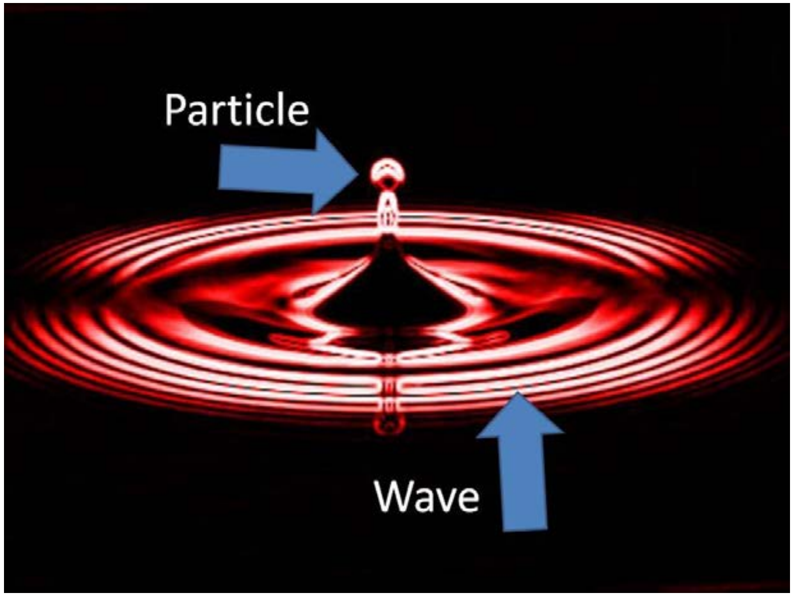
SwedNESS: Real-Space Neutron Imaging

Energy-selective neutron imaging steady-state sources

Nikolay Kardjilov

Particle-wave duality

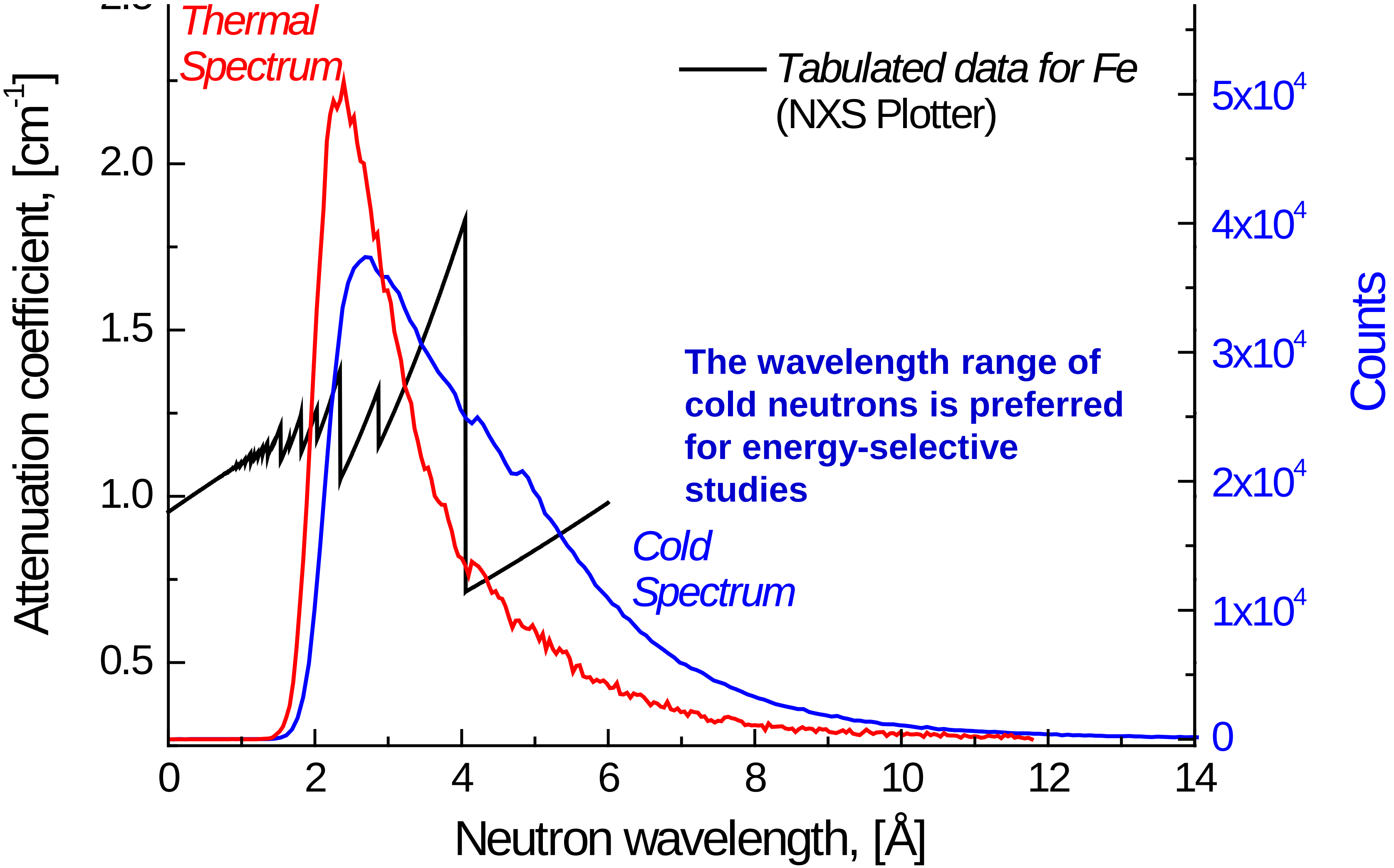


- de-Broglie wavelength: $\lambda = \frac{2\pi\hbar}{mv}$,
- Wave number: $k = 2\pi/\lambda$, $\mathbf{k} = \frac{m_n \mathbf{v}}{\hbar}$.
- Momentum: $p = \hbar k$
- Momentum operator: $\hat{\mathbf{p}} = -i\hbar\nabla$
- Kinetic energy: $E = \frac{\hbar^2 k^2}{2m_n}$,

Wave–particle duality is the concept in quantum mechanics that every particle or quantum entity may be partly described in terms not only of particles, but also of waves.
Hence the material particles like neutrons, also have wave properties such as wavelength and frequency.

