results: Gd test pattern (made @ PSI (LNM))





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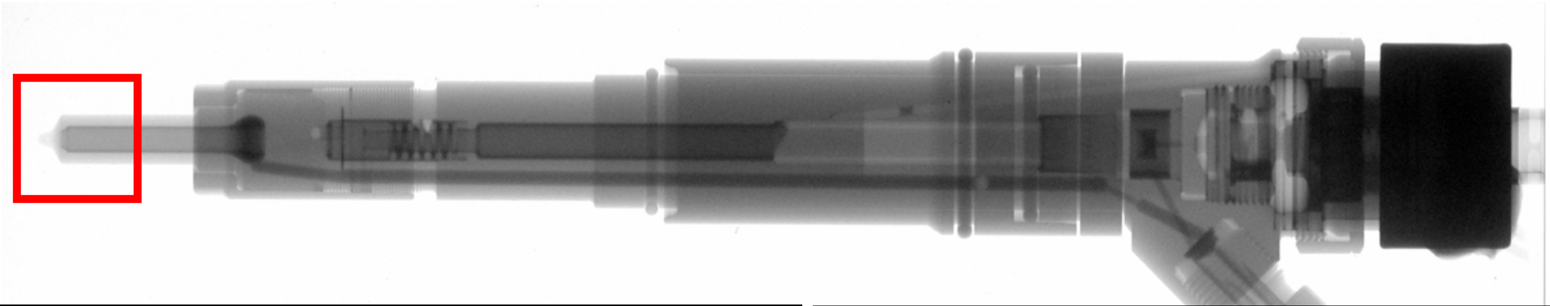
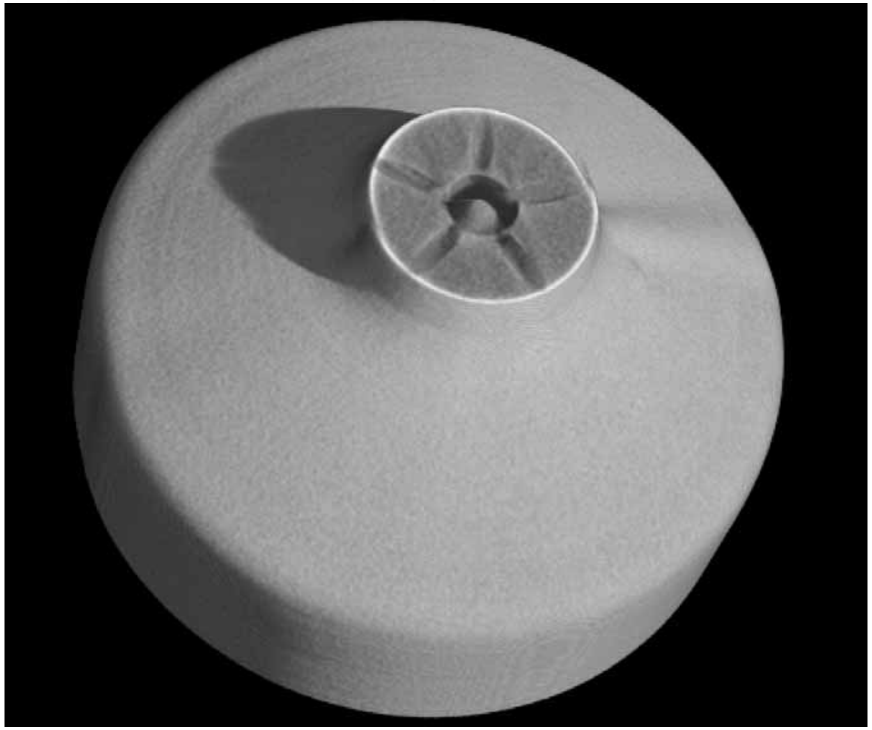
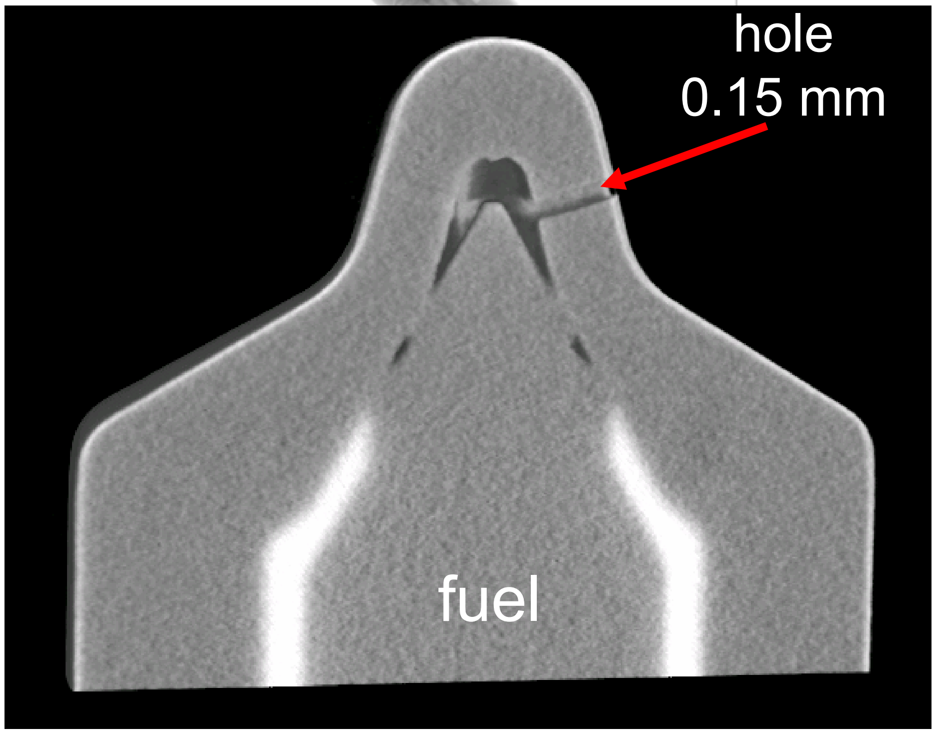
Results: first tomography data – diesel injection nozzle







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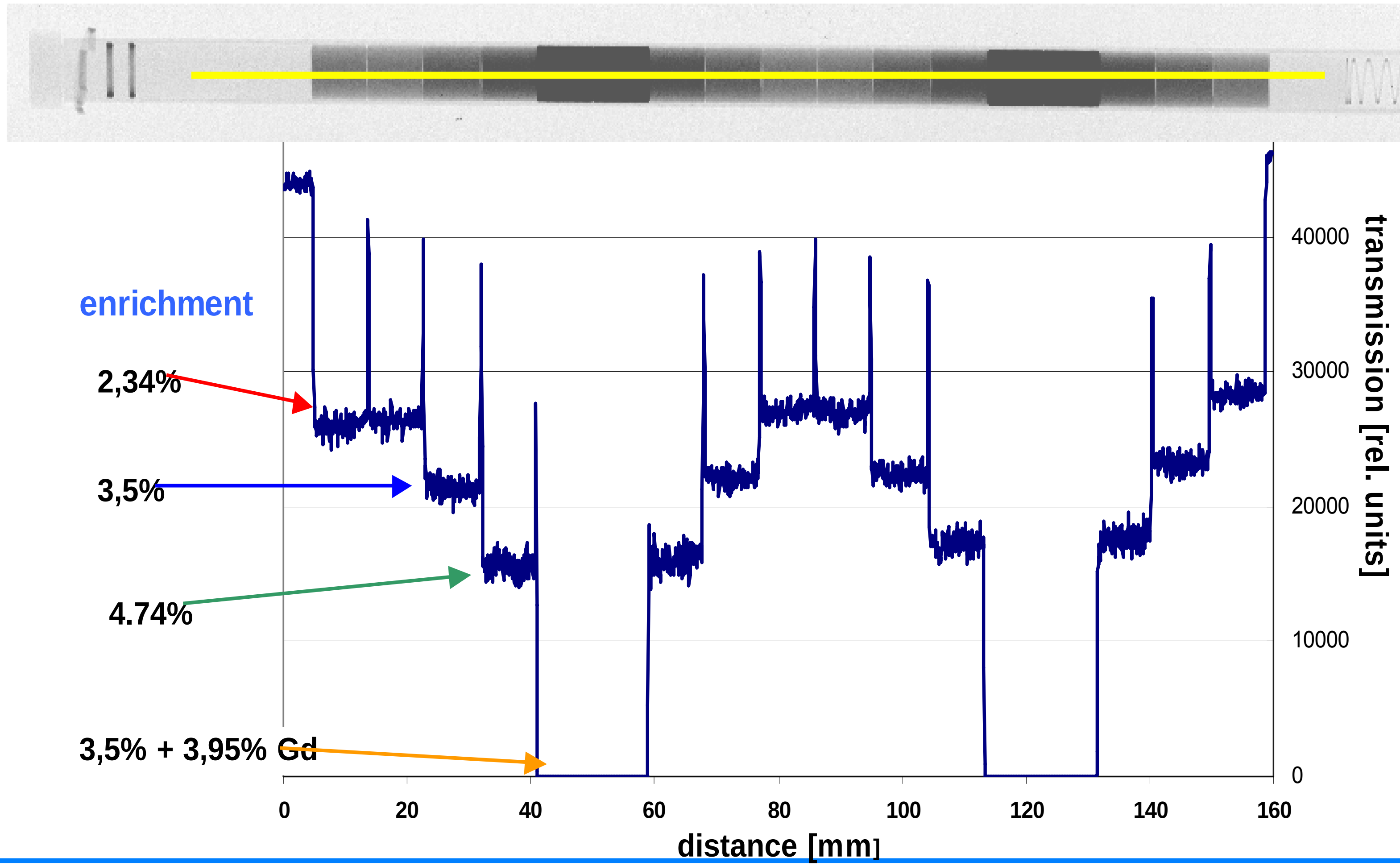
Determination of the U-235 content (enrichment) in nuclear fuel elements



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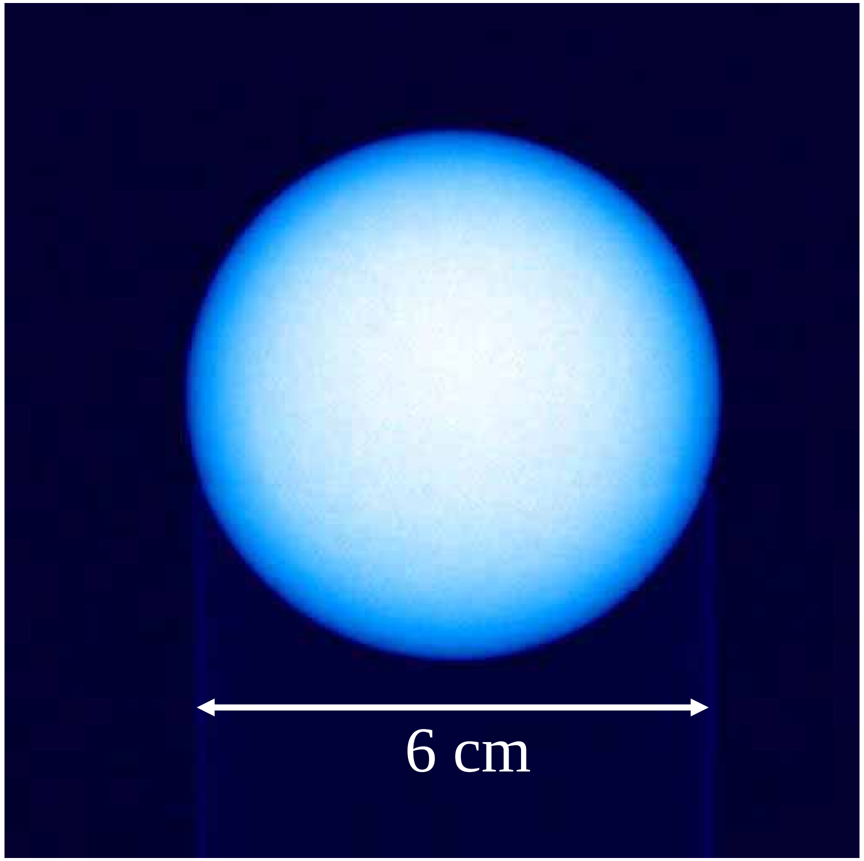
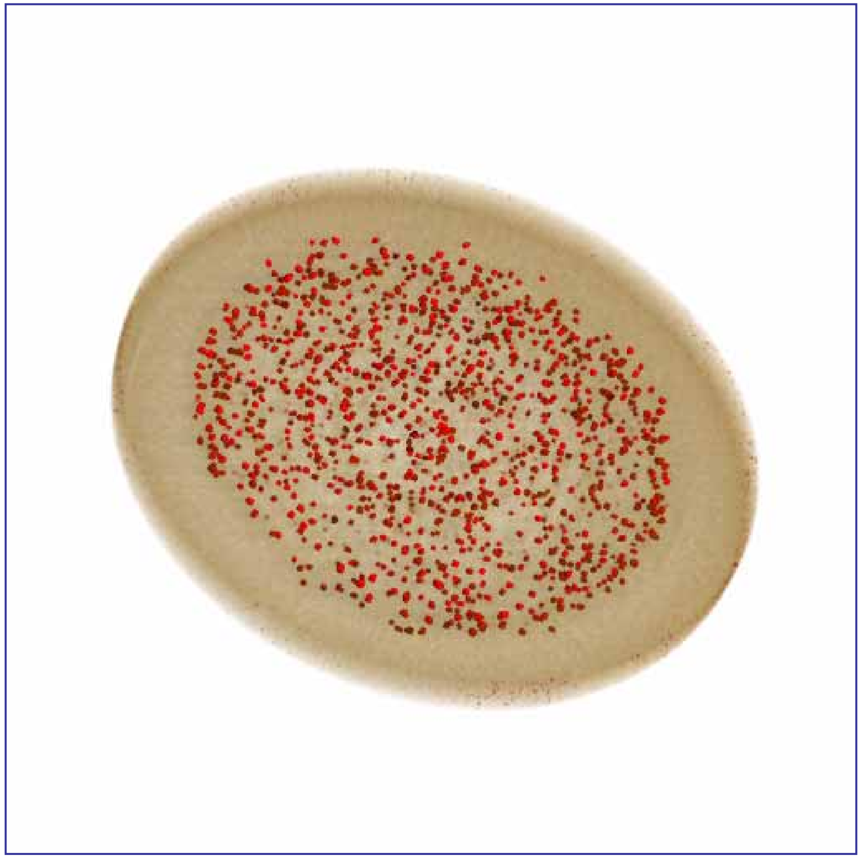
Tomography: investigation of HTR fuel sphere



Transmission image (single projection)

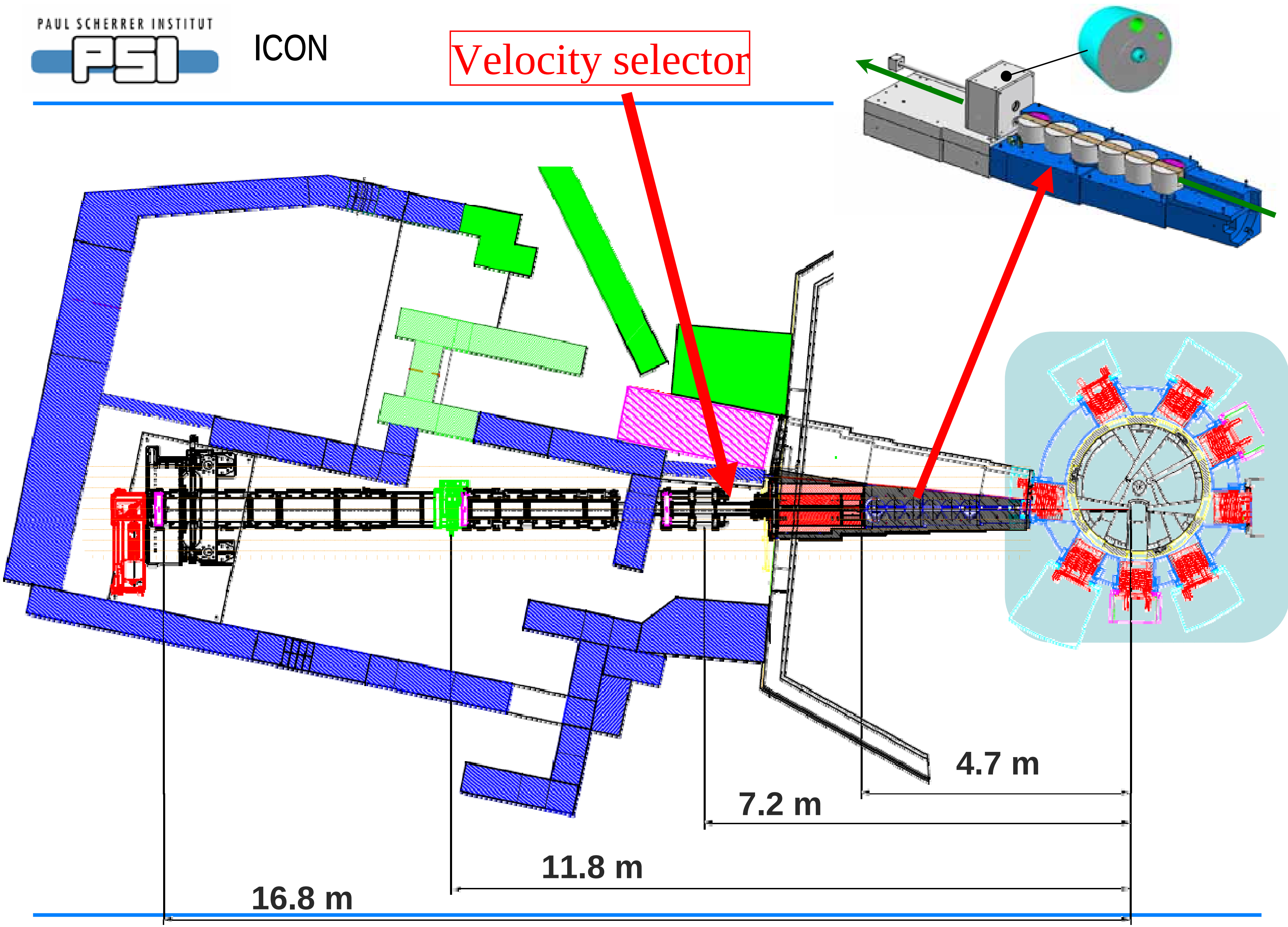


Tomography slice of one layer with CP

HTR fuel, diameter 6 cm

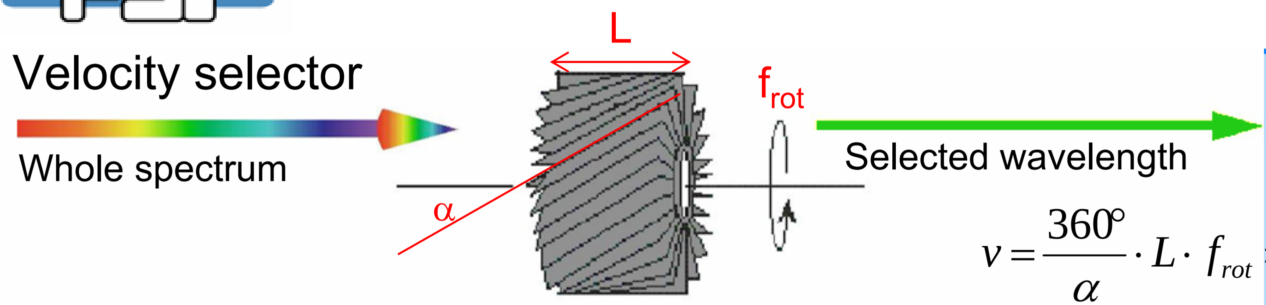
Individual fuel particles are visible (and can be measured in their distribution)

ICON

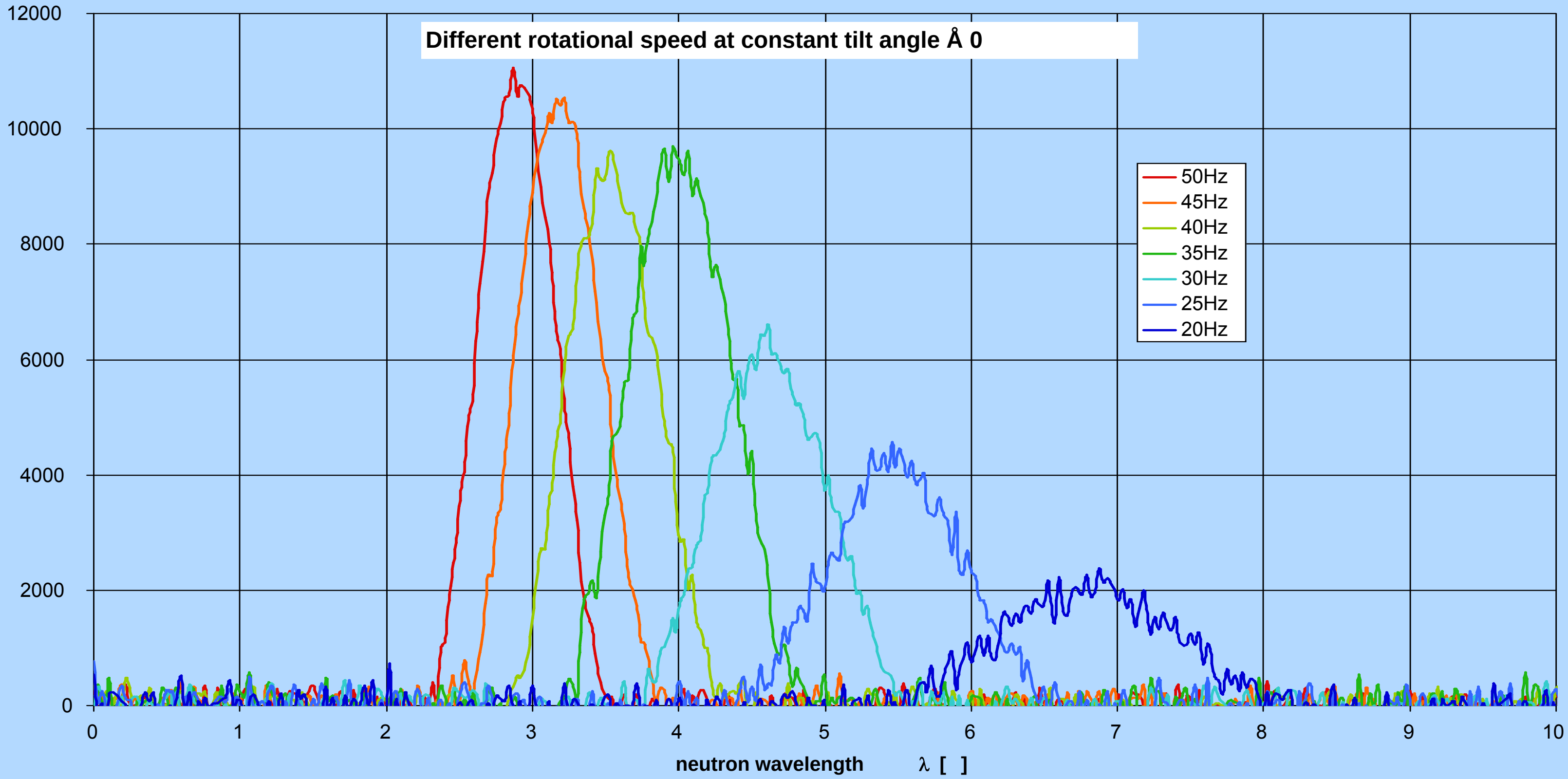


Energy selective neutron imaging

Velocity selector



$$v = \frac{360^\circ}{\alpha} \cdot L \cdot f_{rot} \Rightarrow \lambda = \frac{h}{m \cdot v} = \frac{h}{m} \cdot \frac{1}{360^\circ \cdot L} \cdot \frac{\alpha}{f_{rot}}$$



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Transmission

Incident beam → transmitted + absorbed + scattered

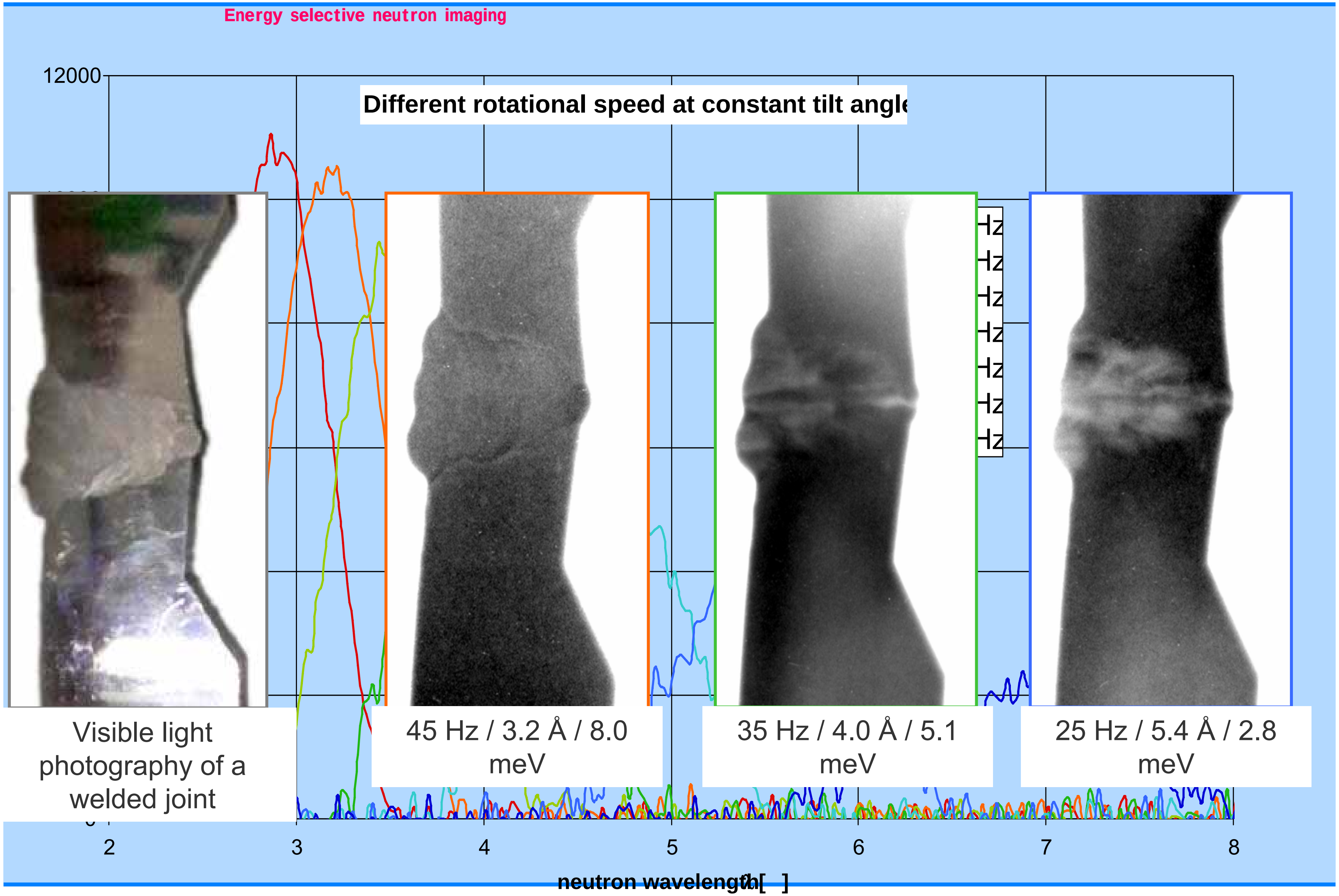
For a crystalline material there is only coherent scattering when the Bragg equation can be fullfilled:

$\lambda = 2\, d \sin(\theta)$ i.e. if $\lambda > 2\, d$ then No coherent scattering!

d is the lattice constant for the crystalline material in the sample

Straining a material → changing d!

Energy selective neutron imaging



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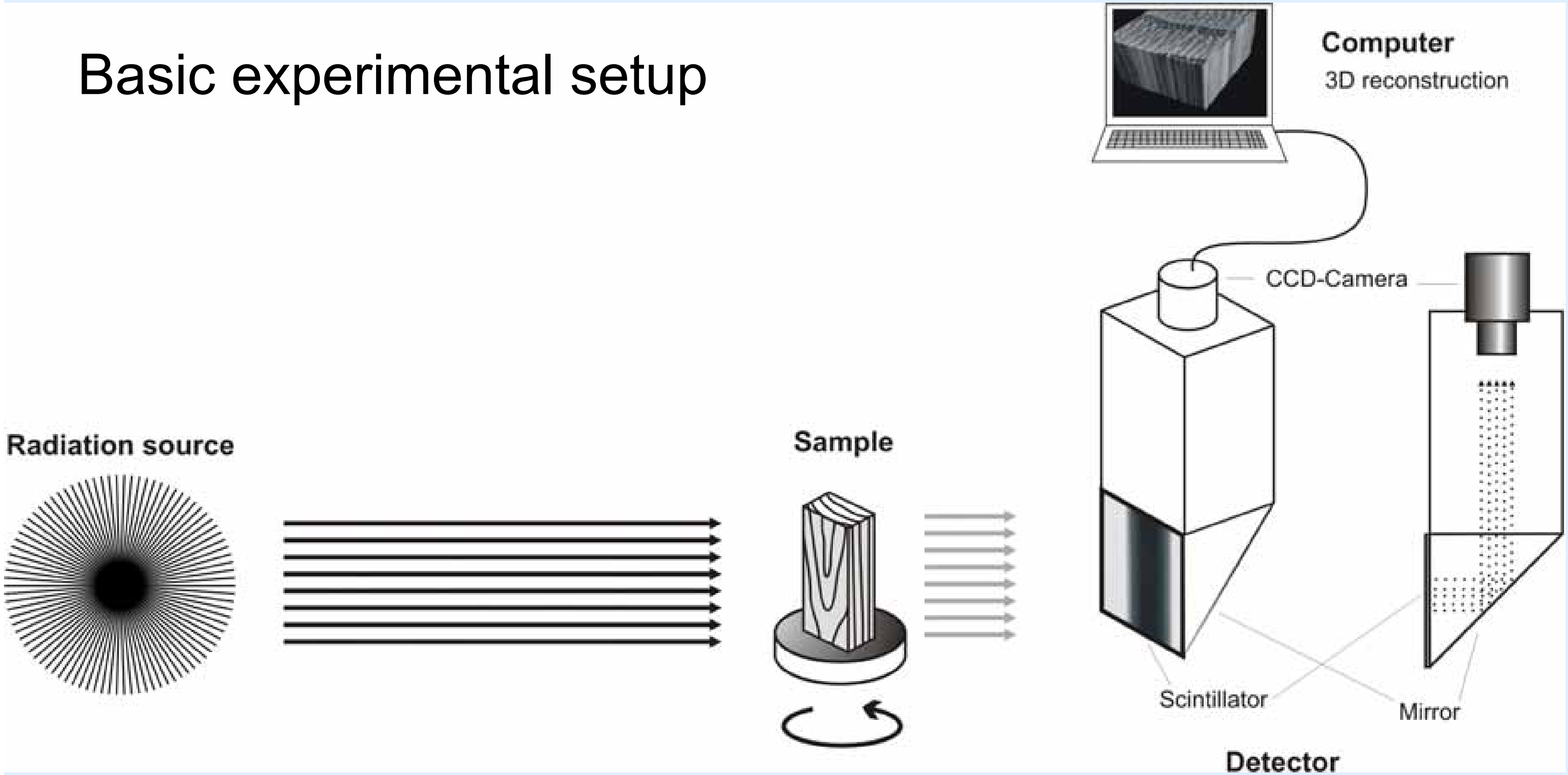
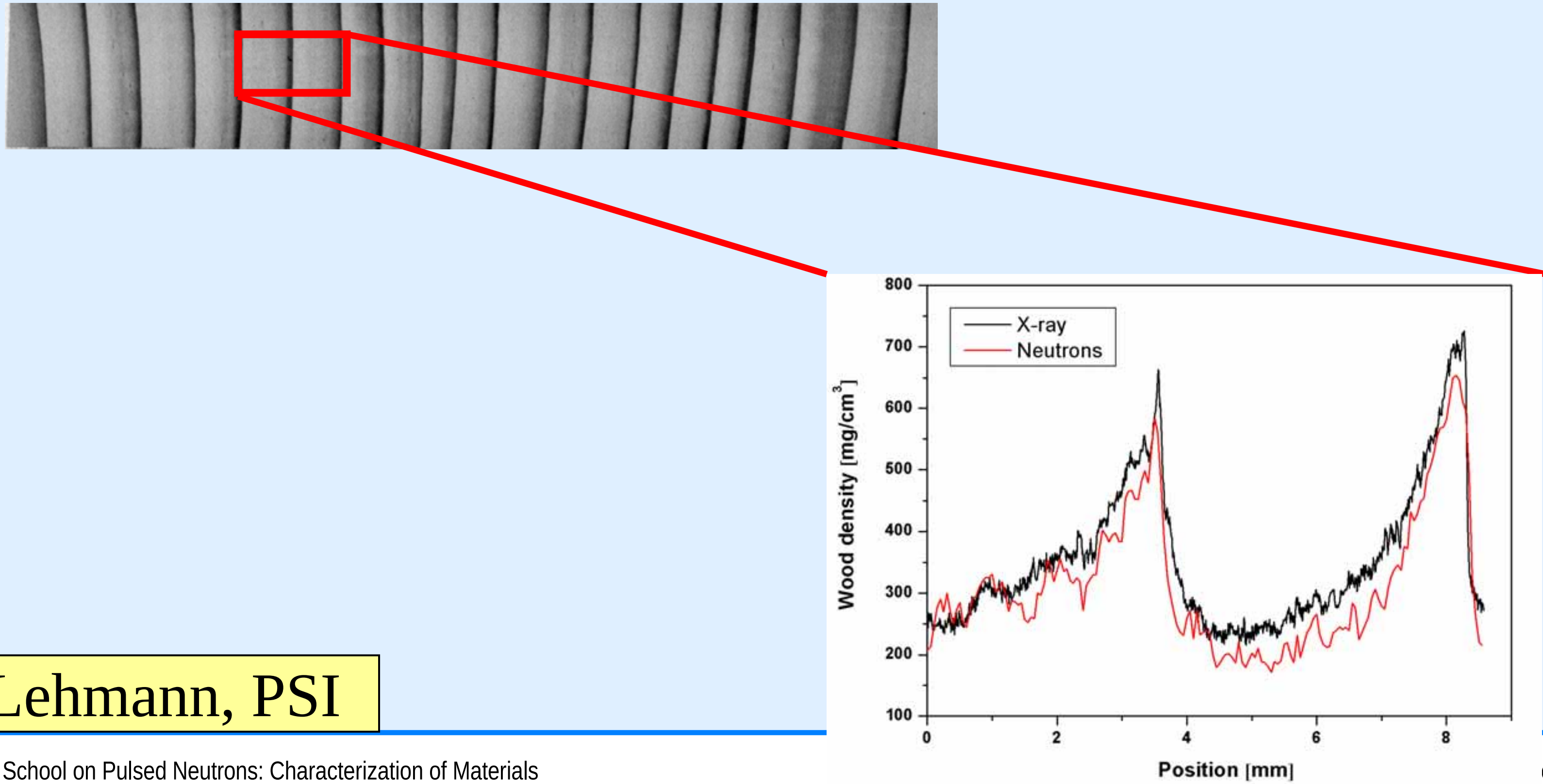
Neutron Imaging / Tomography of Wood