Energy-selective imaging

Wavelength dependence of the attenuation coefficient for Fe



Energy-selective imaging

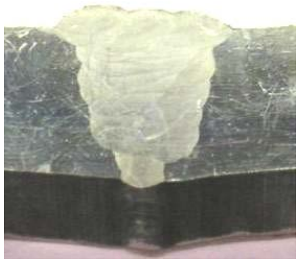
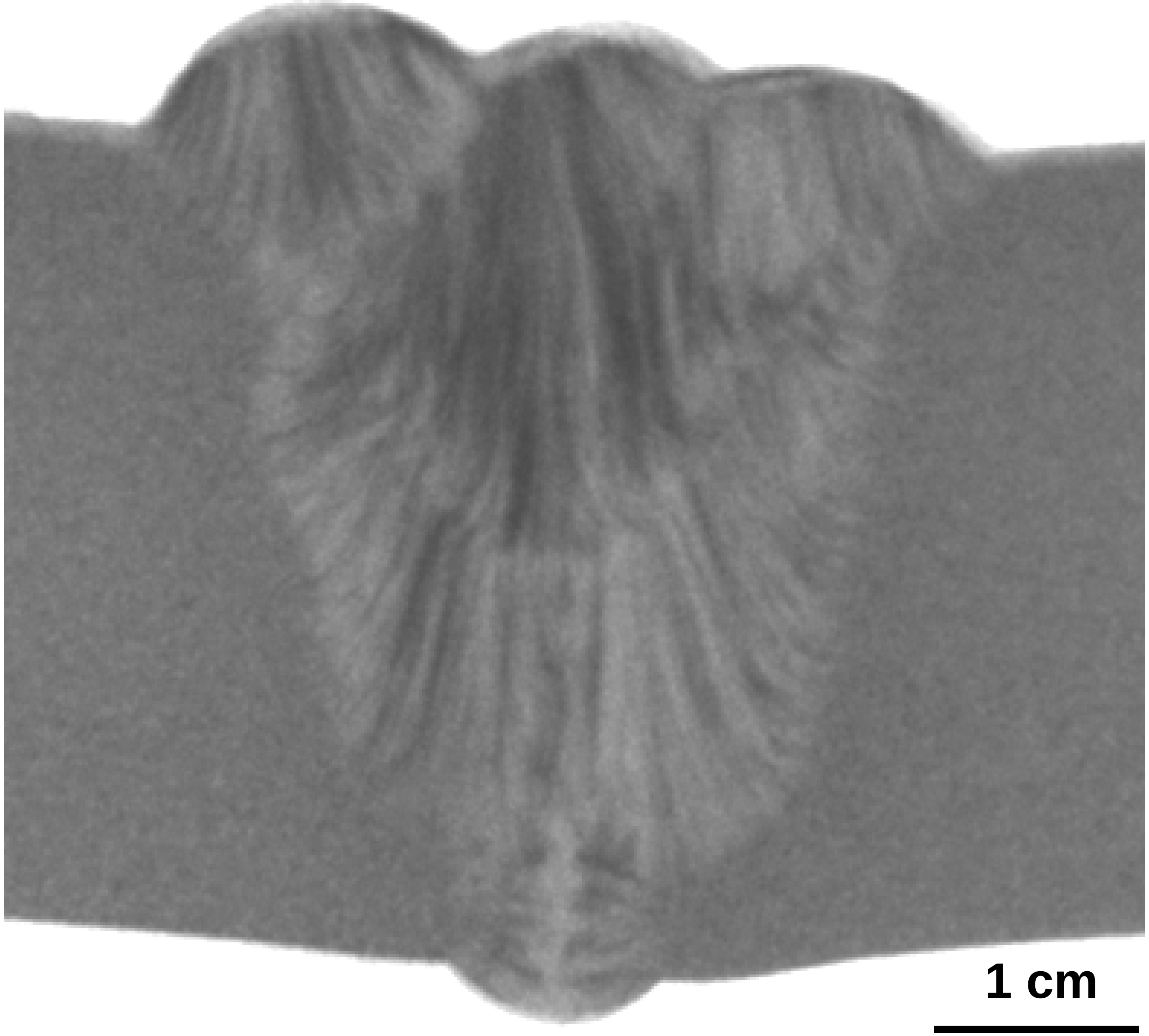


Image of weld taken at neutron wavelegth λ = 4.0 Å



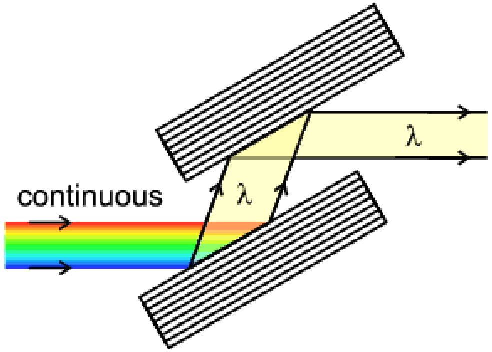
Energy-selective imaging is performed by using a monochromatic neutron beam at certain wavelength λ and resolution Δλ/λ, where Δλ is the spectral broadening of the beam.

Energy-selective imaging

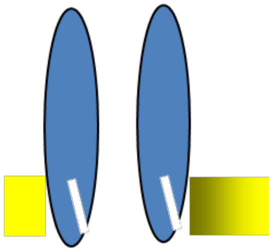
Devices for neutron monochromatization:

Velocity selector (VS)

Double-crystal monochromator (DCM)



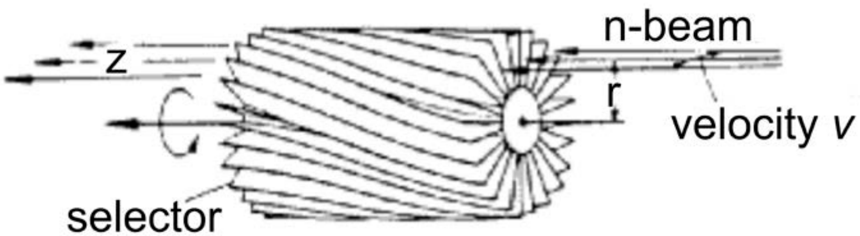
choppers



Time-of-Flight (TOF)

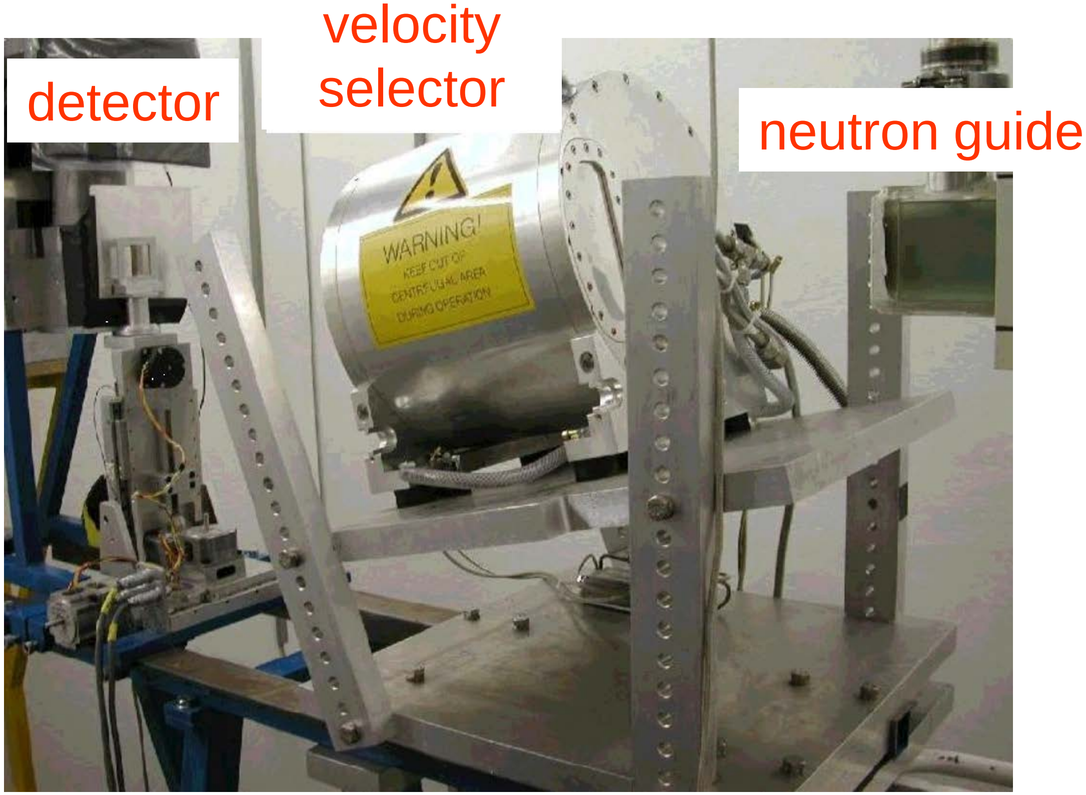
Energy-selective imaging

Velocity selector



The velocity selector has the appearance of a many-bladed turbine. The blades are coated with a strongly neutron-absorbing material, such as boron-10.

A neutron-velocity selector is a device that allows neutrons of defined velocity to pass while absorbing all other neutrons, to produce a monochromatic neutron beam.



Kardjilov, N., et al.
***Nuclear Instruments and Methods in Physics Research Section A* 501.2-3 (2003): 536-546.**

Resolution: $\Delta\lambda/\lambda$ ~ 15-30 %

Energy-selective imaging

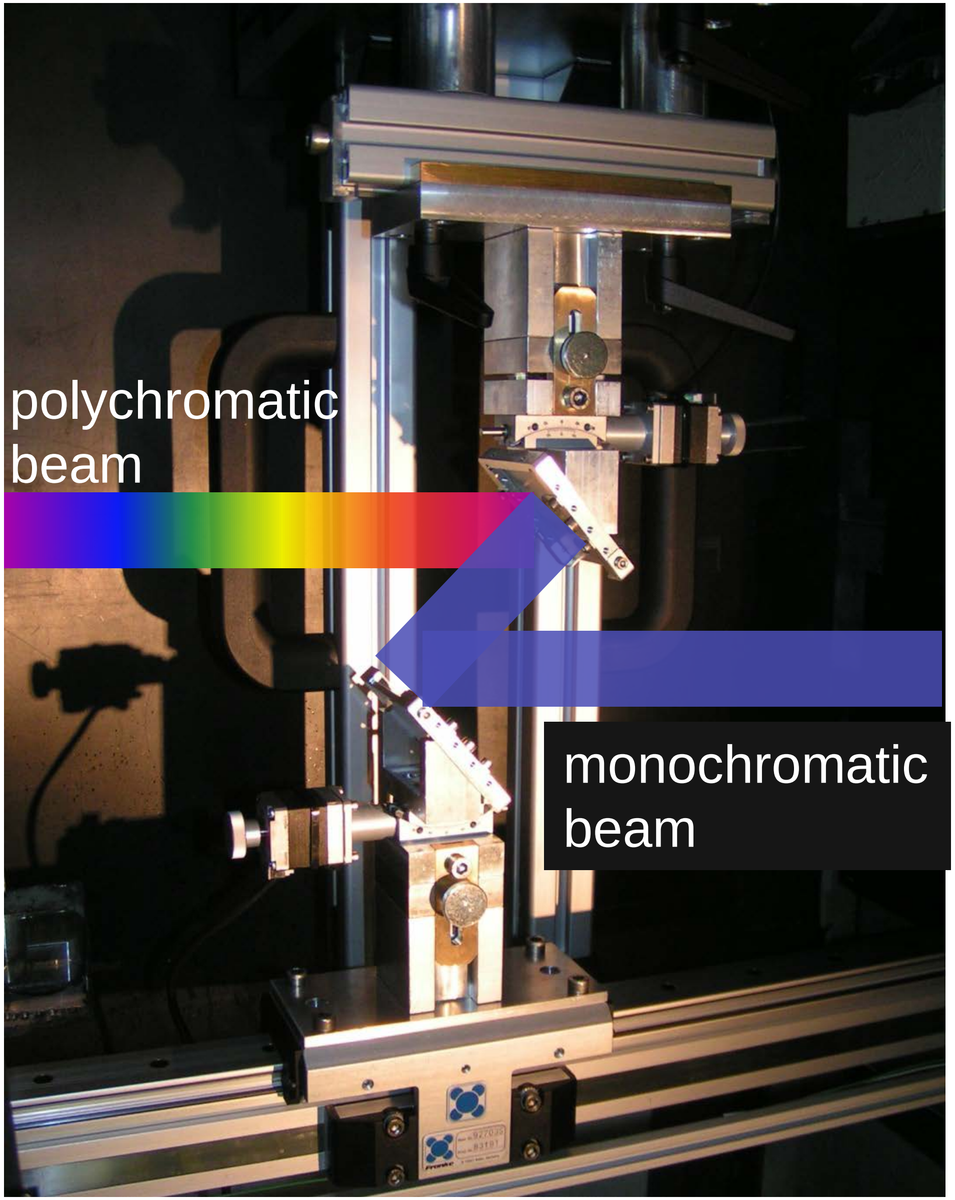
Double crystal monochromator:

Graphite crystals (mosaicity* 0.8°-3.5°)

Resolution ($\Delta\lambda/\lambda$): ~ 3% - 10 %

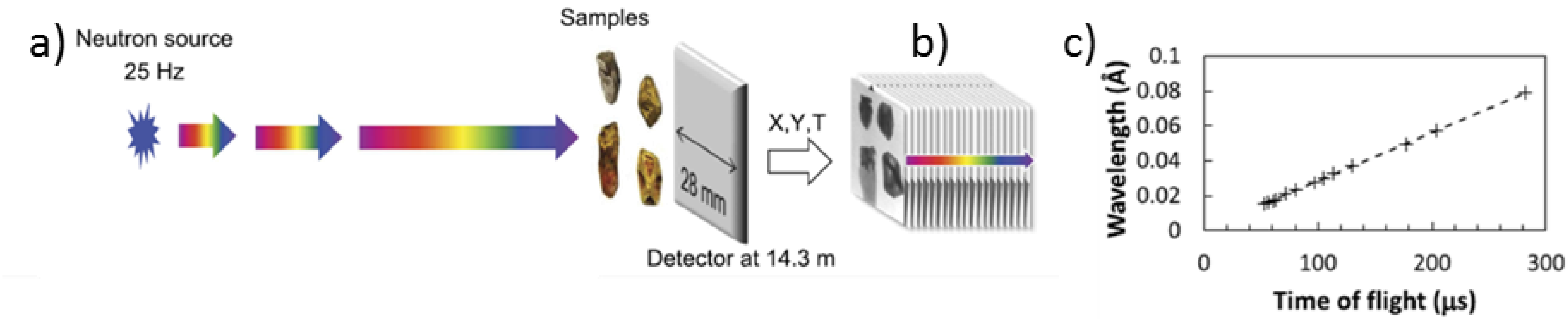
Consists of 2 monochromators where the same rotation angle is chosen for the upper and lower crystals, while translating the lower crystal.

The wavelength can be adjusted continuously between 1 Å and 6 Å, while the beam direction remains unchanged, but shifted vertically.



Treimer, W., et al.
Applied Physics Letters 89.20 (2006): 203504.

Time-of-Flight Metod:



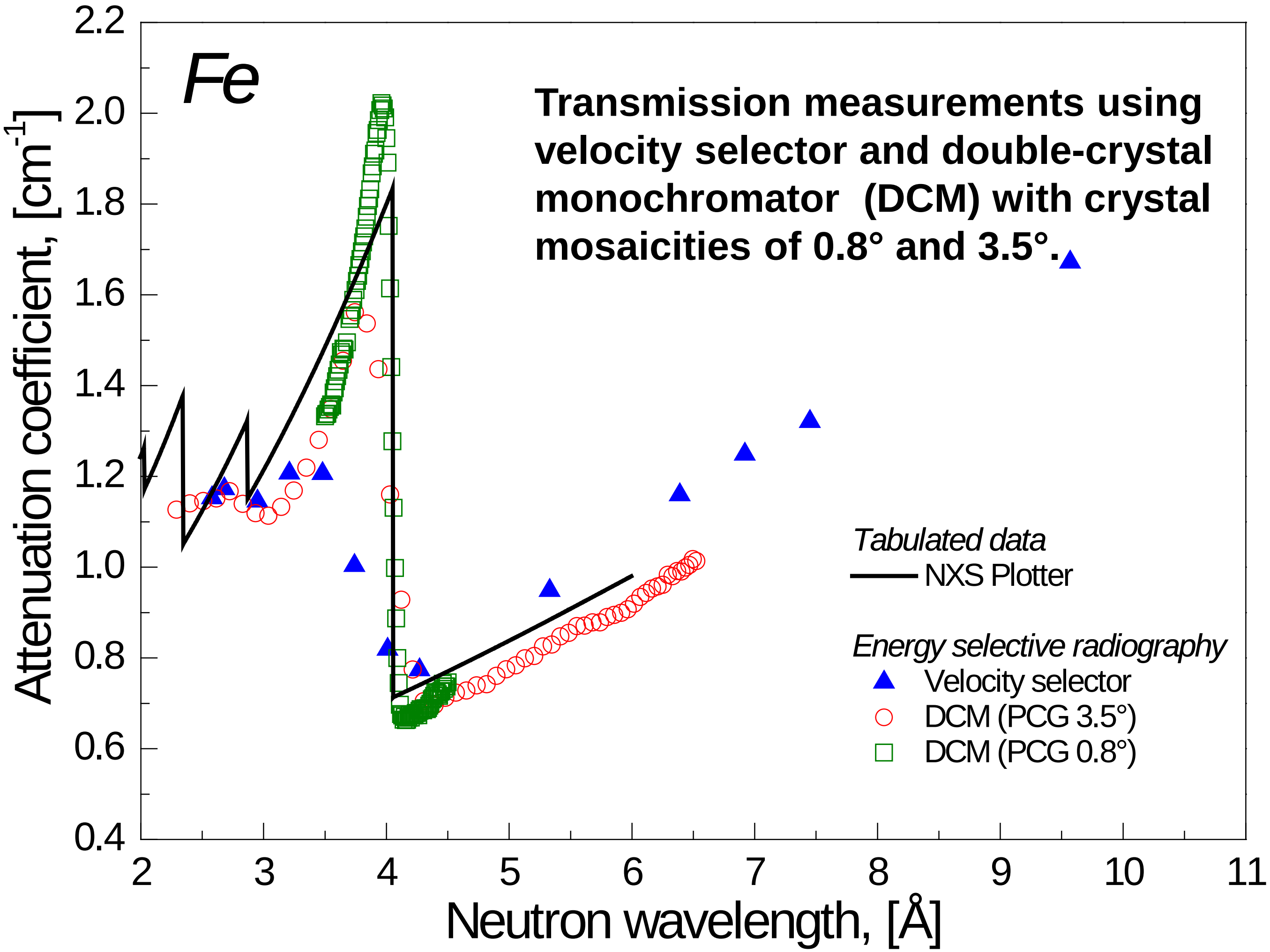
a) Neutron pulses (white beam) travel from the source towards the sample and detector, which measures position X,Y and time T (determined relative to the time of pulse) for each registered neutron. b) The result is a set of neutron transmission images, each corresponding to a specific neutron energy. c) The relation between neutron Time of Flight and Wavelength is linear.

Tremsin, A. S., et al. Scientific reports 7.1 (2017): 1-9.

Resolution ($\Delta\lambda/\lambda$): ~ 0.1% - 1 %

Energy-selective imaging

Comparison of different methods for monochromatization:



Al-Falahat, A. M., et al. *Nuclear Instruments and Methods in Physics Research Section A* 943 (2019): 162477.

Energy-selective imaging

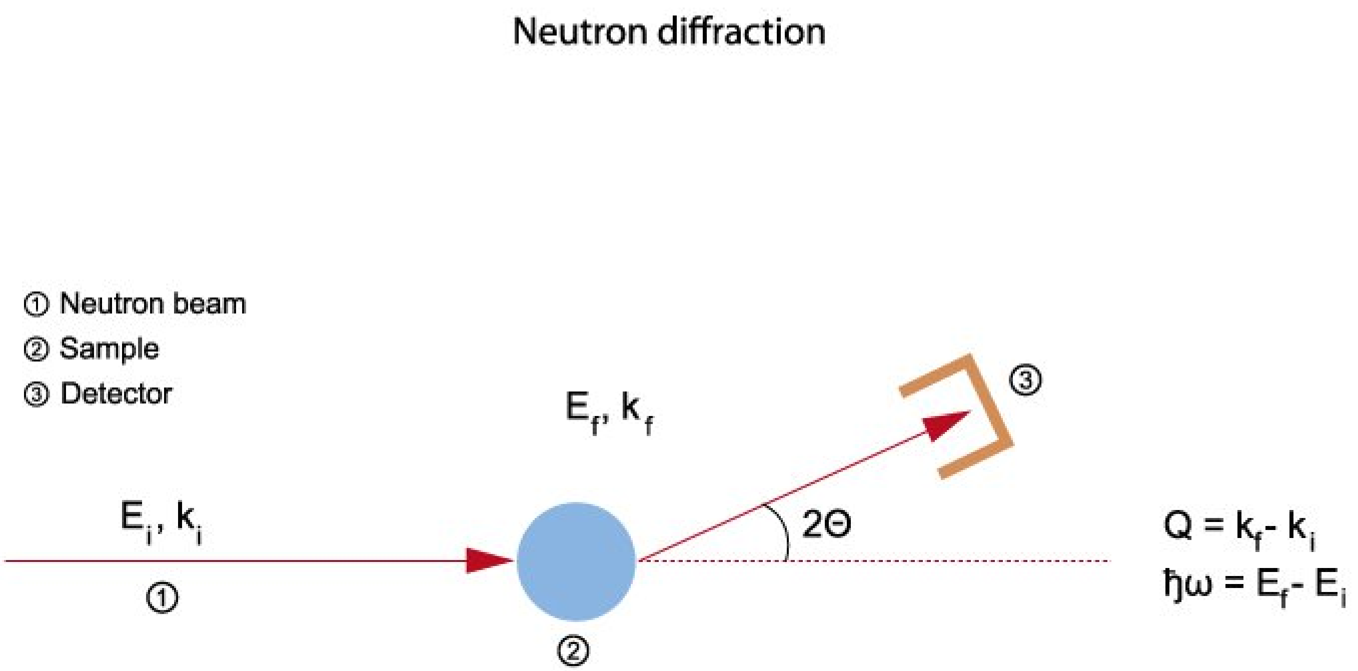
Method	Wavelength resolution	Exposure times
Velocity selector	15-30 %	seconds
Double-crystal monochromator	3-10 %	minutes
Time-of-Flight	0.1-3.0 %	time stamping (µs)

Wavelength resolution = $\Delta\lambda/\lambda$, where $\Delta\lambda$ is the spectral broadening of the monochromatic beam.