Basic experimental setup



Densitometry with neutron imaging

Digital data of the absorption yields density information



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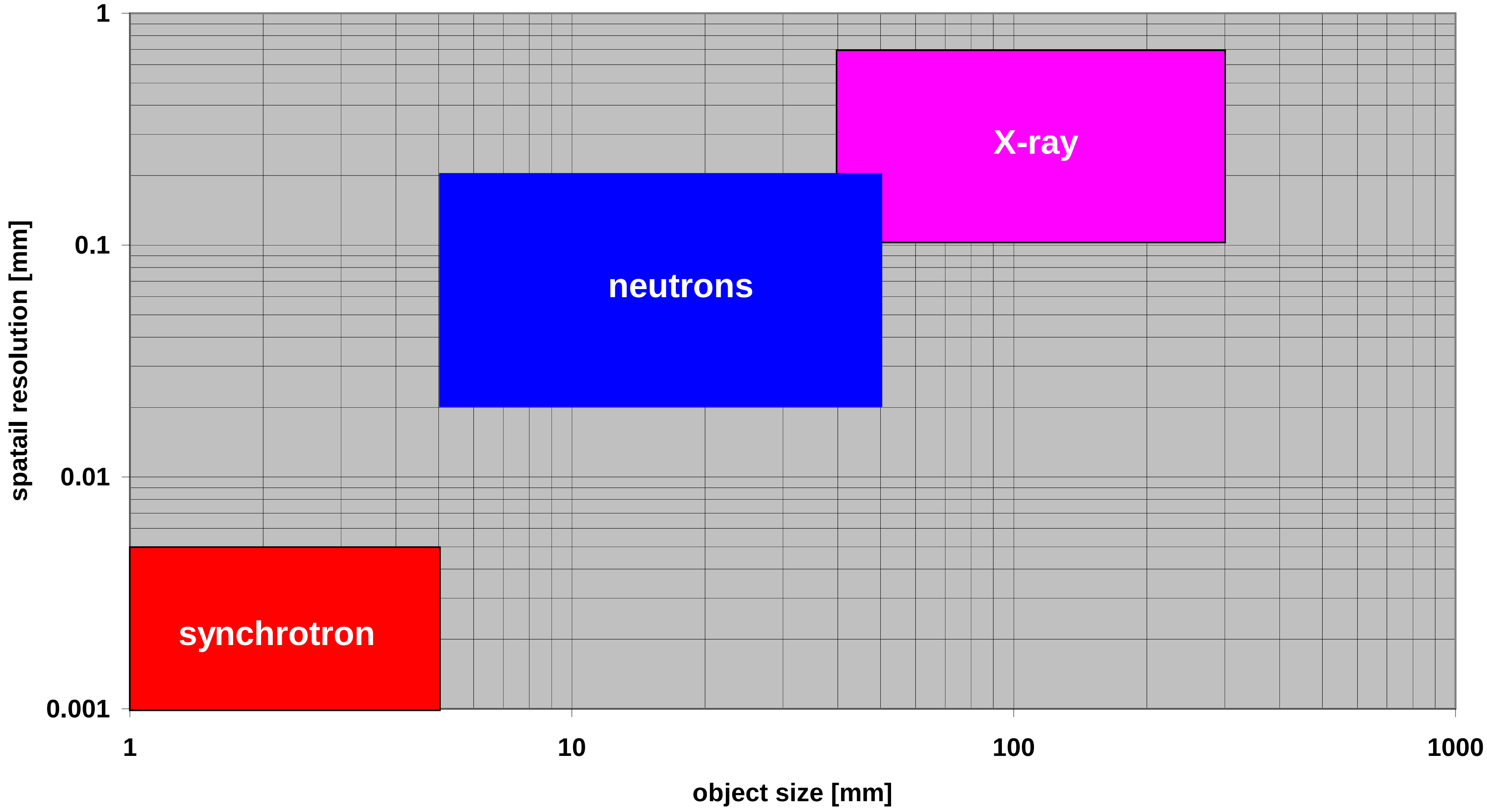
Application range for different transmission methods in respect to wood studies



Wood research –X-rays and Neutrons

MICRO	MIDI	MACRO
Synchrotron X-rays	Neutrons	X-rays
FOV: 1-3 mm	FOV: 1-5 cm	FOV: 5-30 cm
RES: ~1µm	RES: 50-200µm	RES: 0.2–0.5 mm
Cell structure	Moisture distribution	Density structure

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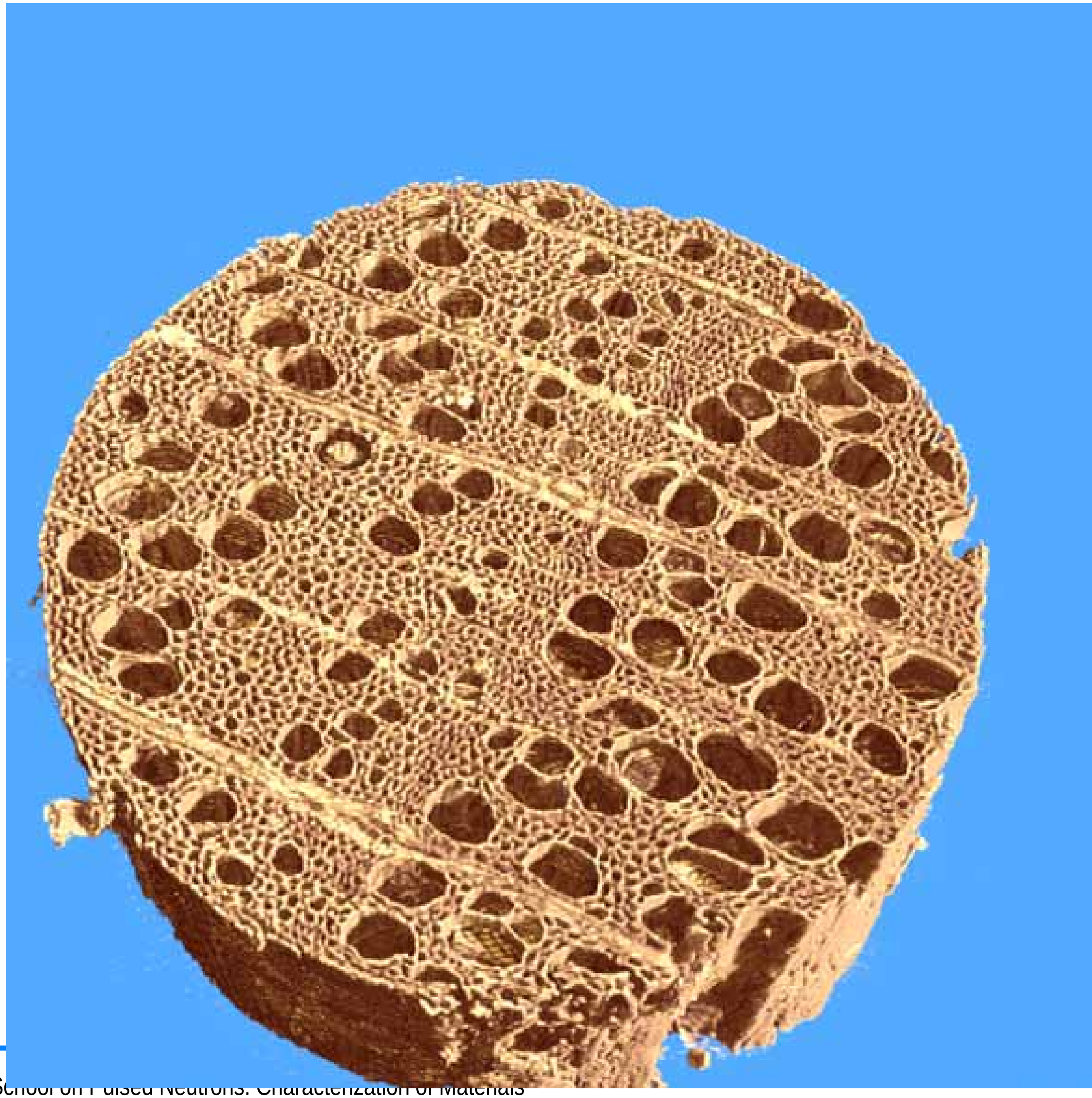
MICRO – synchrotron radiation



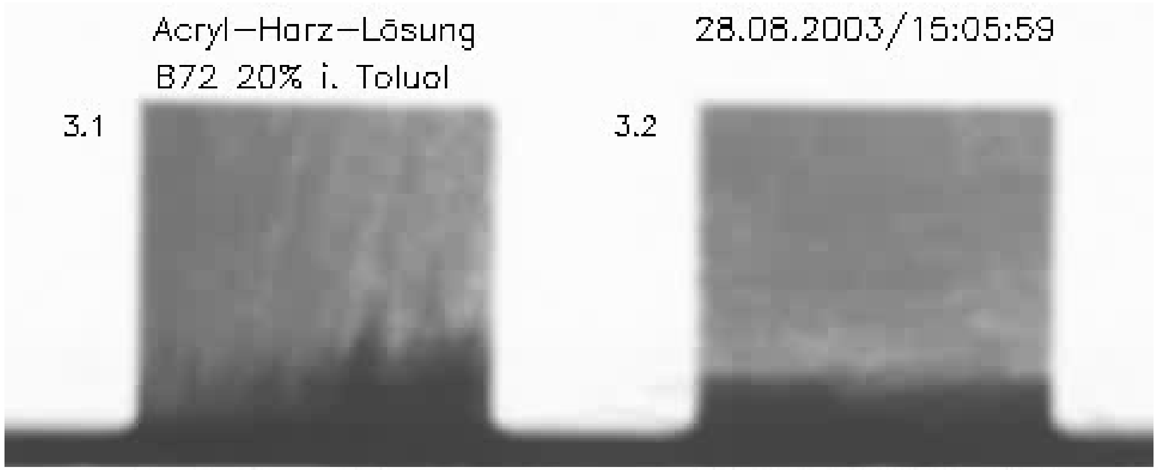
Beech tree

Diameter: 3 mm
Resolution: 3µm

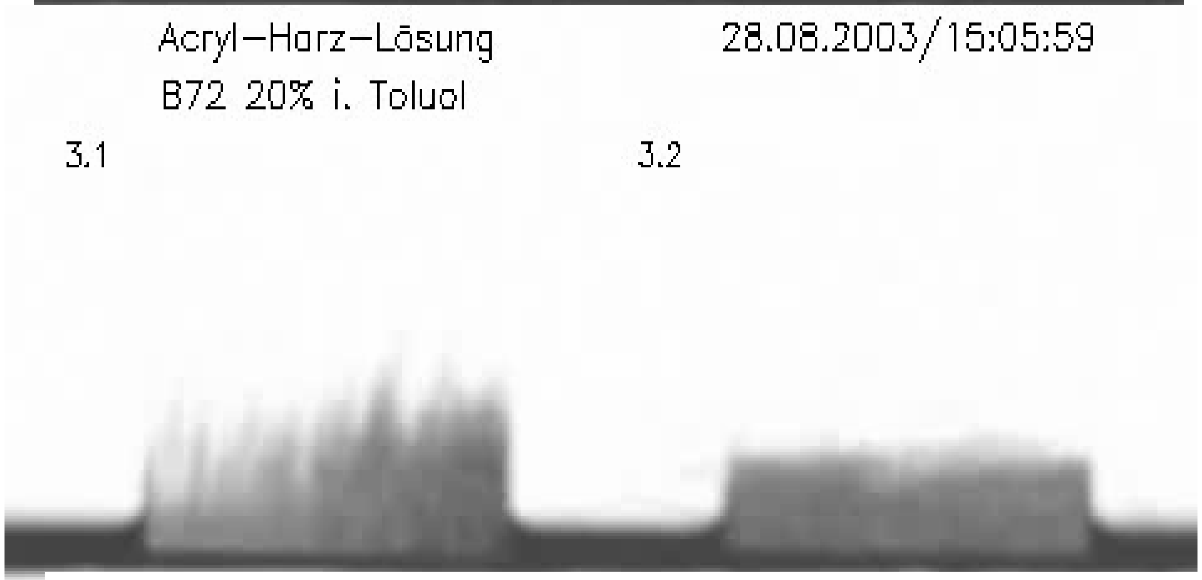
SLS-beam line
TOMCAT
energy: 20 keV

Stampanoni, PSI

MIDI – thermal neutrons



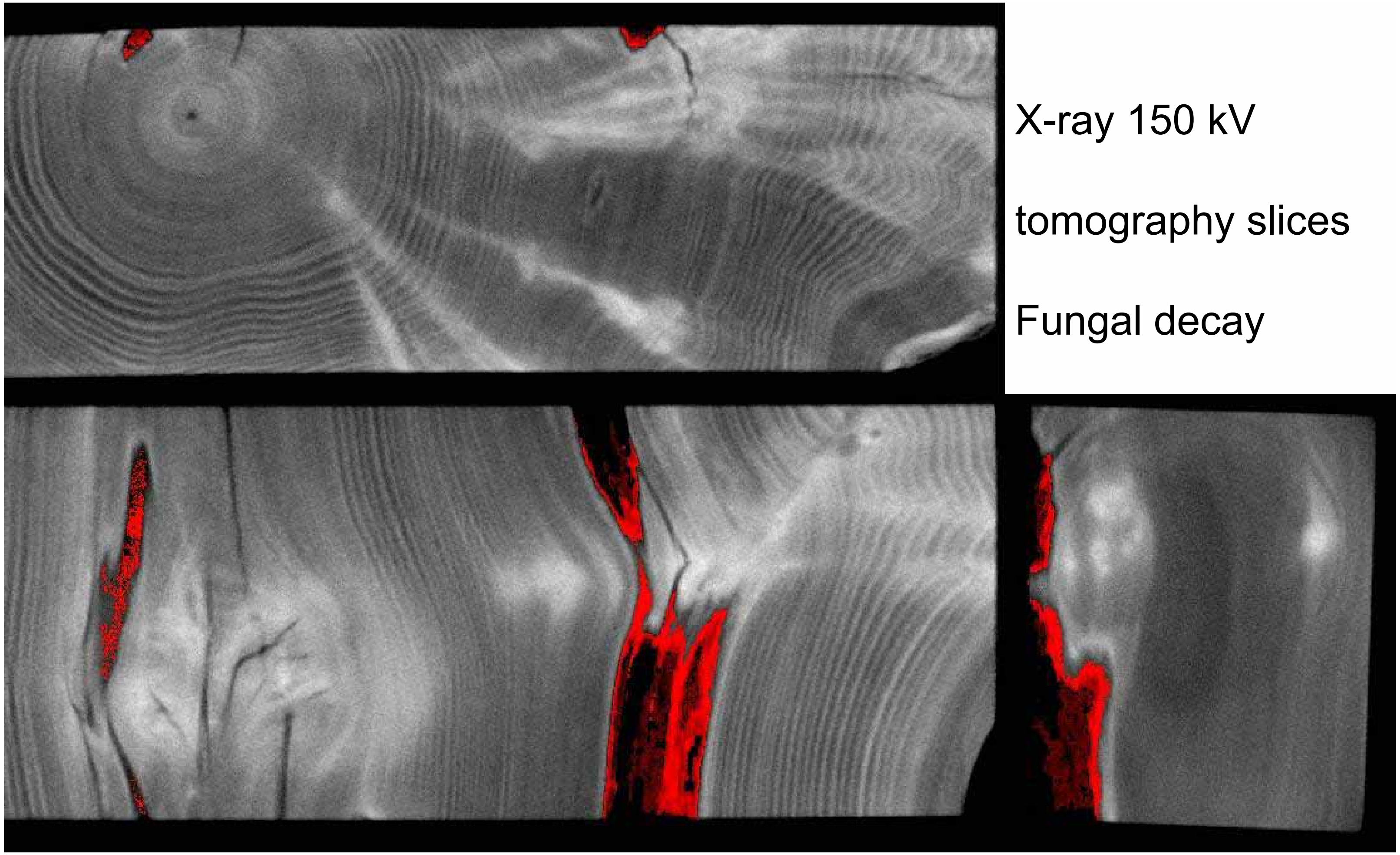
Direct Run



Referenced Run

Analysis of the process of impregnation of resin solution into wood

MACRO – X-rays



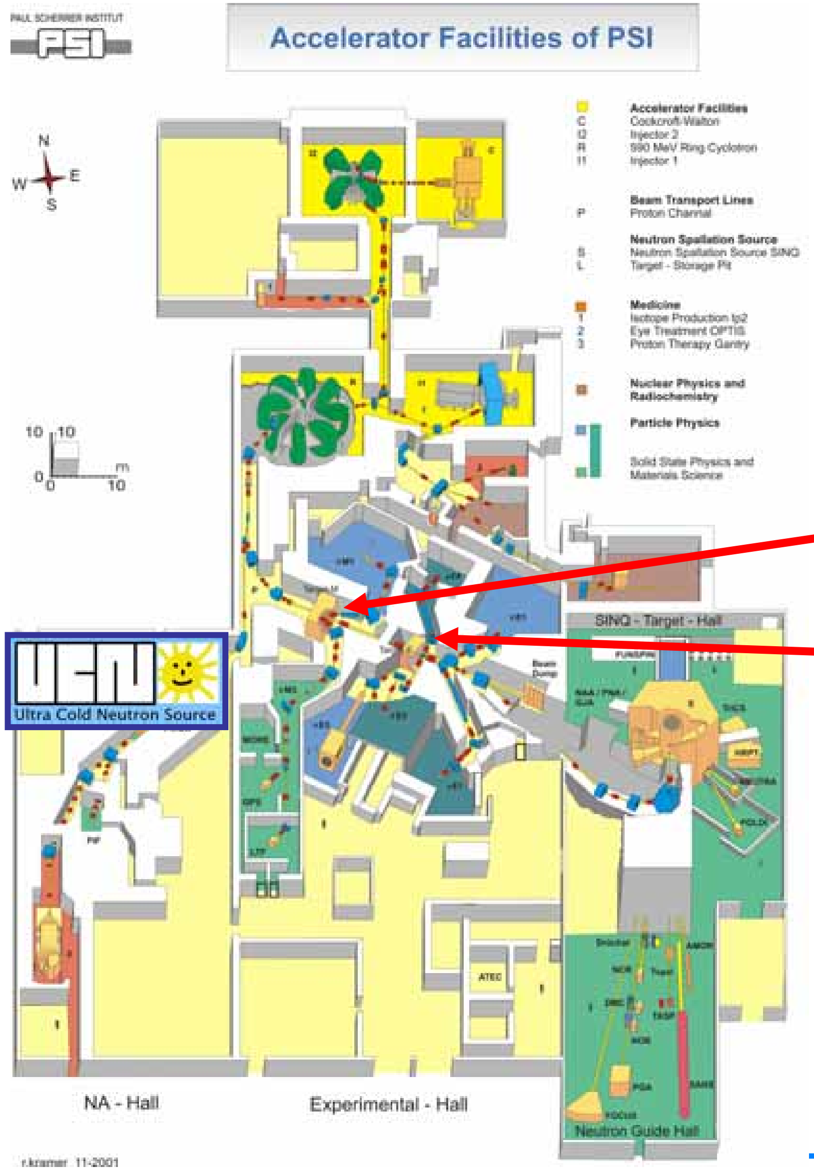
X-ray 150 kV

tomography slices

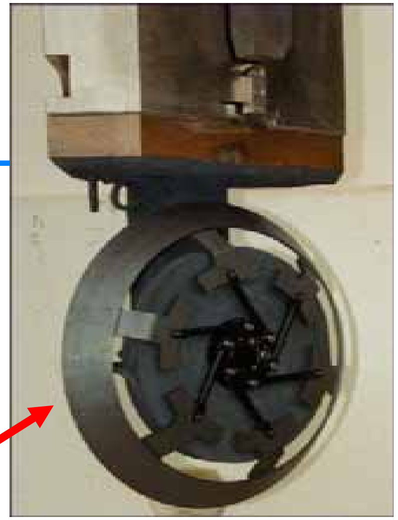
Fungal decay

Slice through the object with about 20 cm diameter

Proton accelerator Complex PSI



600 MeV proton beam
2 → 3 mA proton current
1.2 → 1.8 MW



CW Muon Source at PSI:

Target M: 2 mm Graphite wheel target

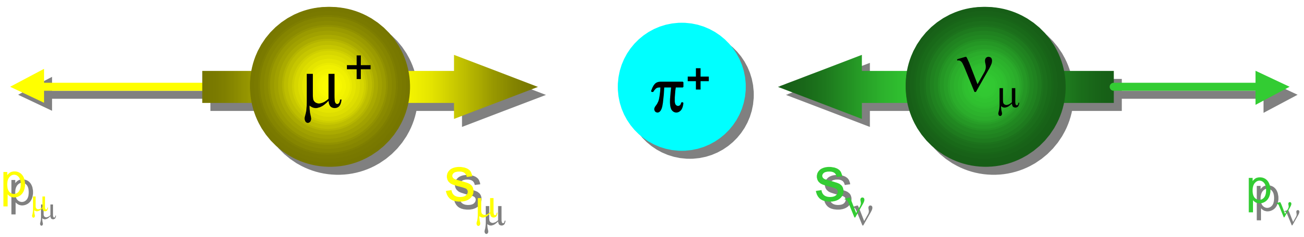
Target E 40 mm Graphite wheel target (>250 kW heat cooled away by radiation > 1500 K).