Energy-selective imaging

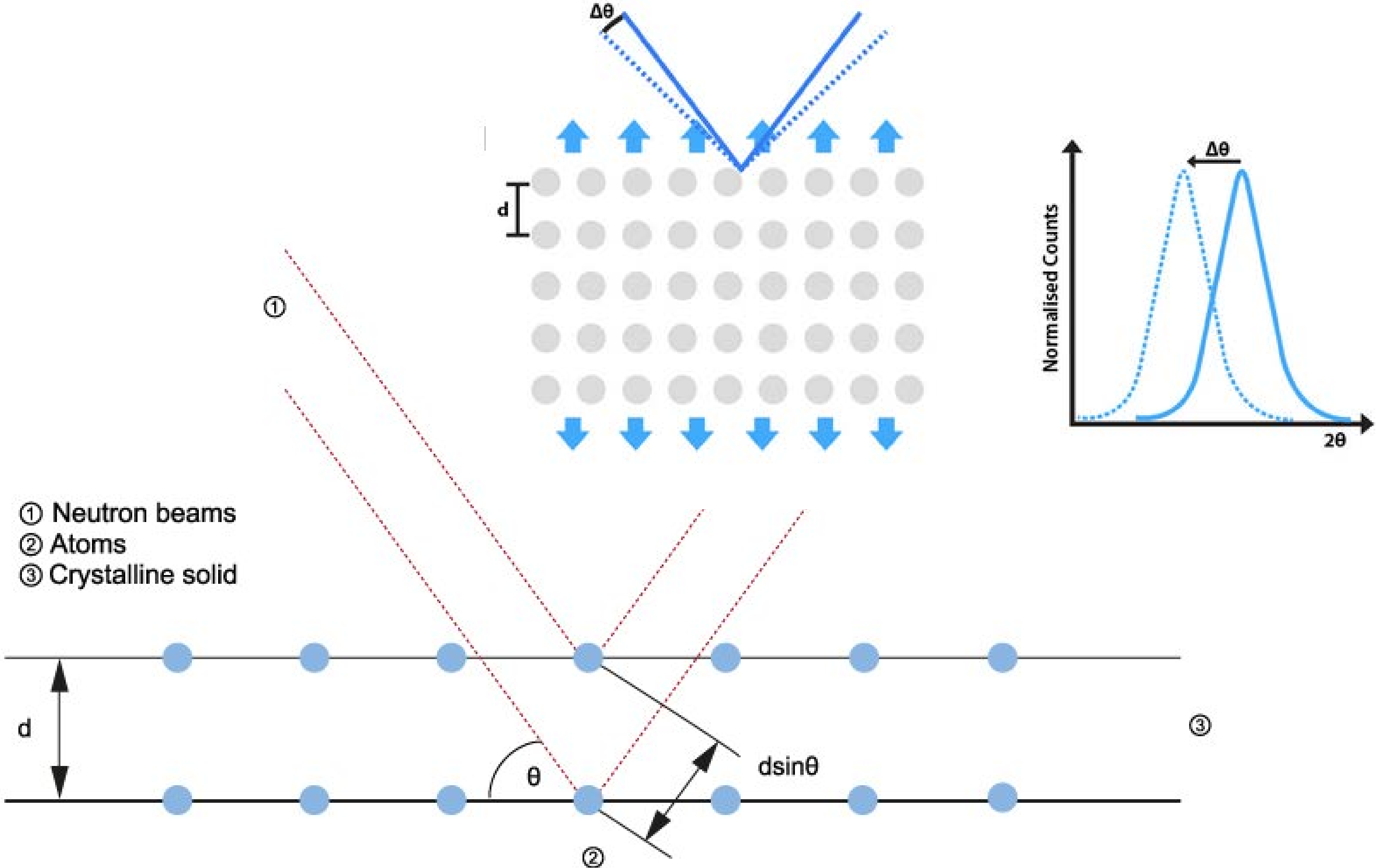
- In polycrystalline materials, the neutron beam attenuation coefficient may owe some of its wavelength dependence to the fact that some neutrons are scattered out of the incident beam by Bragg diffraction

- At certain wavelengths, in analogy to Bragg peaks in a diffractometer, Bragg edges are observed. The associated imaging method is hence often termed “Bragg Edge Imaging” and is carried out using a tunable monochromatic neutron beam.



https://nmi3.eu/neutron-research/techniques-for-/structural-research.html

Theory

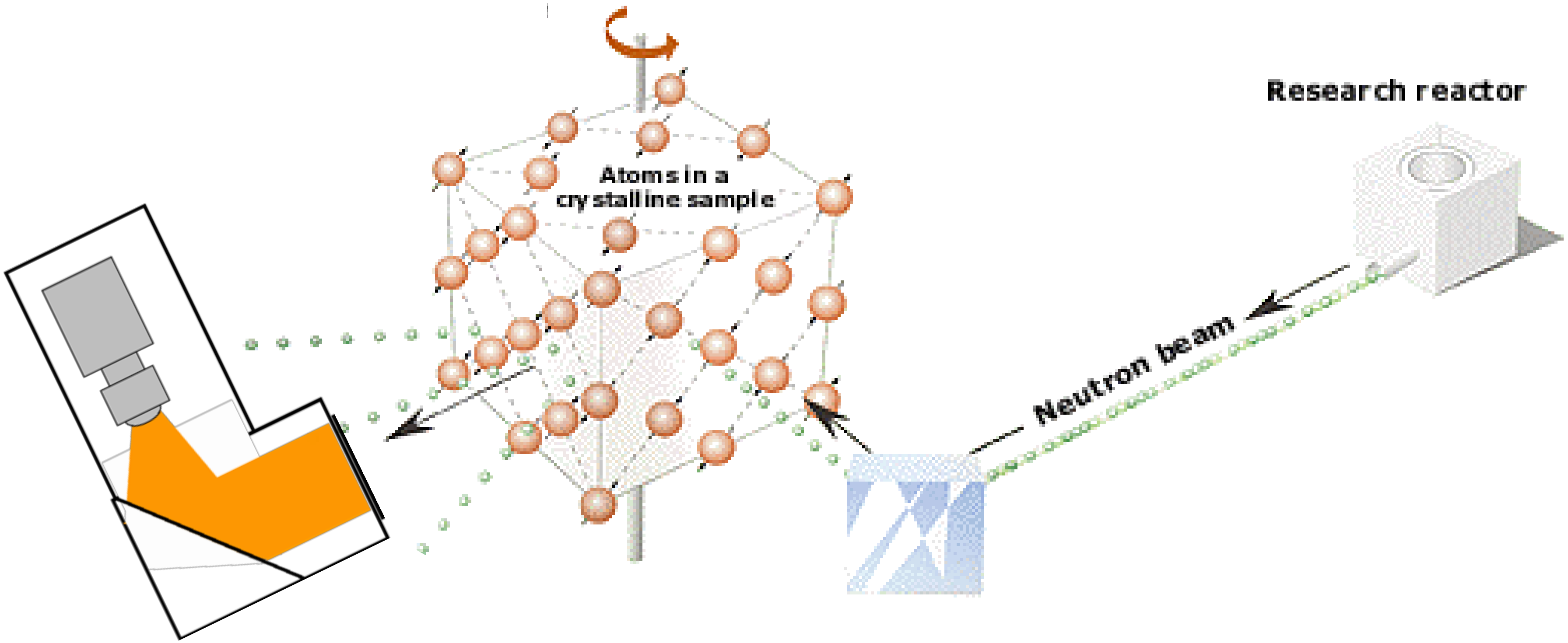


$$2d \cdot \sin(\theta) = n\lambda$$

https://nmi3.eu/neutron-research/techniques-for-/structural-research.html

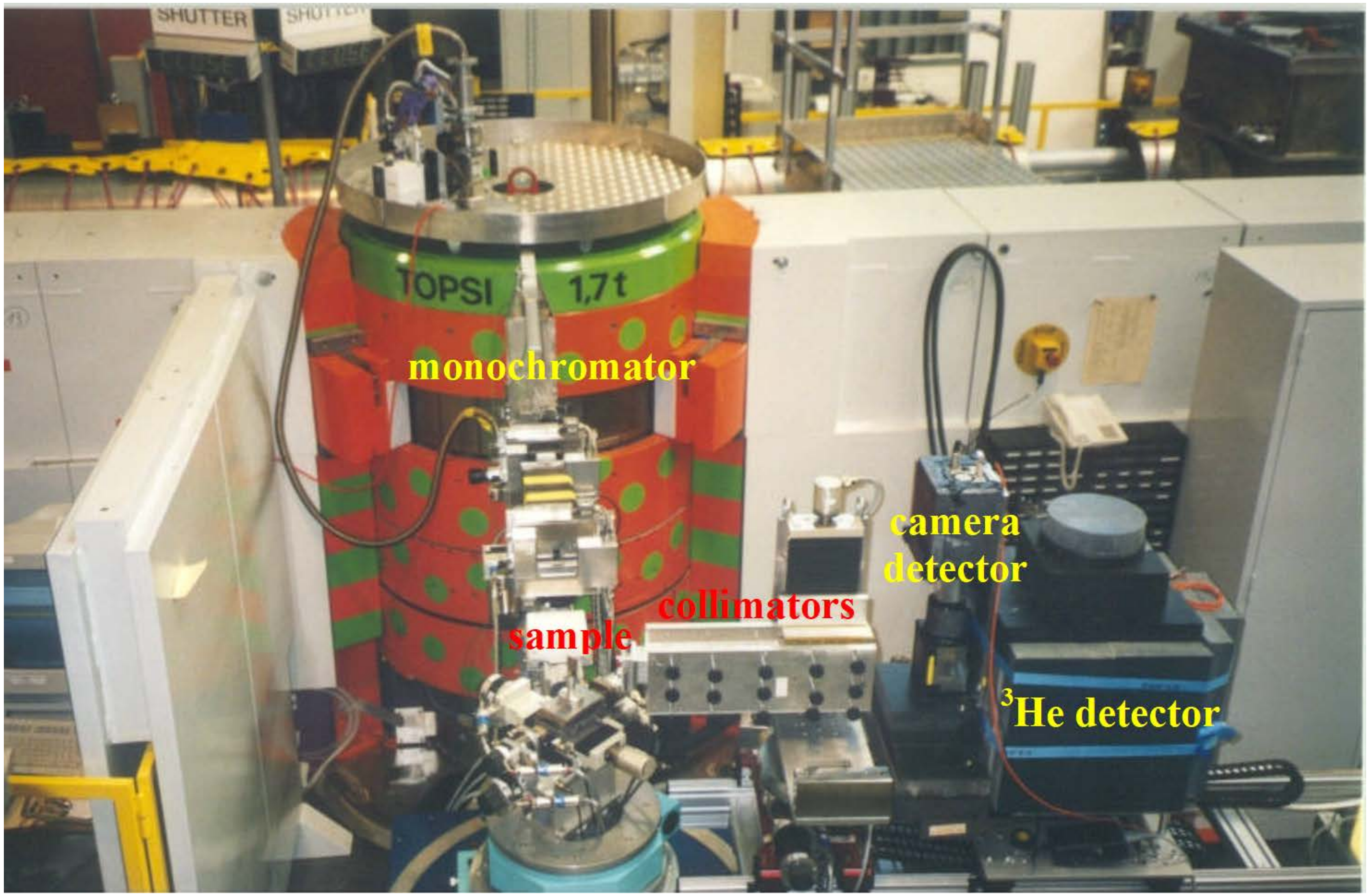
Neutron diffraction instrument

Topography: Scattering configuration



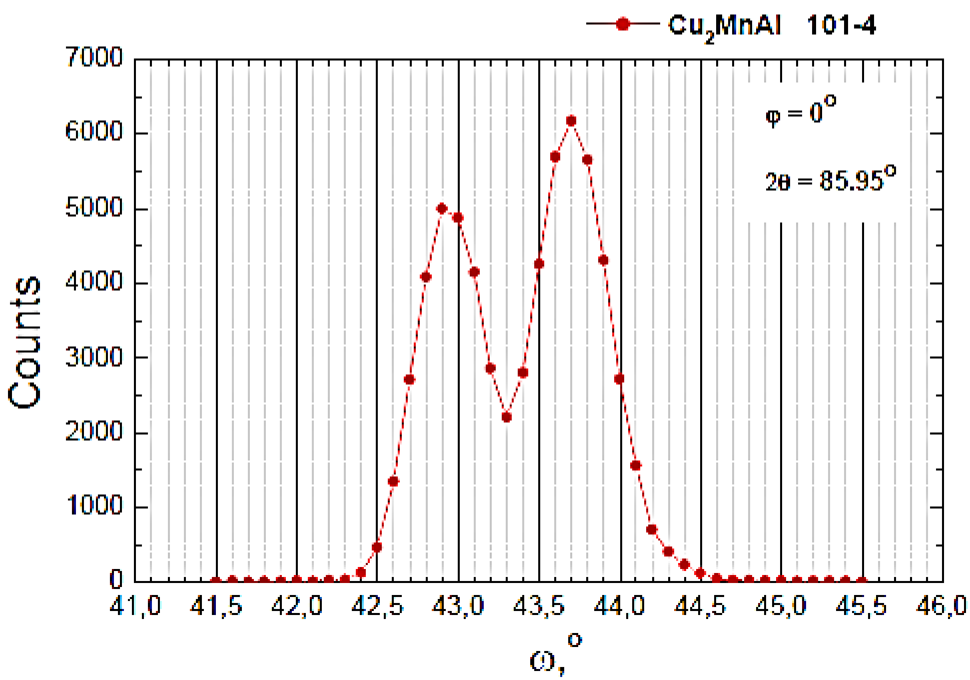
https://www.psi.ch/sinq/hrpt/neutron-diffraction-practicum