Generation of Pions that decays into Muons (Pion lifetime 26 ns).

4 sources worldwide, Triumf Canada, J-Parc Japan, ISIS UK and PSI Switzerland

Muon production from pions

Charge state	π^+	π^-
Mean lifetime (s)	26×10^{-9}	26×10^{-9}
Spin	0	0
Mass (MeV)	139.57	139.57
Decay mode	$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$

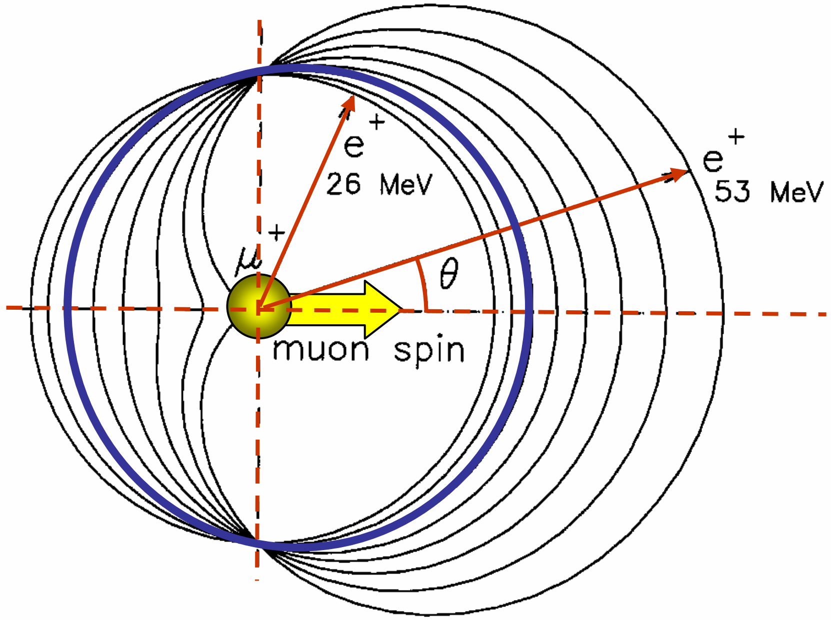


100% polarised "*surface*" positive muons (~4MeV) are generally used for condensed matter studies

Muon decay

Lifetime: 2.19714μs

Decay asymmetry: $W(\theta) = 1 + a_0 \cos\theta$



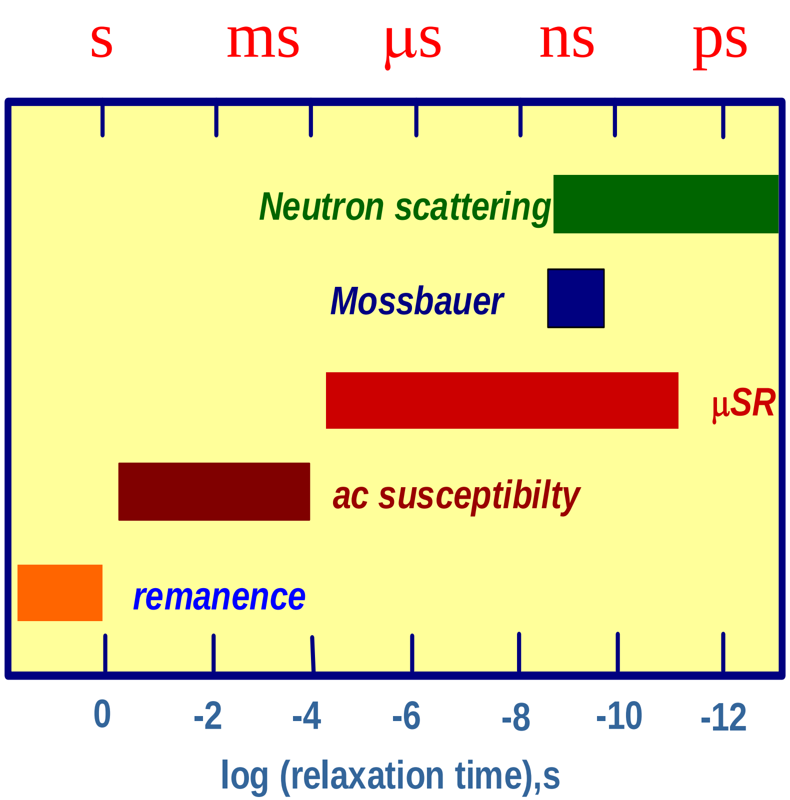
$a_o \sim 0.25$

Gyromagnetic ratio: $1.355342 \times 10^8 \times 2\pi\ s^{-1} T^{-1}$

Muon spin relaxation - time scales

A time window sufficiently wide for studies of fast itinerant electron spin fluctuations through to slow distributed spin relaxation in spin glasses

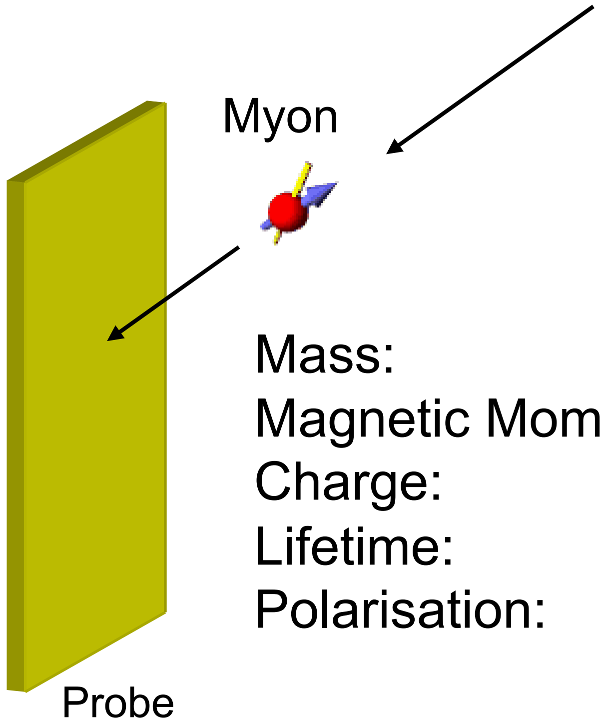
…or of fast muon hopping through to slow diffusional processes….



…..and μSR is sufficiently sensitive for ultra-small magnetic moments (~$10^{-3}\mu_B$) and nuclear moments to be detected

The principles of a μSR Experiments

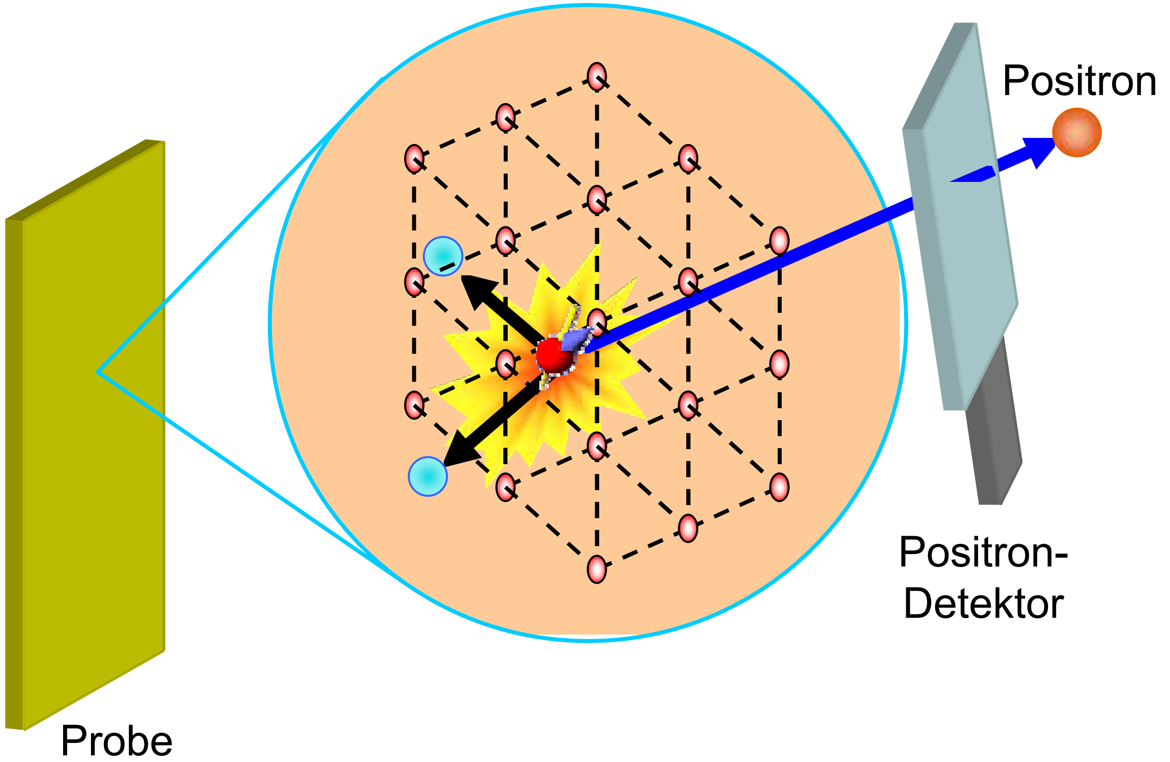
Implantation of Muons in the Probe



Mass: $m_\mu \approx 207\ m_e \approx 1/9\ m_p$
Magnetic Moment: $\mu_\mu \approx 3\ \mu_p$
Charge: +e
Lifetime: $t_\mu \approx 2.2\ \mu s$
Polarisation: 100 %

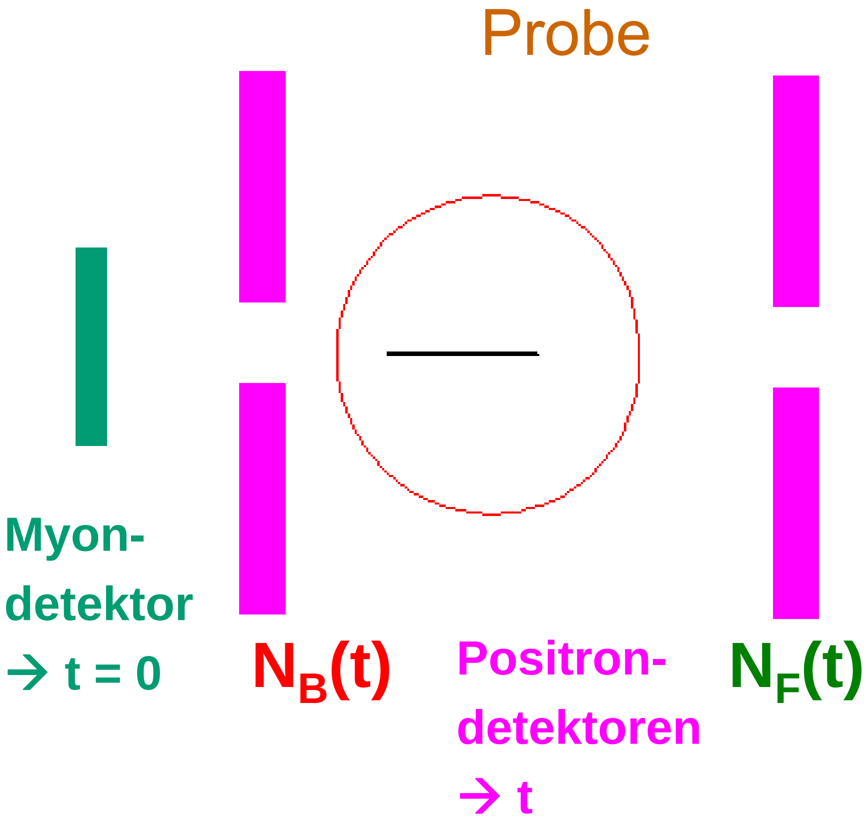
The principles of a μSR Experiments

Detection of the decay positron



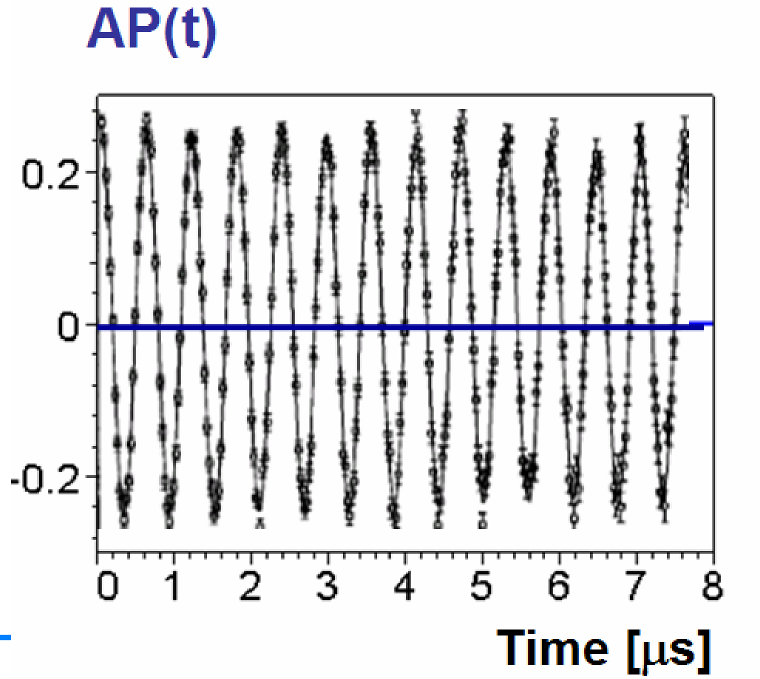
2 μs

μSR: Myon Spin Rotation/Relaxation



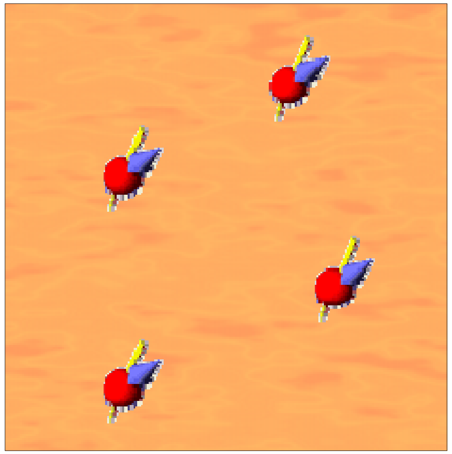
$$\frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = AP(t)$$

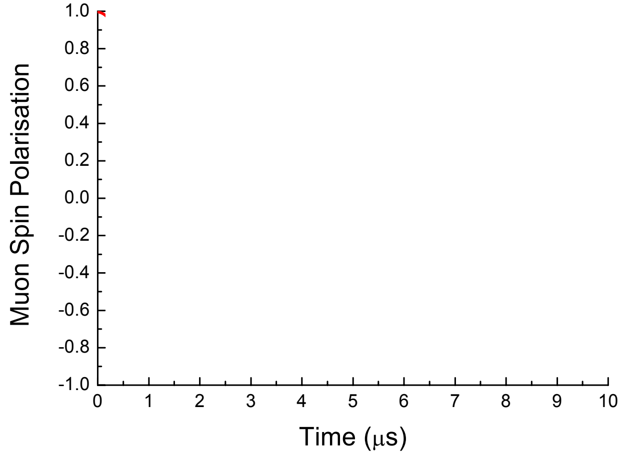
$$P(t) = \vec{P}(t) \cdot \vec{n}$$



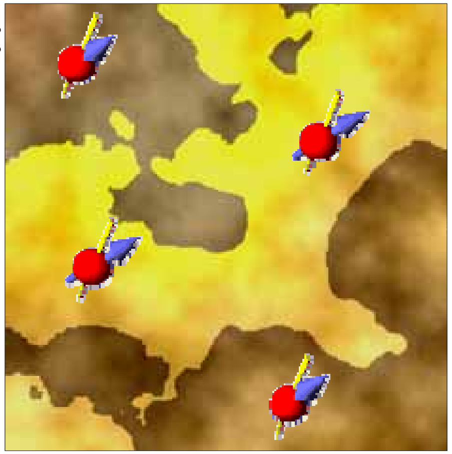
Inhomogenious Materials

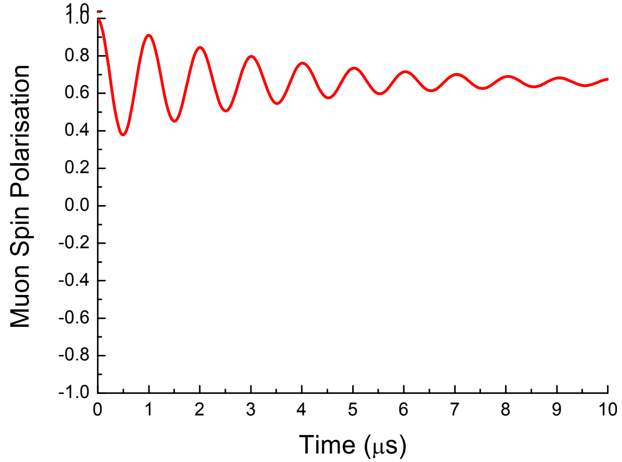
Homogenious:





Inhomogenious:





Amplitude = Magnetic Volume Fraction
Frequency = Magnitude of the local Magnetic field
Damping = Inhomogeniety

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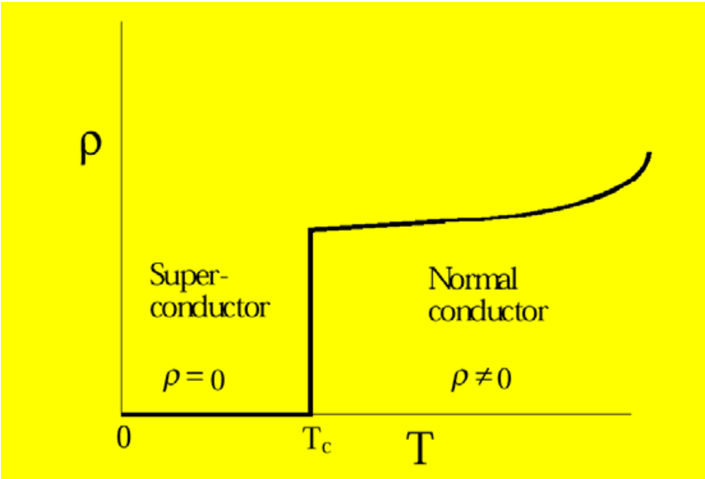
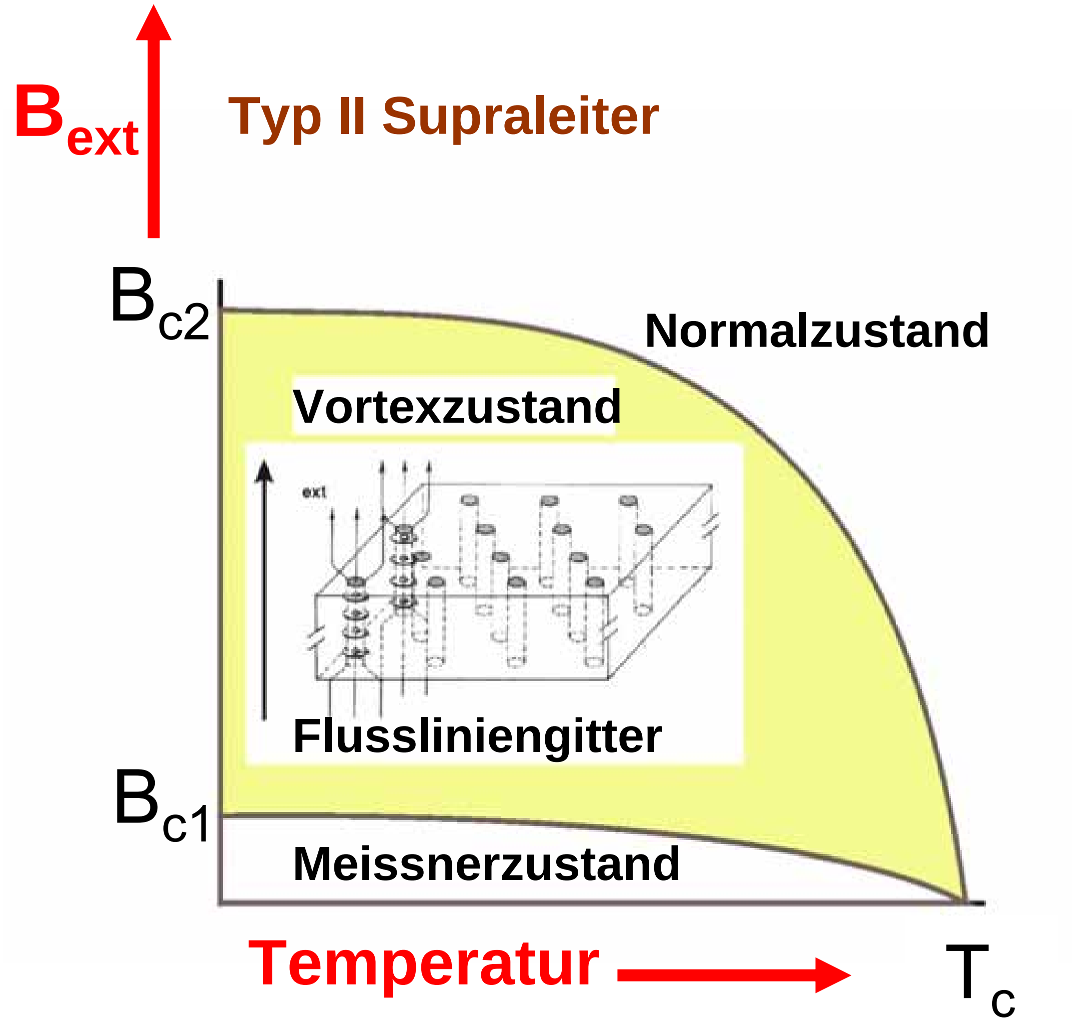
Feldverteilungen in Supraleitern

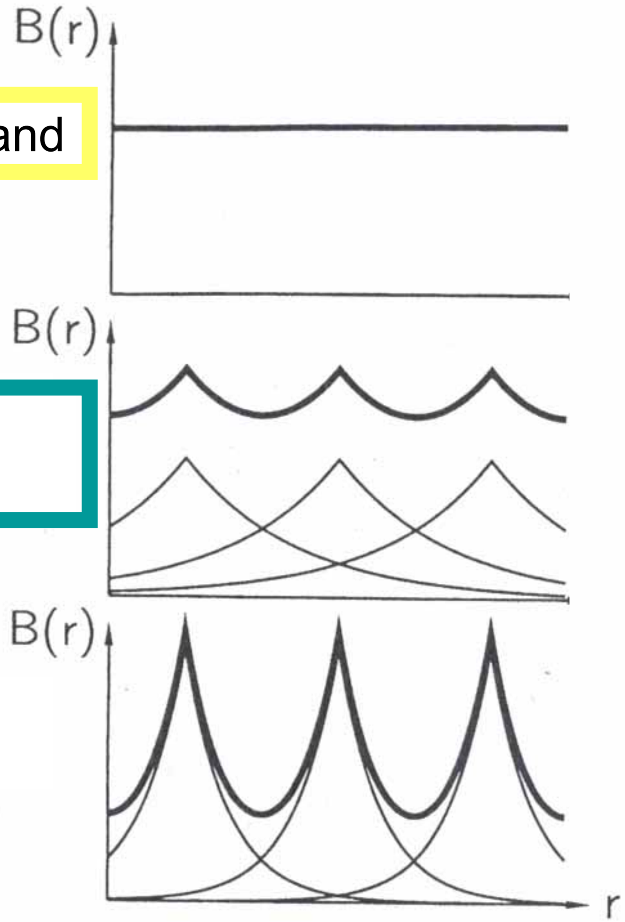




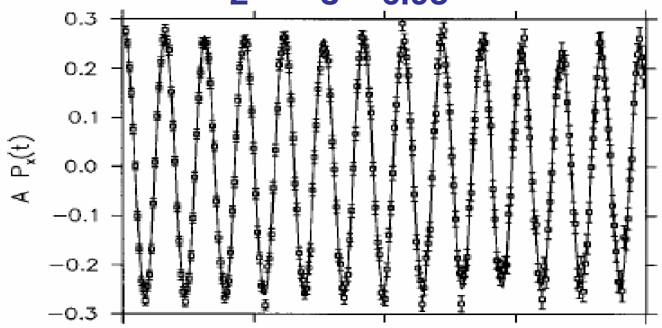
Myon Spin Rotation und Relaxation in einem Supraleiter

Normalzustand

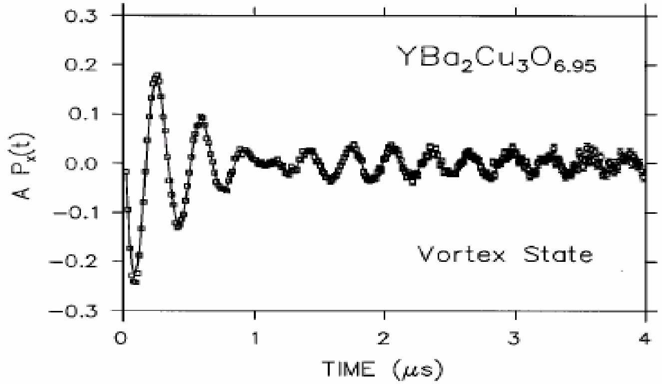
Vortex-Zustand



$YBa_2Cu_3O_{6.95}$



$$AP_x(t) = A\cos(\gamma_\mu Bt + \Phi)$$

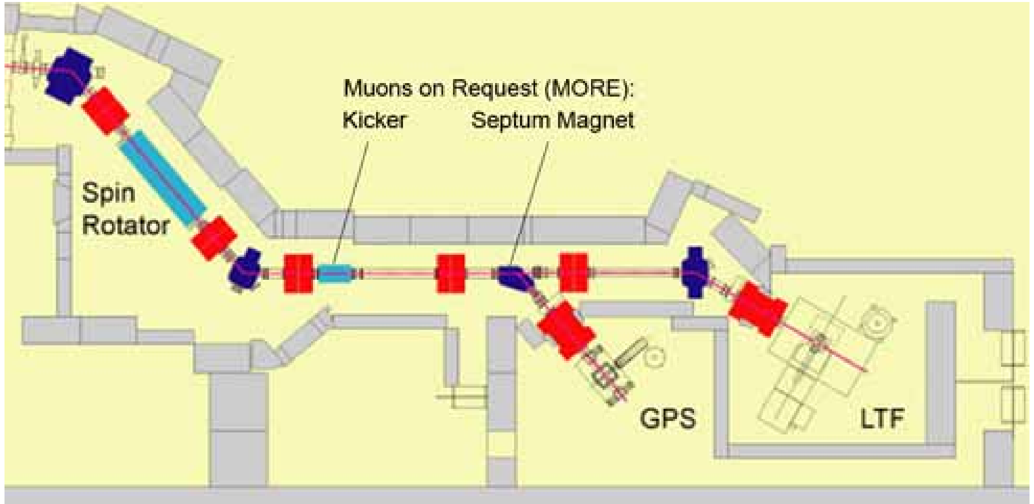


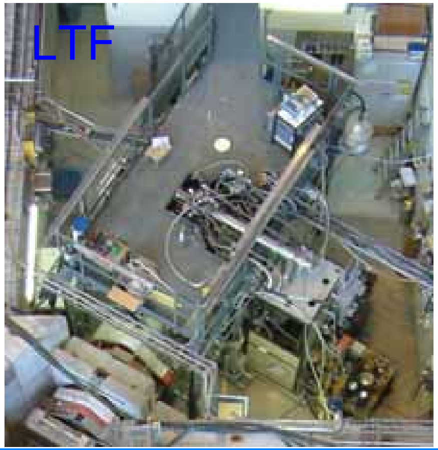
$$P_x(t) = \frac{1}{N}\sum_{i=1}^{N}\cos(\gamma_\mu B(\vec{r}_i)t + \Phi)$$

$$P_x(t) = \int p(B)\cos(\gamma_\mu Bt + \Phi)\,dB$$

Surface Muon Instruments

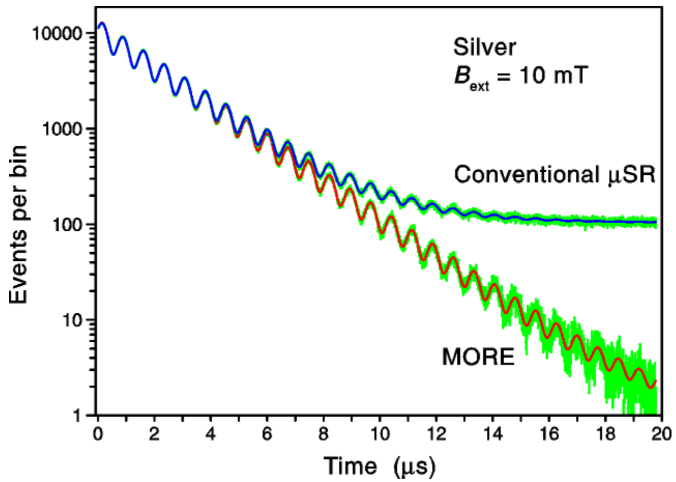
πM3 Dedicated Shared-Beam Surface Muon Facility: GPS and LTF





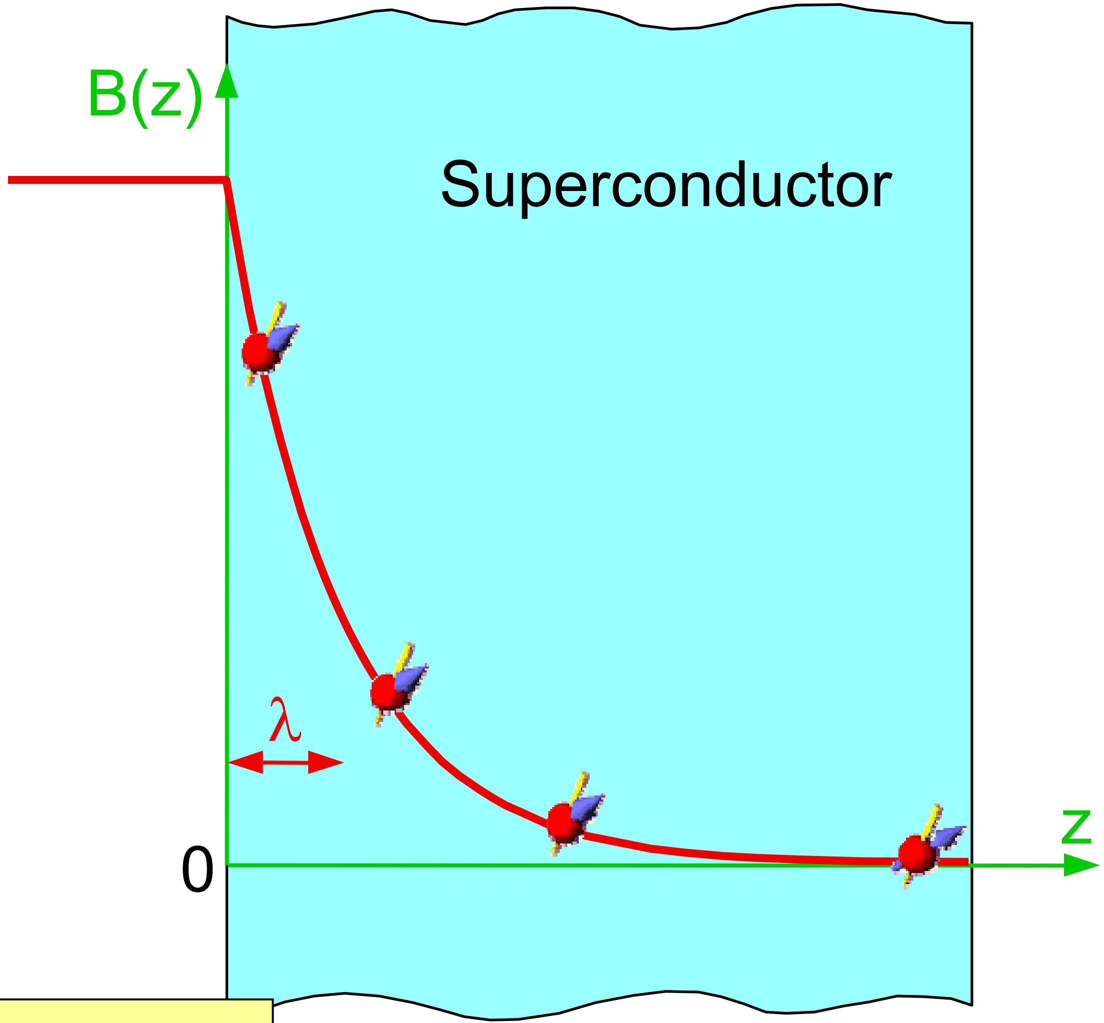
- 4 MeV μ^+, 100% polarized
- B_{ext}: GPS 0 - 0.6 T, LTF 0 - 3 T
- T: 1.8 - 900 K, 0.01 - 4.2 K
- 5 modes of operation

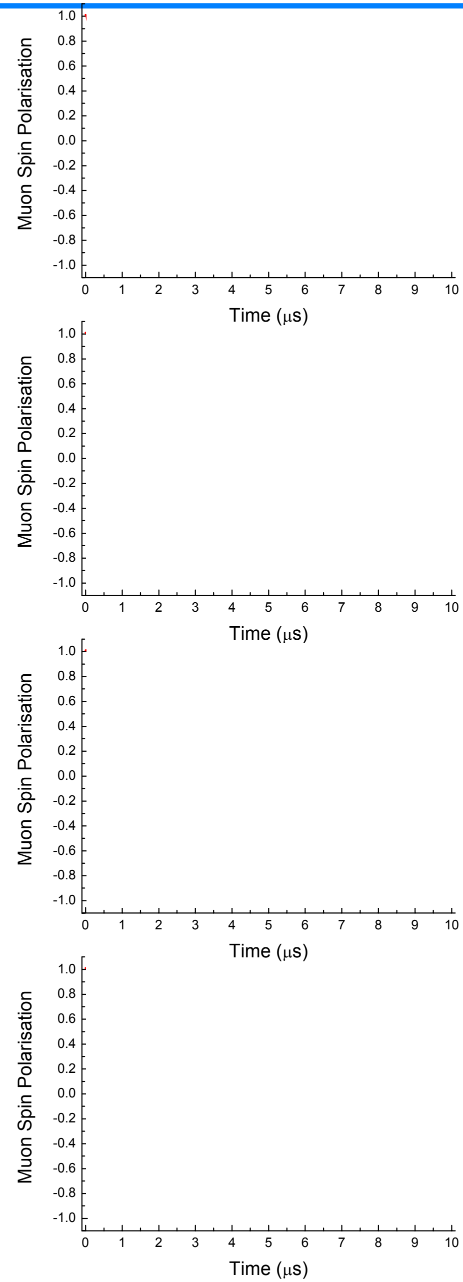
Worldwide Unique:
Muons on Request, MORE



Low Energy Muons as Low Microscopic Magnetic field sensors

An external Magnetic field B(z) only penetrates a certain distance z of the order of λ into a SC.





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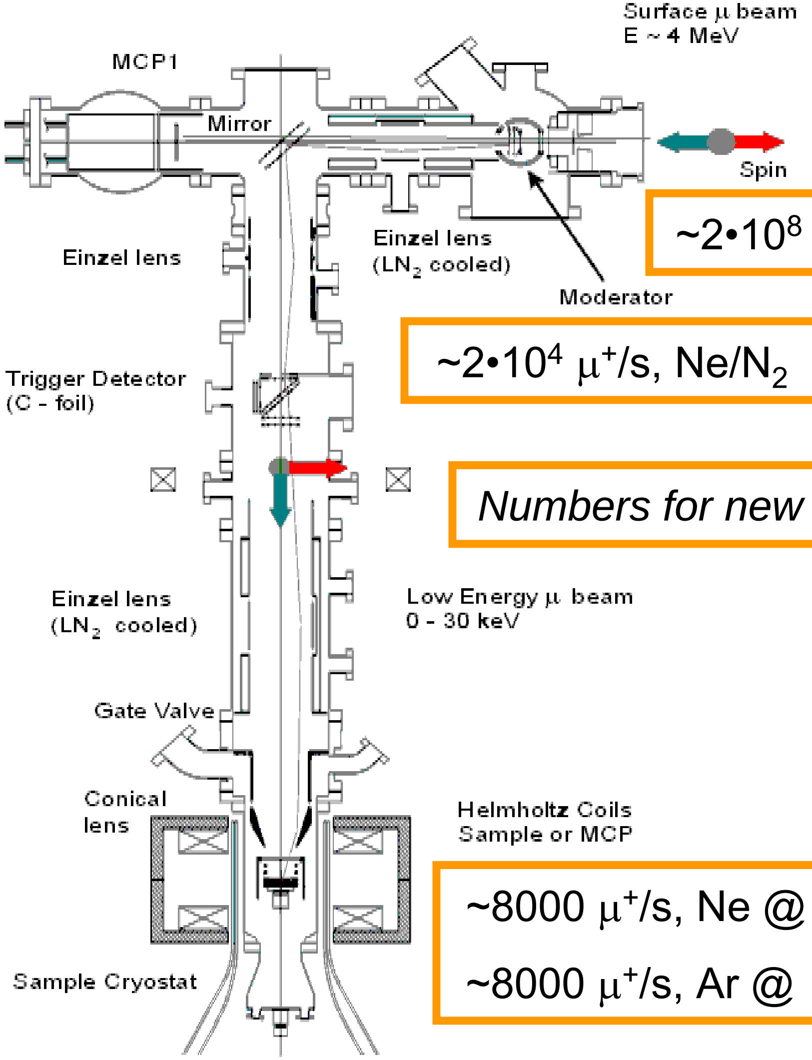
Low Energy Muon Beam and Instrument – LEM



~$2 \cdot 10^8$ μ^+/s

~$2 \cdot 10^4$ μ^+/s, Ne/N_2

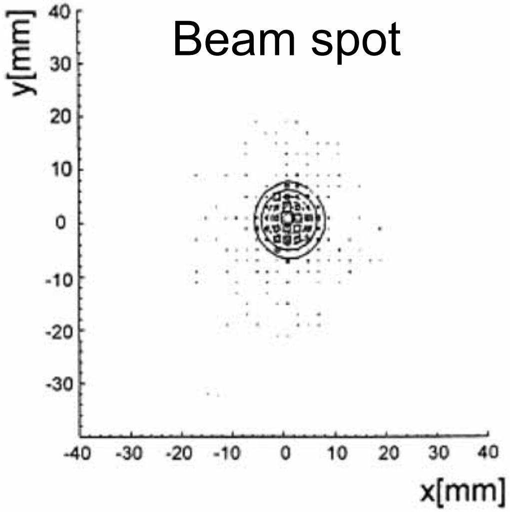
Numbers for new μE4

~8000 μ^+/s, Ne @ 12 kV

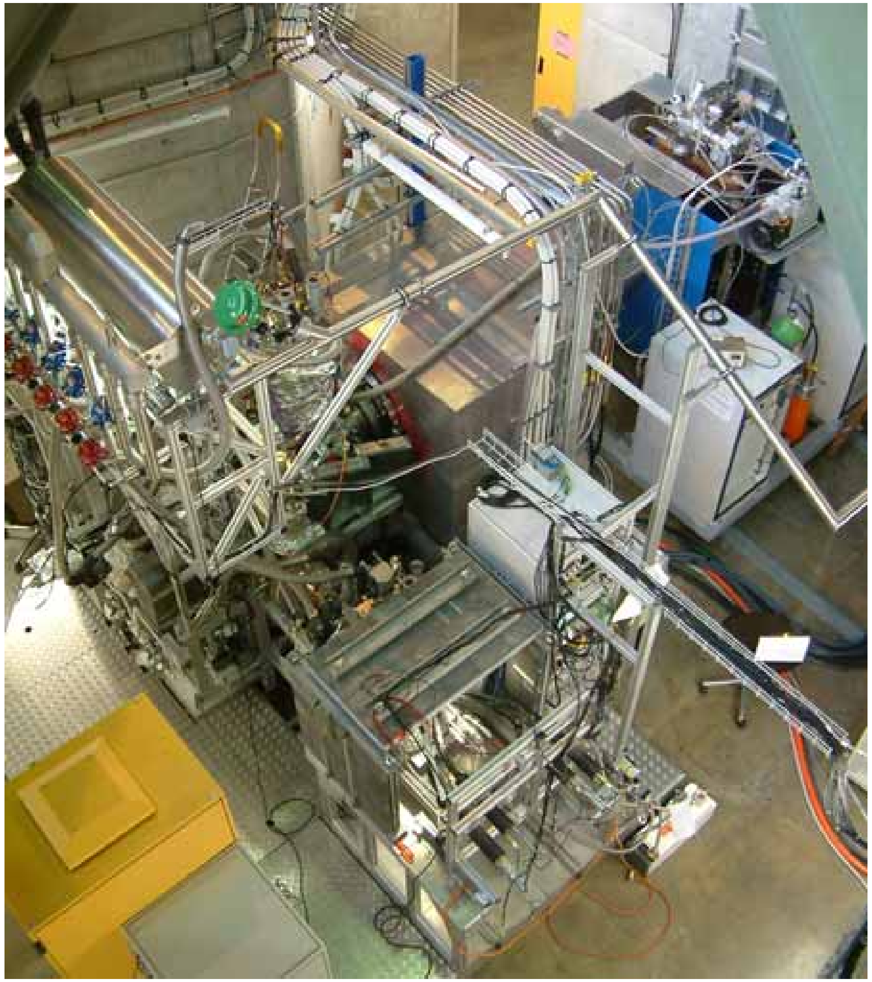
~8000 μ^+/s, Ar @ 20 kV

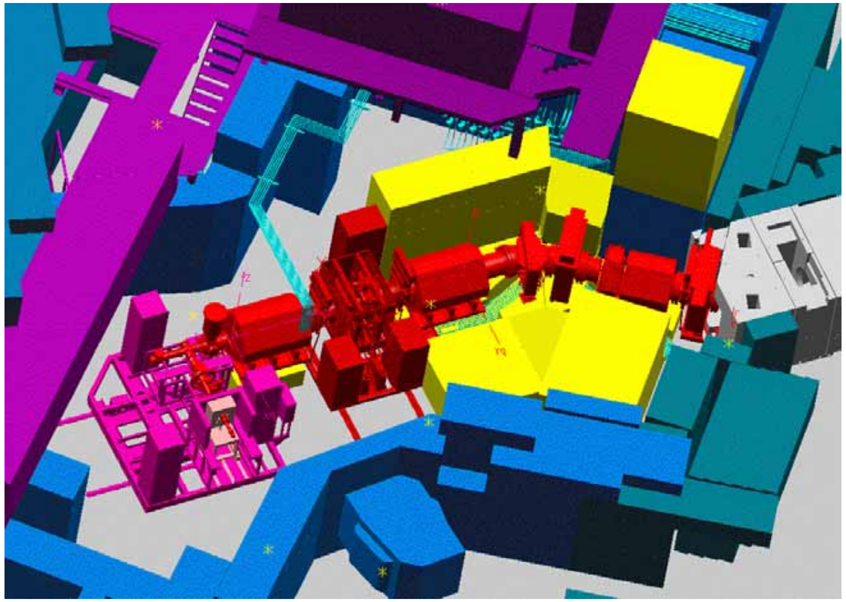
Worldwide unique:

- Polarized Low Energy μ^+ Beam
  ~ 0.5 - 30 keV (uncertainty 400 eV)
- Tunable implantation depth
  ~ 1 – 200 nm



Low Energy Muon Beam and Instrument – LEM



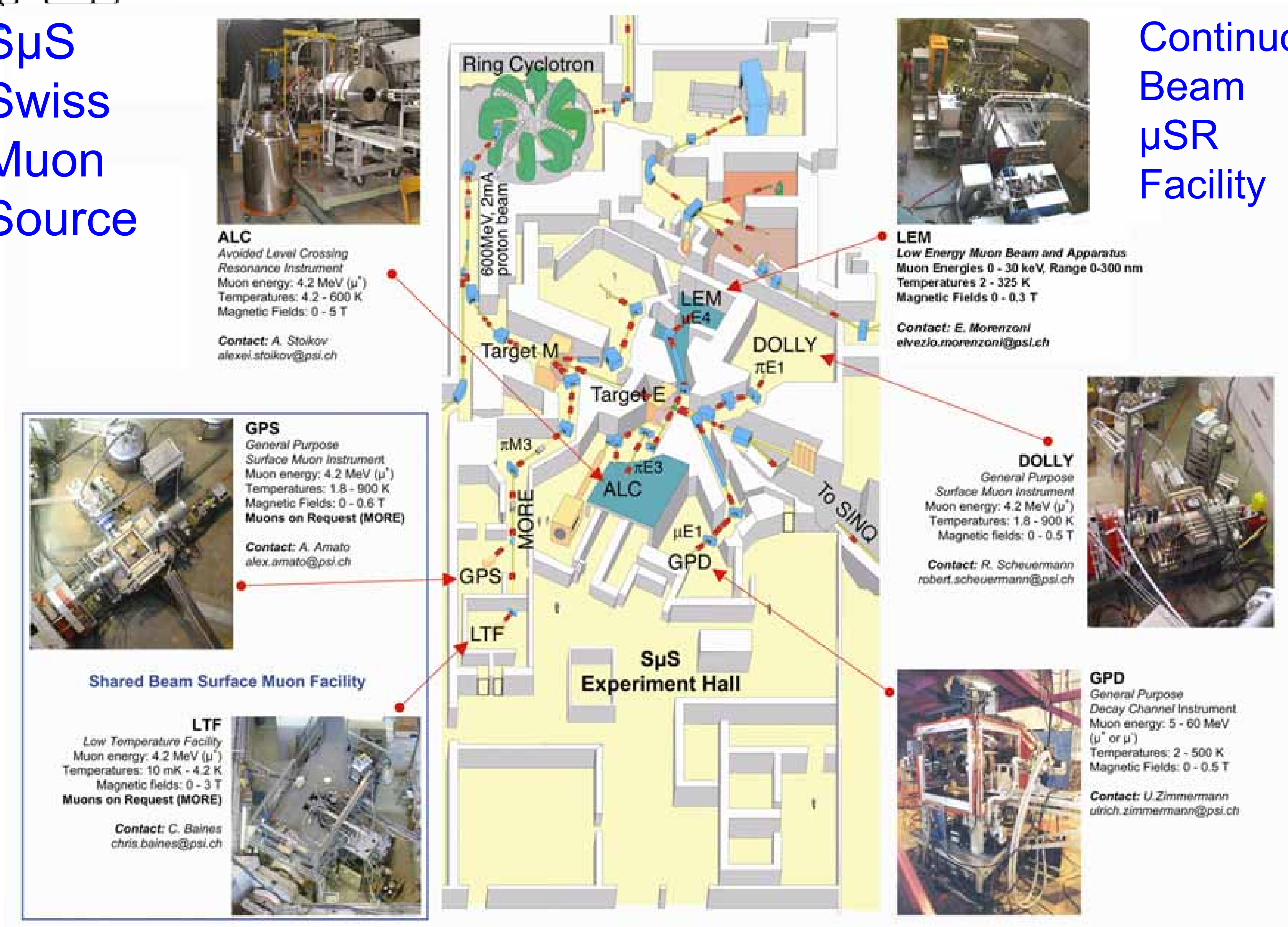


Layout of new µE4 beam
Commissioned end 2005

New LEM Instrument

SμS Swiss Muon Source

Continuous Beam μSR Facility



Surface Magnetism in Superconducting $La_{2-x}Ce_xCuO_4$ Films

H. Luetkens [a], Y. Krockenberger [b], L. Alff [c], A. Tsukada [d], M. Naito [d], E. Morenzoni [a], T. Prokscha [a], A. Suter [a], R. Khasanov [a,e], T. Gutberlet [f], J. Stahn [f], M. Gupta [f], and H.-H. Klauss [g]

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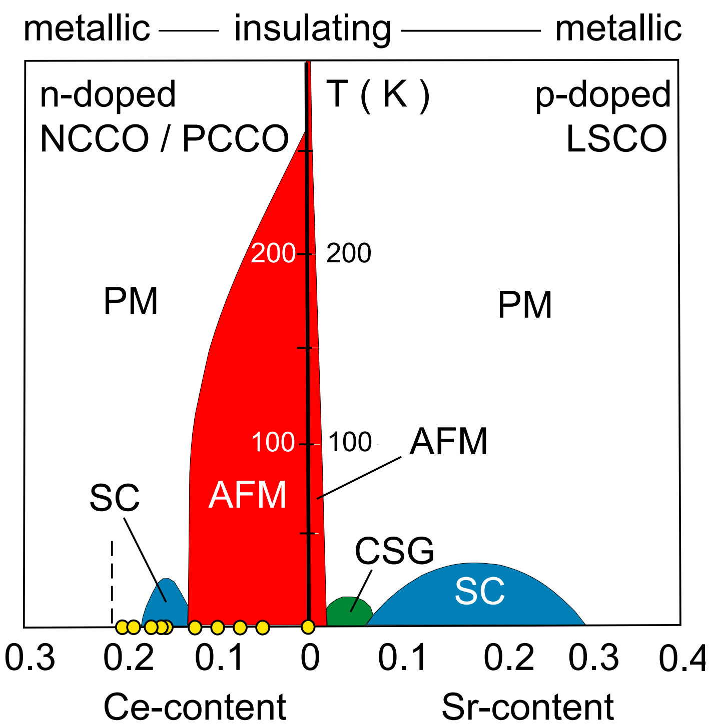
f) Labor für Neutronenstreuung, ETH Zürich & Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

g) Institut für Physik der Kondensierten Materie, Technische Universität Braunschweig, D-38106 Braunschweig, Germany

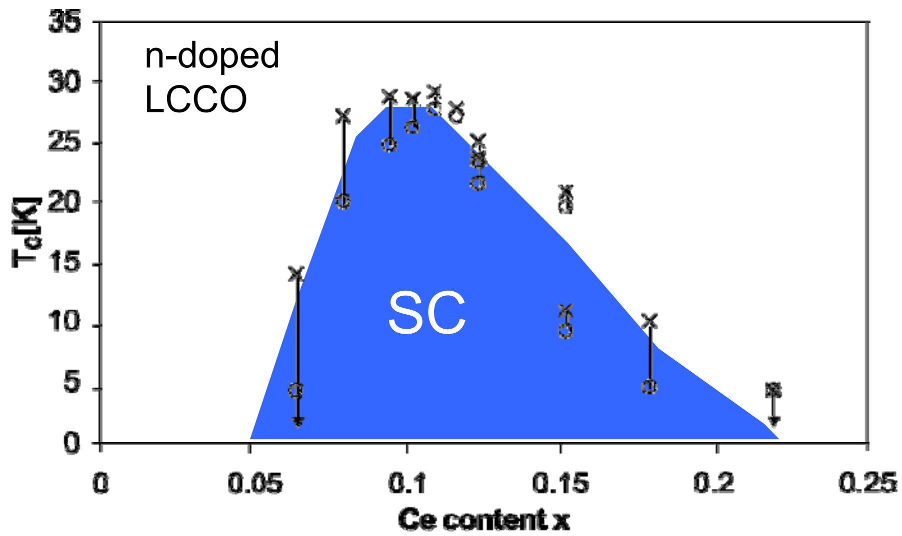
Introduction

Generic phase diagram of high-T_C- cuprates:



[M.B. Maple, MRS Bulletin 15 (1990) 60.]

Different phase diagram for electron- doped thin films:

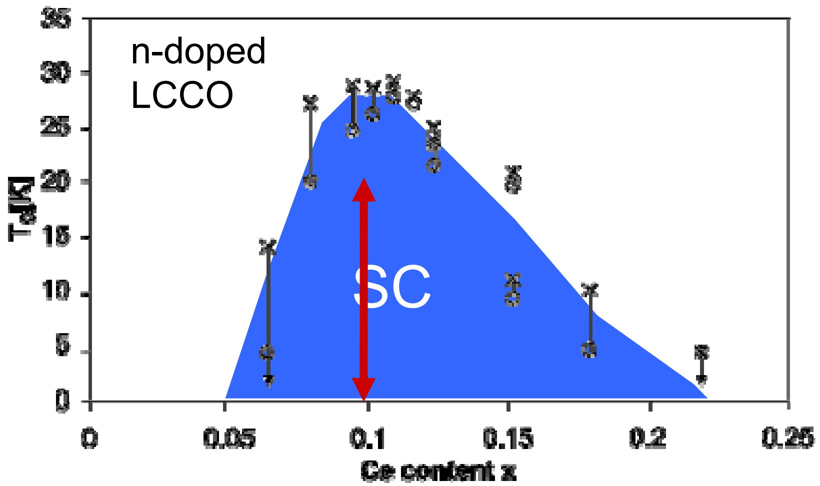


Naito et al., Jpn. J. Appl. Phys. 39 (2000) L485

Is there an electron-hole symmetry?