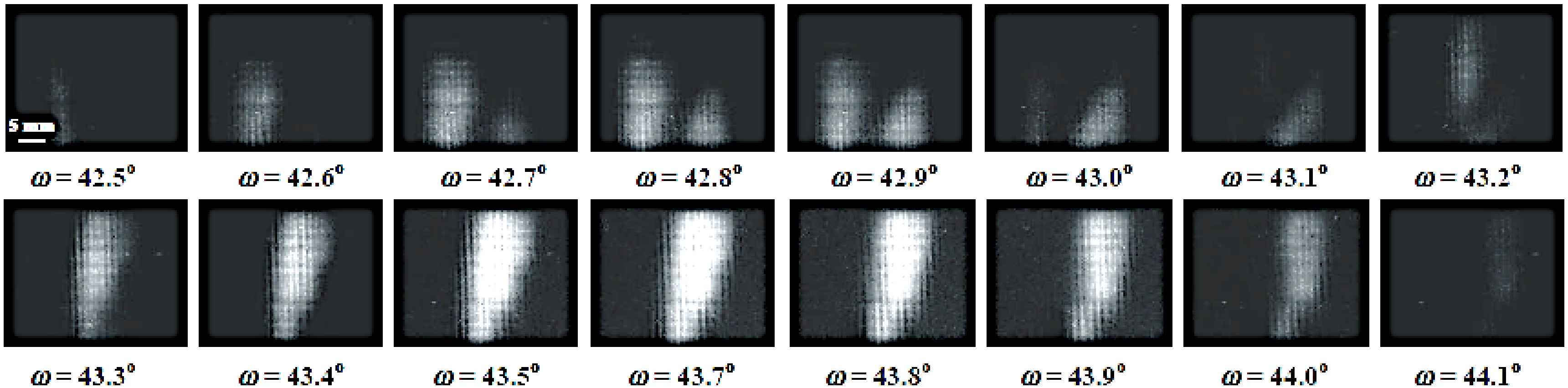
Topography


SHUTTER
TOPSI 1,7t
monochromator
camera
detector
collimators
sample
3He detector

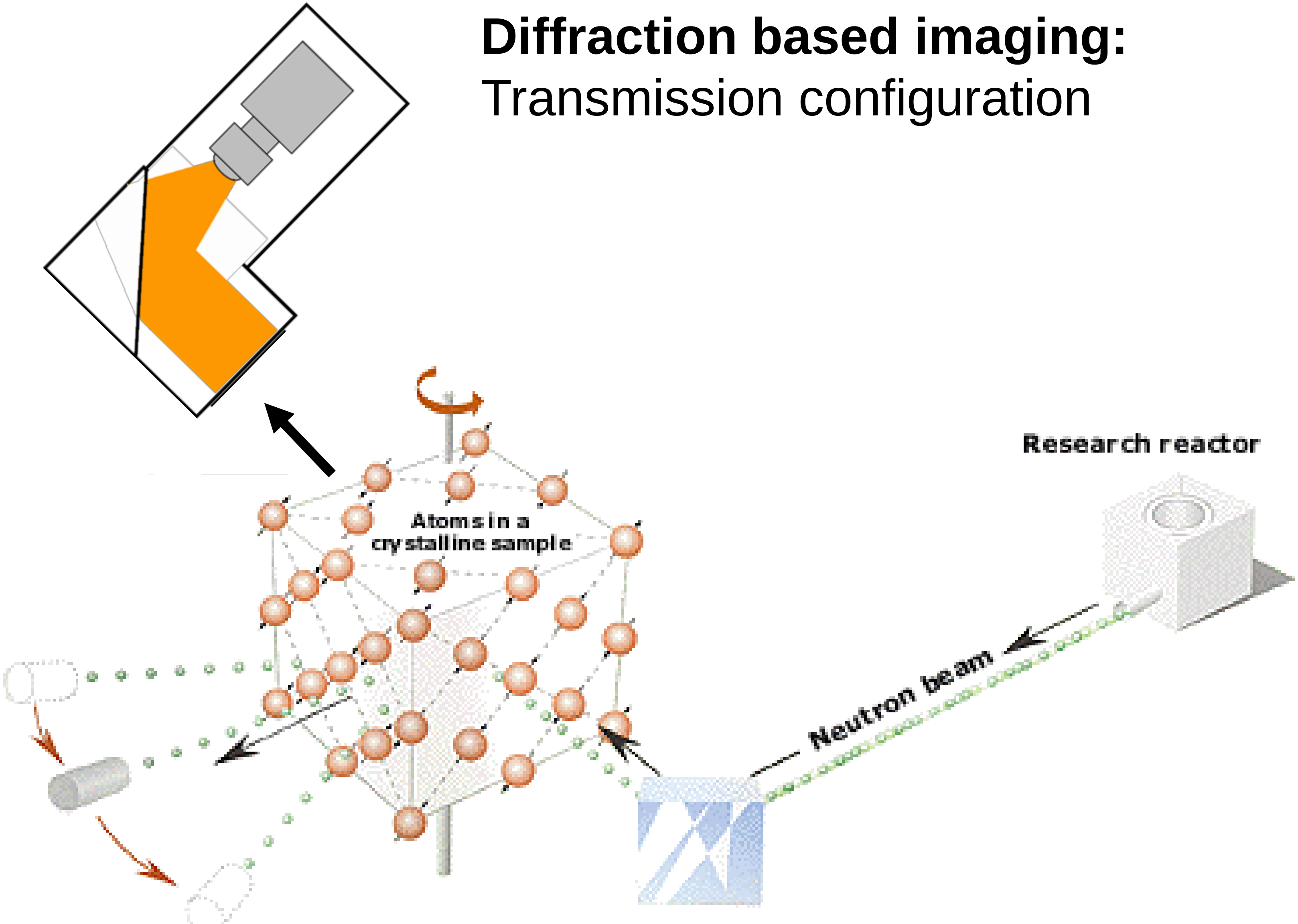
Topography

Figure 4.8 c:
TOPSI Diffractometer, PSI
λ = 4.74 Å
Sample: Cu_2MnAl Crystal with two domains
Date: 26.06.2001





Diffraction based imaging:
Transmission configuration



https://www.psi.ch/sinq/hrpt/neutron-diffraction-practicum

Beam monochromatisation

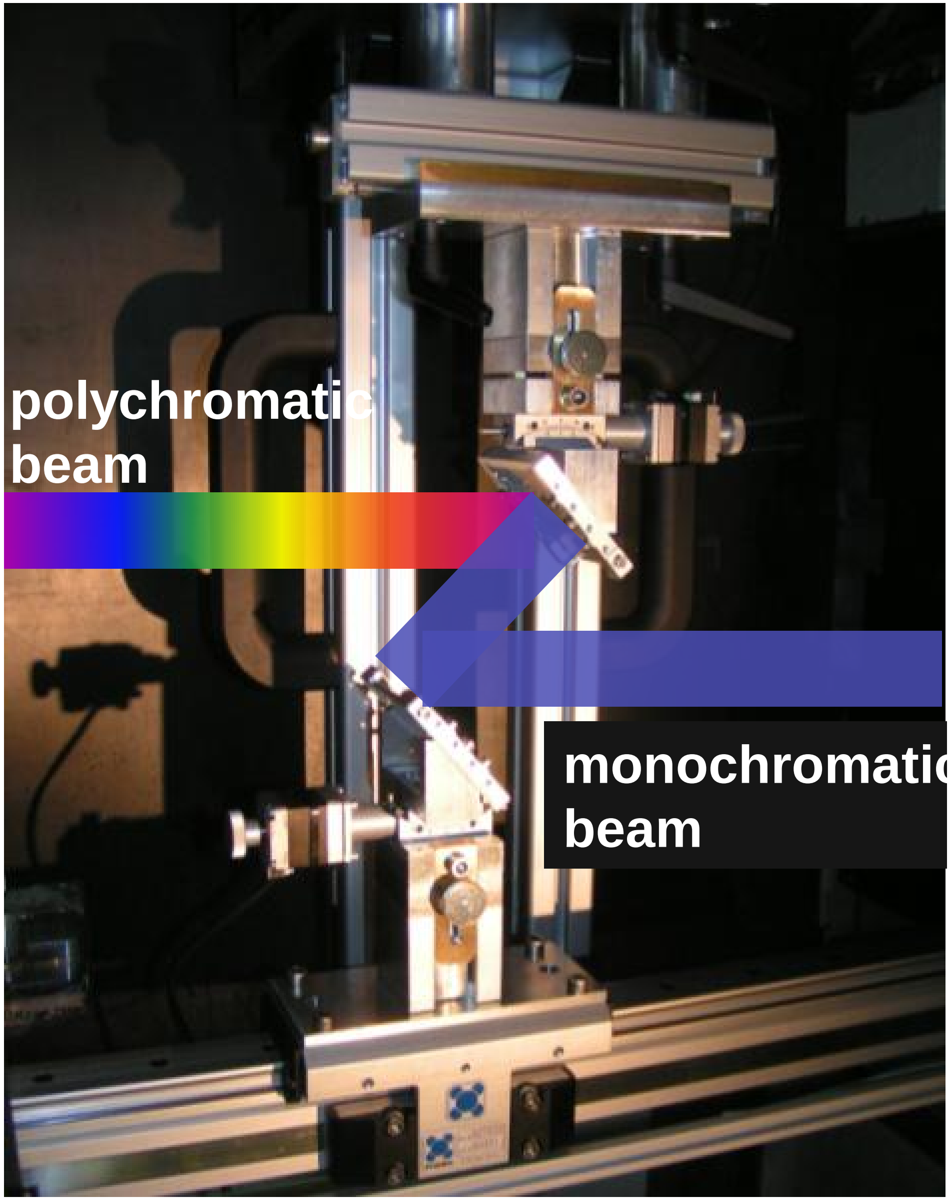
Double crystal monochromator: PCG crystals (mosaicity of 0.8°)