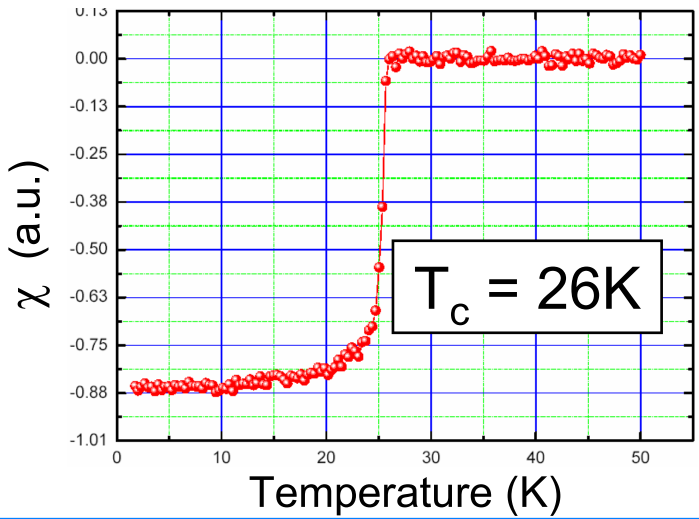
Why do we use $La_{2-x}Ce_xCuO_4$ films?

- La^{3+} is non-magnetic
- $La_{2-x}Ce_xCuO_4$ exists only as a thin film
- High quality films can be prepared
- High transition temperatures (Tc ~28K)



First sample:

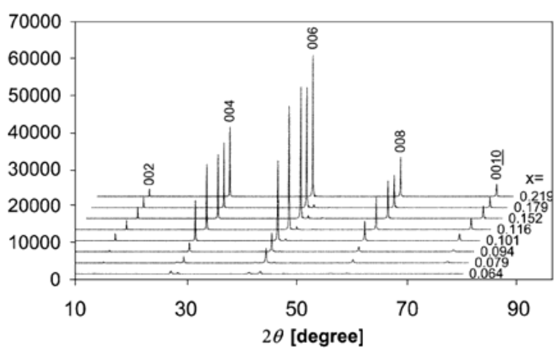
20nm Ag/ 300nm $La_{1.9}Ce_{0.1}CuO_4$



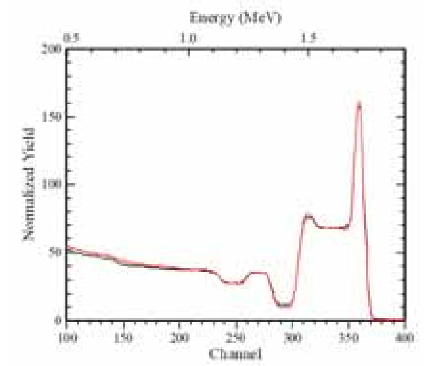
Sample Characterization

E Morenzoni, PSI

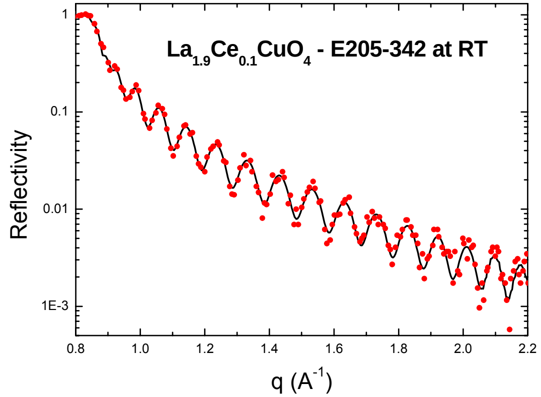
X-ray:



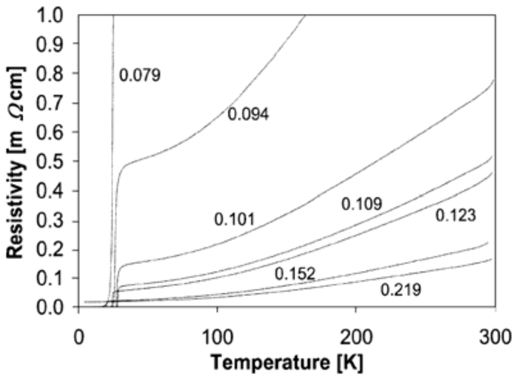
RBS:



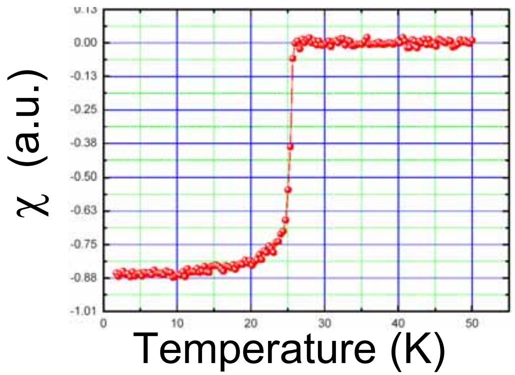
Neutron reflectivity:



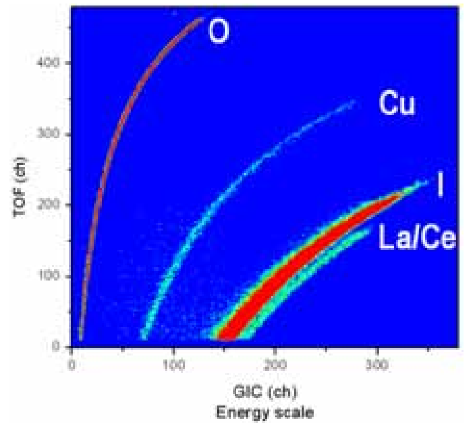
Resistivity:



Susceptibility:



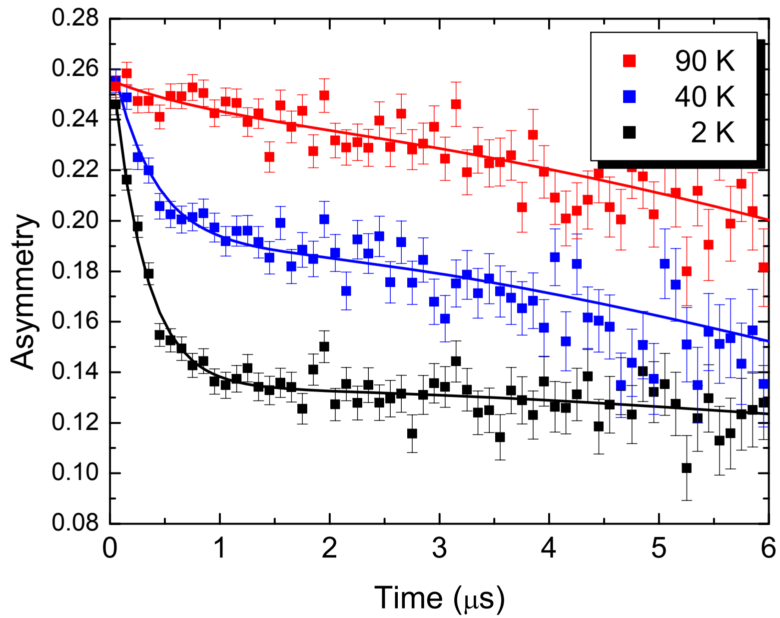
ERDA:



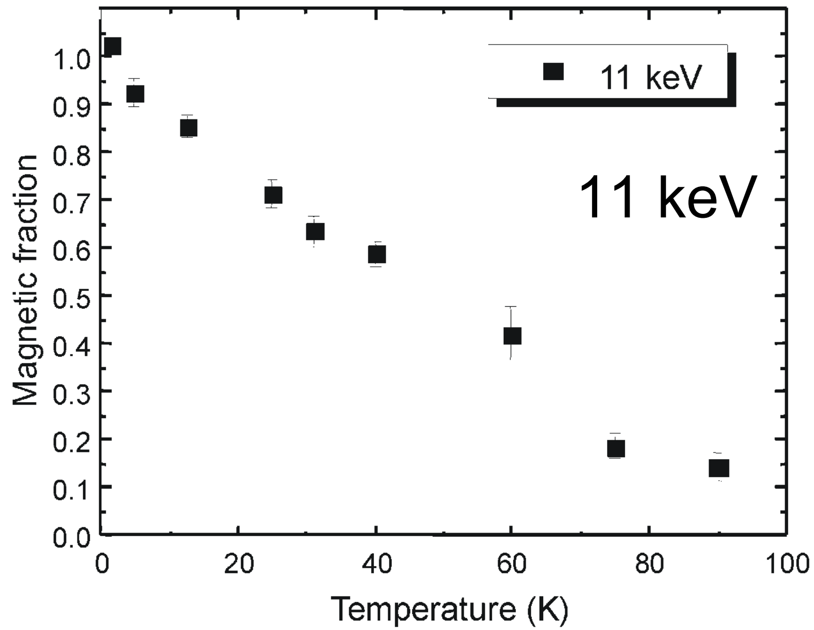
Elastic Recoil Detection analysis (@ETH-Z): for Oxygen profile

ZF-LEμSR using 11keV muons

ZF-LEμSR:



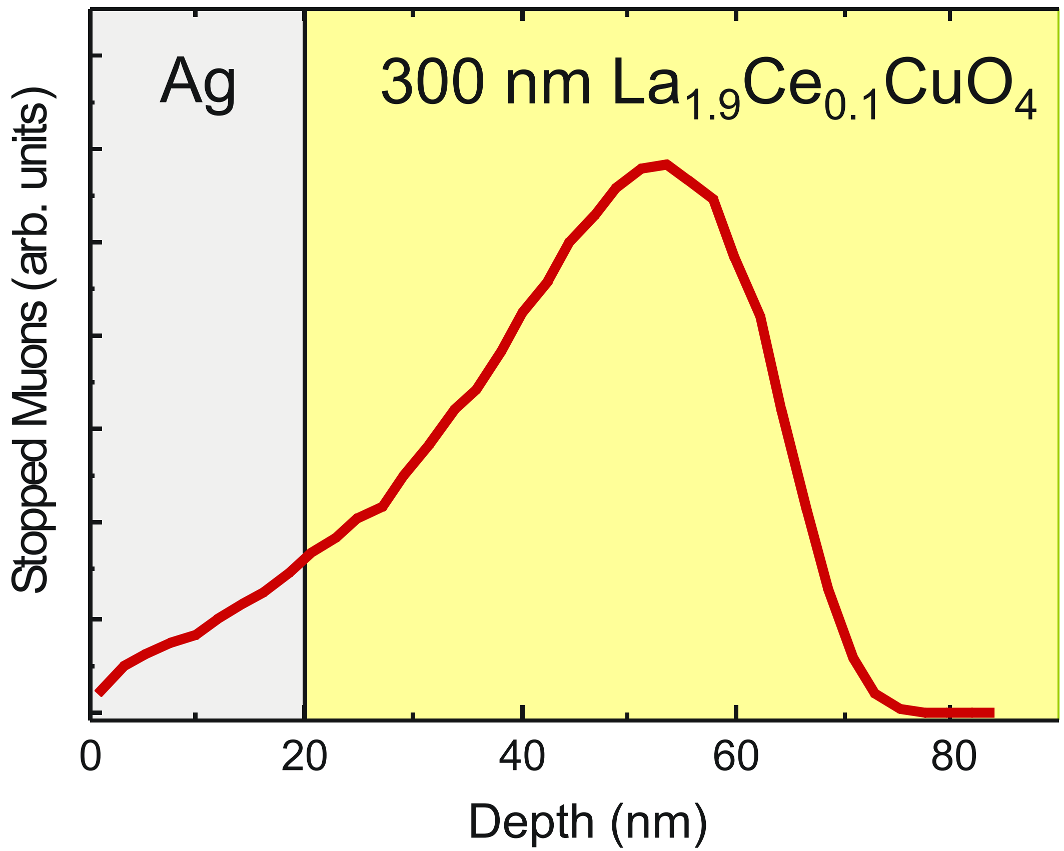
Magnetic volume fraction:

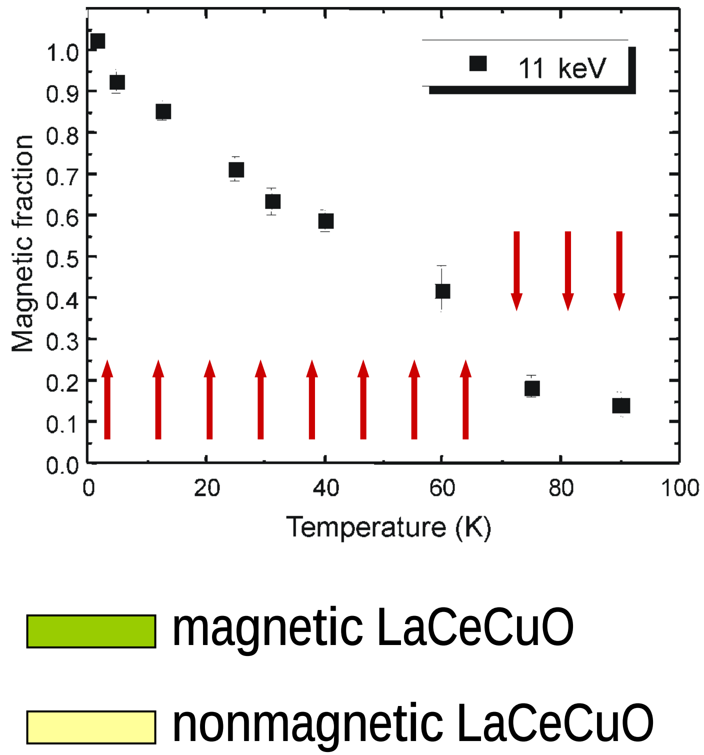


- Static magnetism (disordered)
- Relatively small relaxation rate ($\lambda \approx 3\ \mu s^{-1}$)

  $\Rightarrow$ small or diluted Cu moments (inhomogeneity on a nm scale)
- Magnetic volume fraction decreases with increasing temperature

ZF-LEμSR using 11keV muons

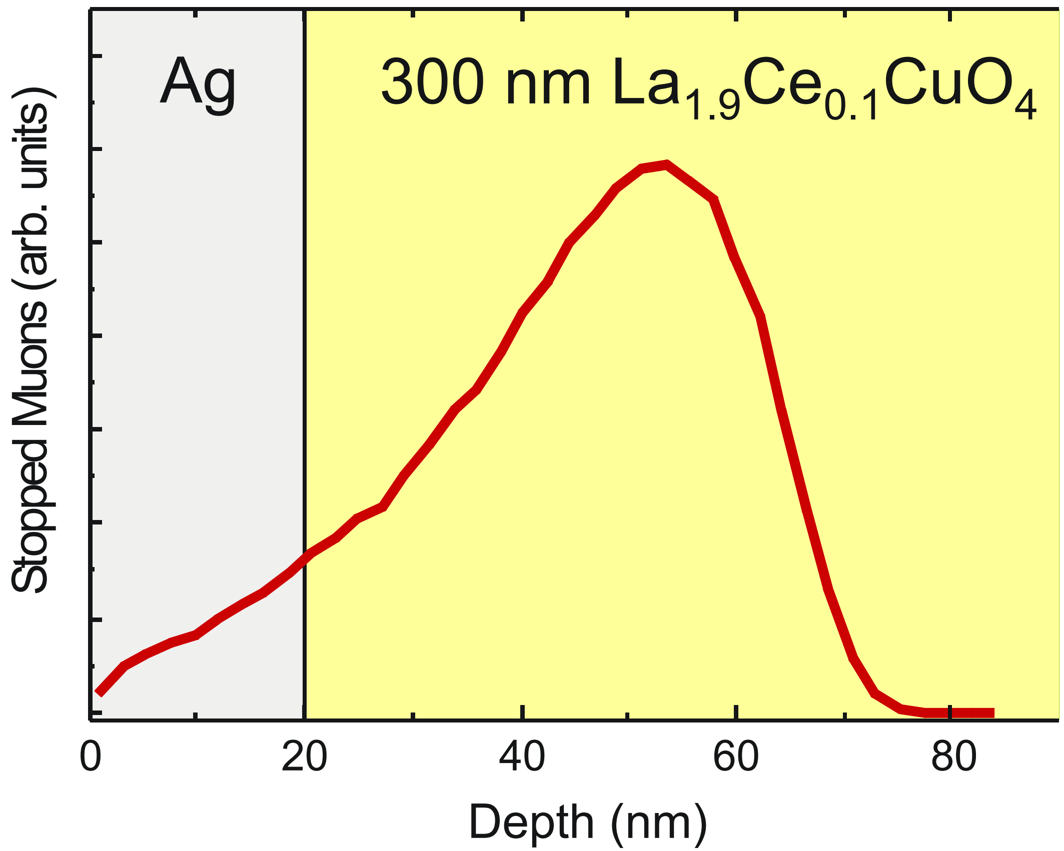


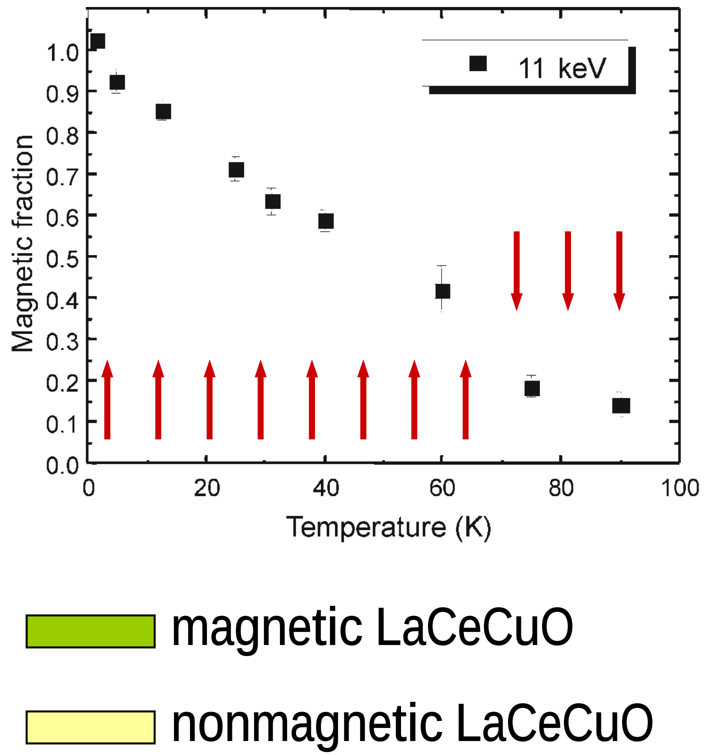


Scenario 1:

Large clusters with different ordering temperatures

ZF-LEμSR using 11keV muons



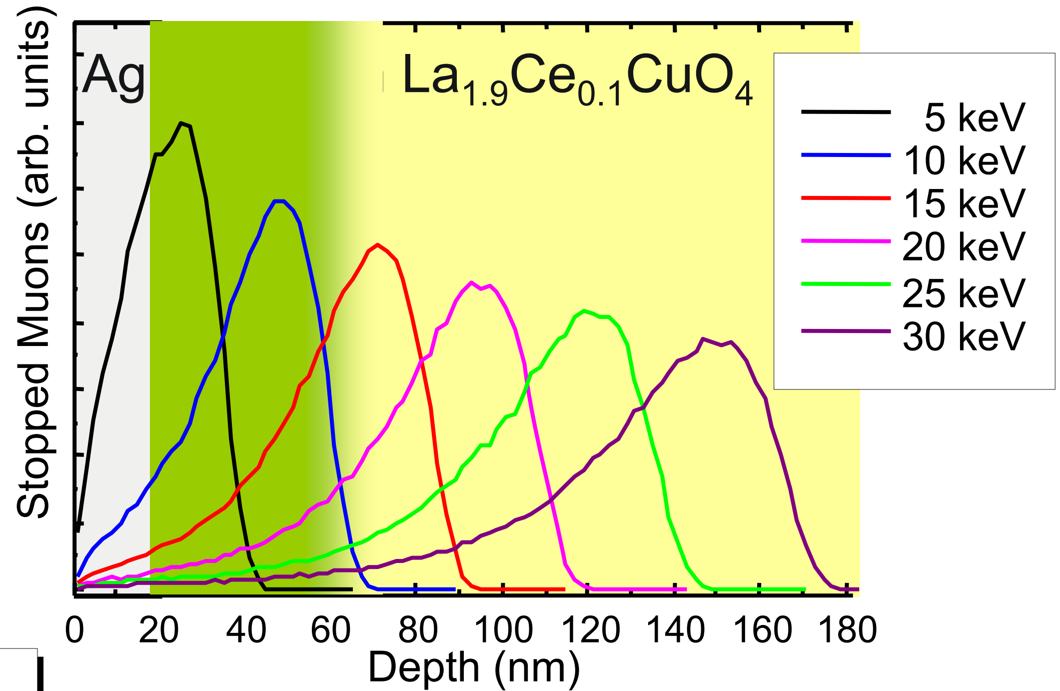


Scenario 2:

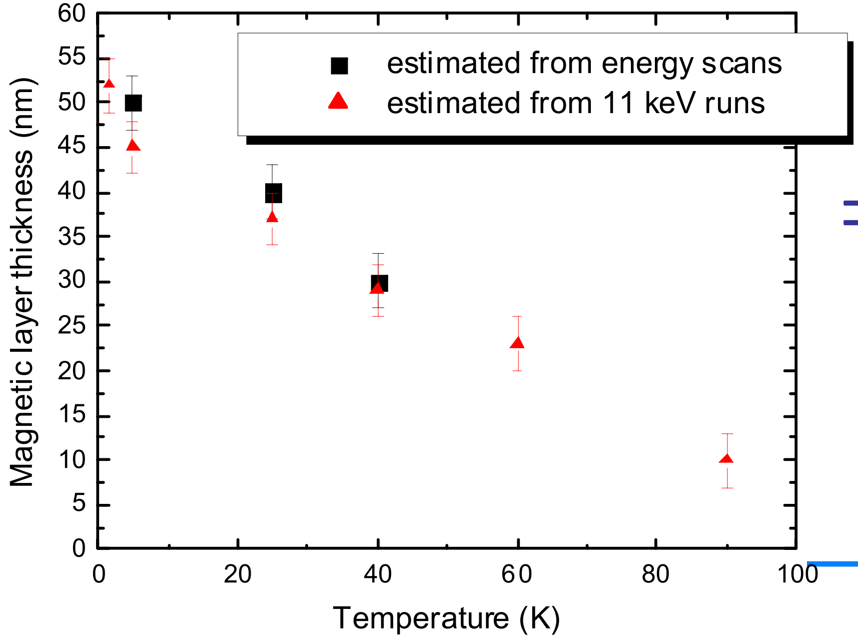
Temperature-dependent magnetic layer thickness

Depth-selective ZF-LEμSR

LE-μSR at controllable depth of the sample:



Magnetic layer thickness:

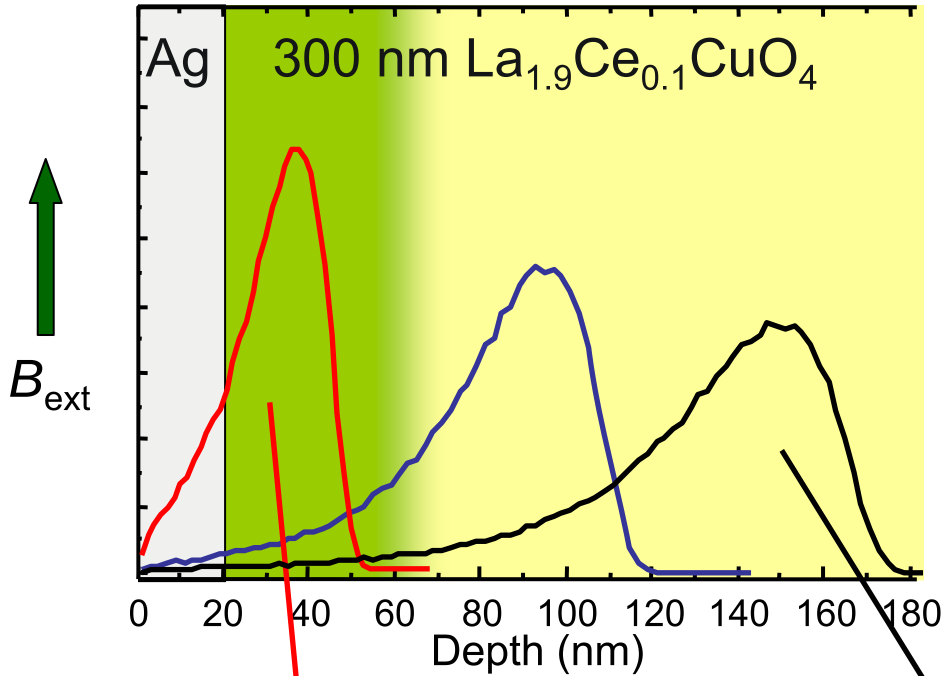


⇒ Magnetism is concentrated at the Ag/LaCeCuO interface

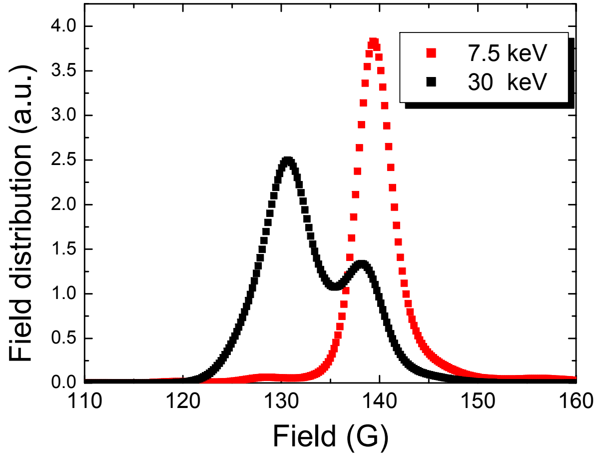
The thickness of the magnetic layer decreases with temperature

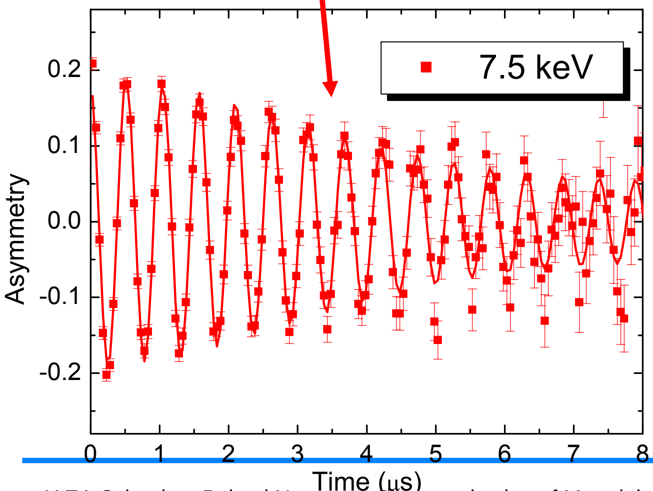
Morenzoni & Luetkens PSI

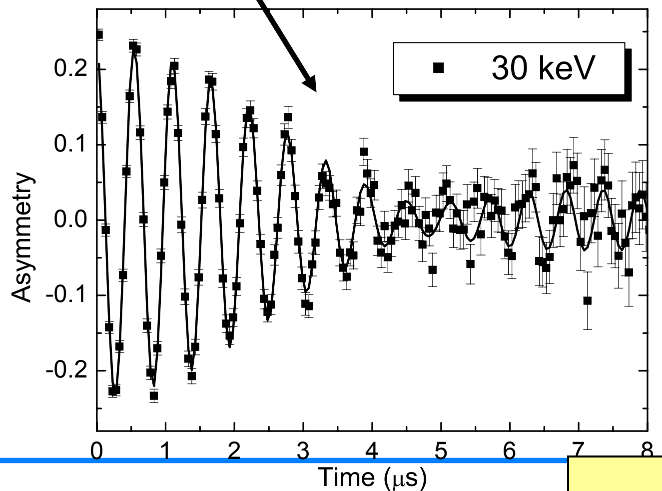
Superconducting Properties



Meissner Screening !

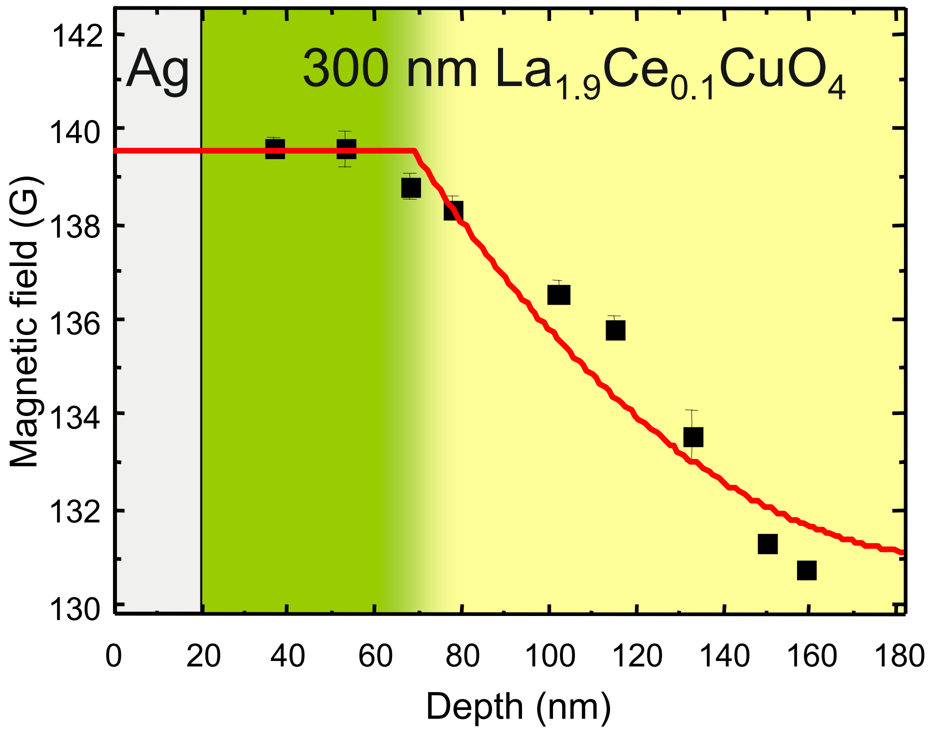




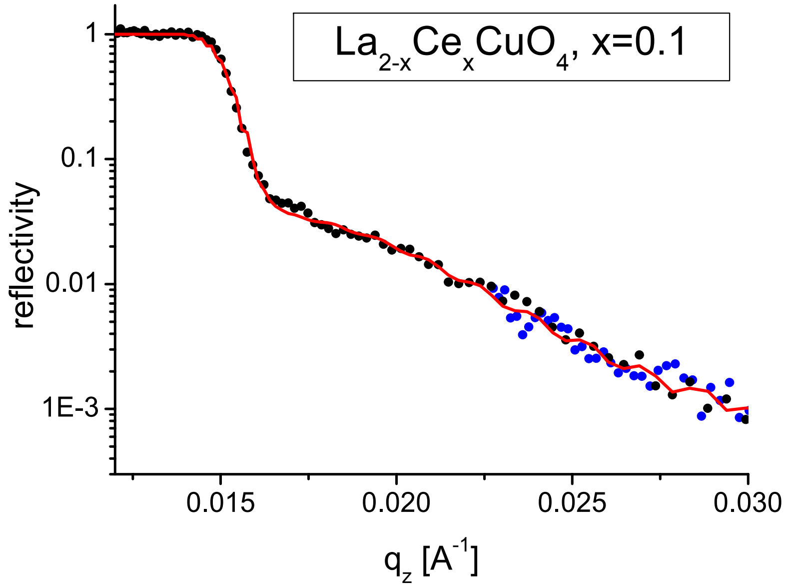


Morenzoni & Luetkens PSI

Magnetic Field Profile



Neutron reflectivity:



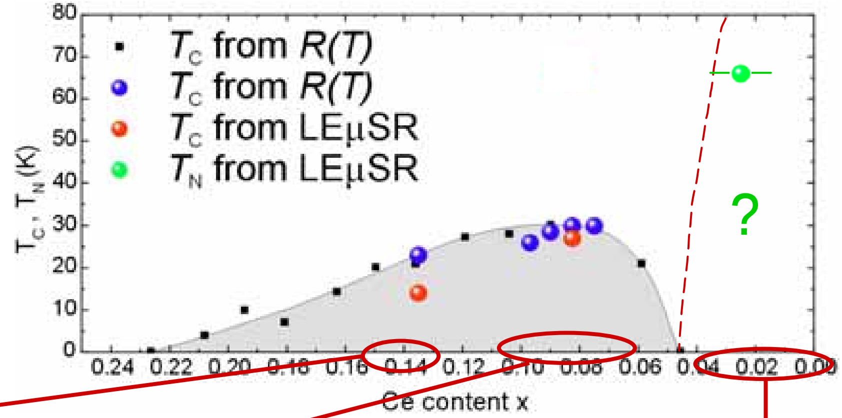
- Effective Meissner screening ⇒ bulk superconductivity
- Magnetic penetration depth $\lambda \approx 350$ nm
- Complementary PNR measurements in progress

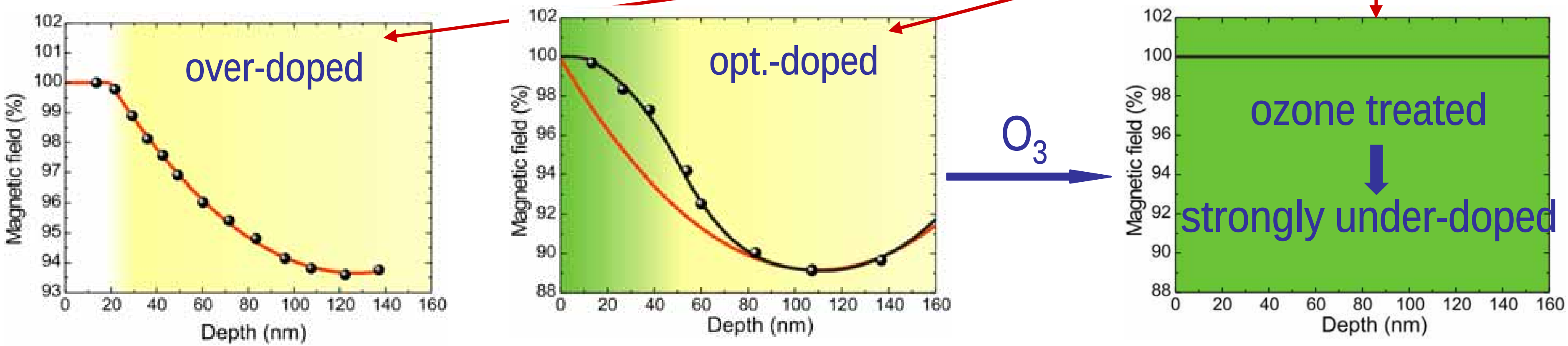
Coexistence of magnetism and superconductivity in the same sample

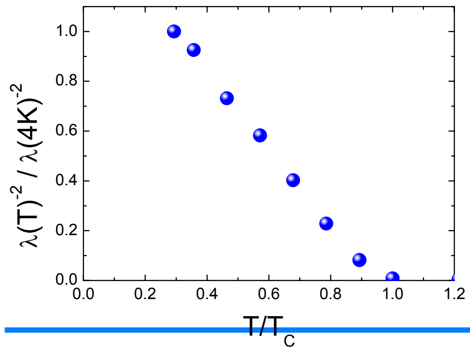
Morenzoni & Luetkens PSI

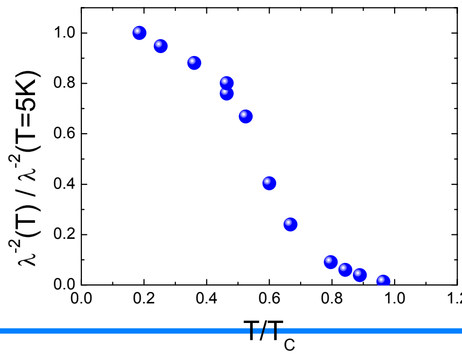
$La_{2-x}Ce_xCuO_4$ more samples

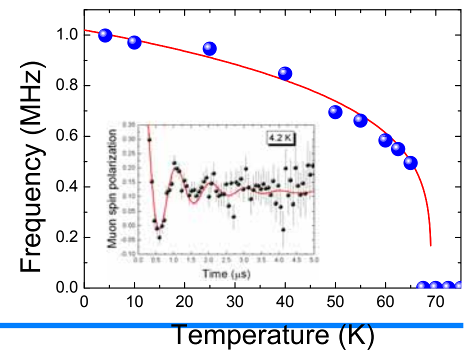
Morenzoni & Luetkens PSI











Acknowledgement – thanks to:

The ESS project: D Richter, G Bauer, R McGreevy, CPT, …….
http://neutron.neutron-eu.net/n_documentation/n_reports/n_ess_reports_and_more

SNS – Oak Ridge, USA: T Mason, N Holtkamp, I Anderson, http://www.sns.gov/

J-SNS Japan: M. Arai, … http://jkj.tokai.jaeri.go.jp/

The UK Neutron Strategy Document: www.neutrons.cclrc.ac.uk/Activity/ScienceCase

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