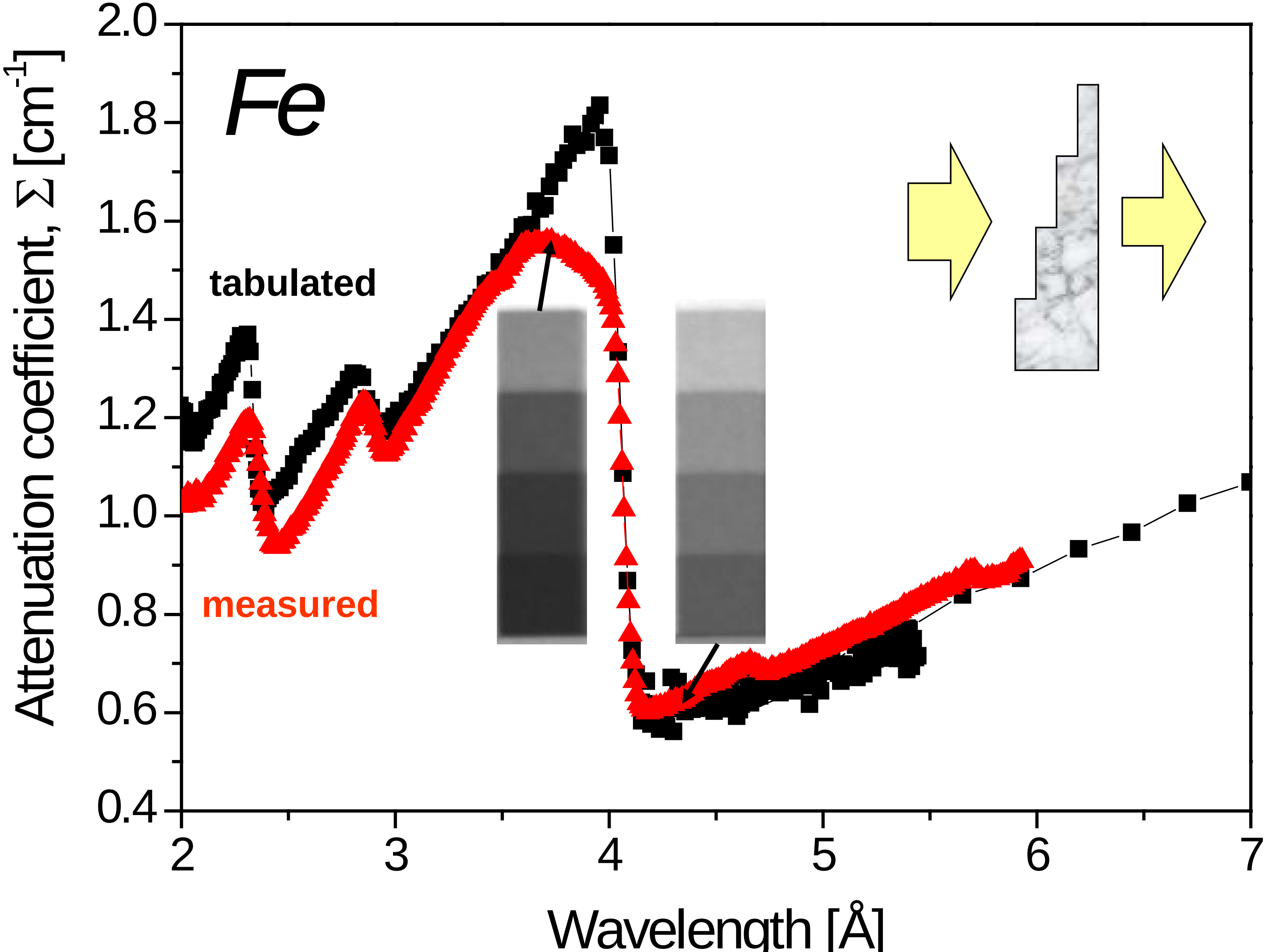
Range: 2.0 – 6.5 Å

Resolution ($\Delta\lambda/\lambda$): ~ 3%

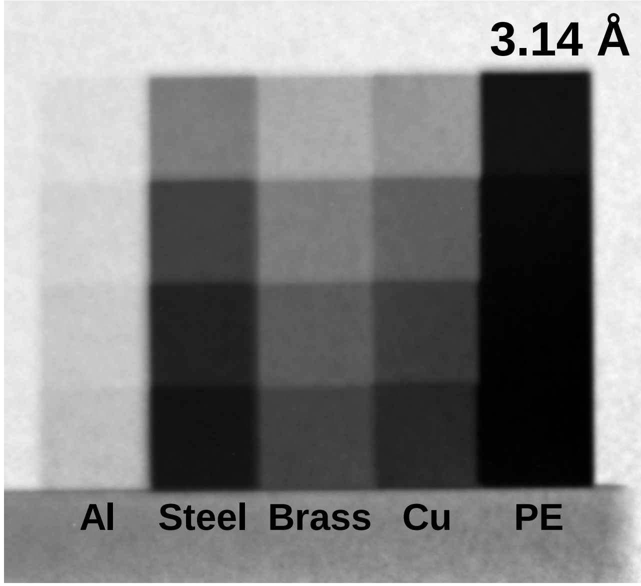
Neutron flux: ~ 4×10^5 n/cm^{2}s (at λ=3.0 Å)

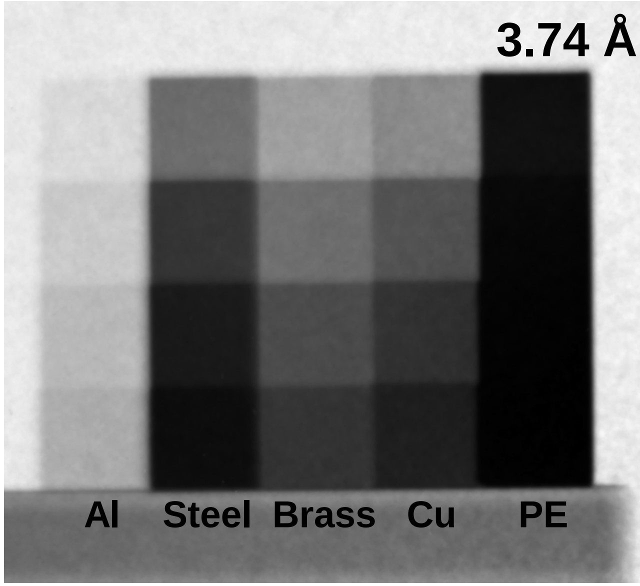
Beam size: 5 x 20 cm^2

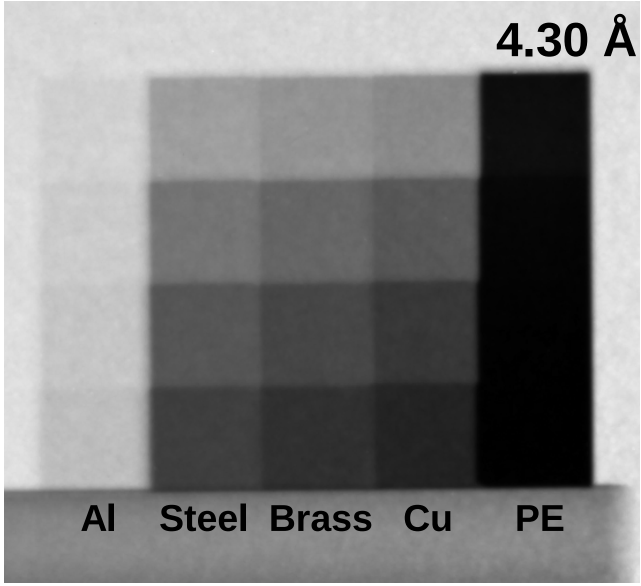


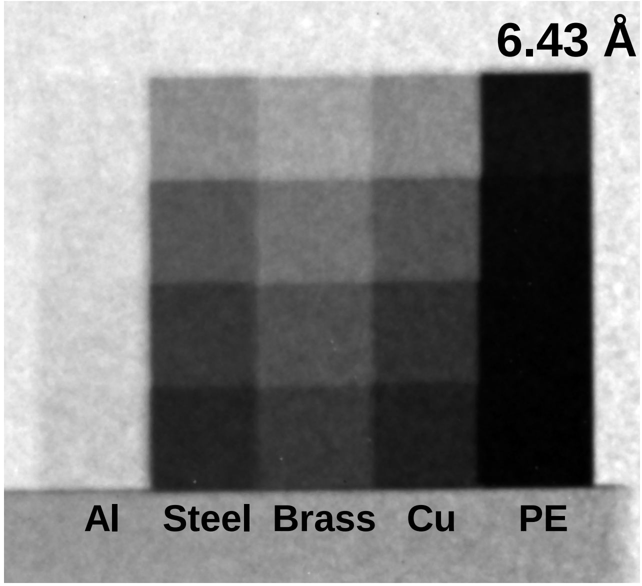


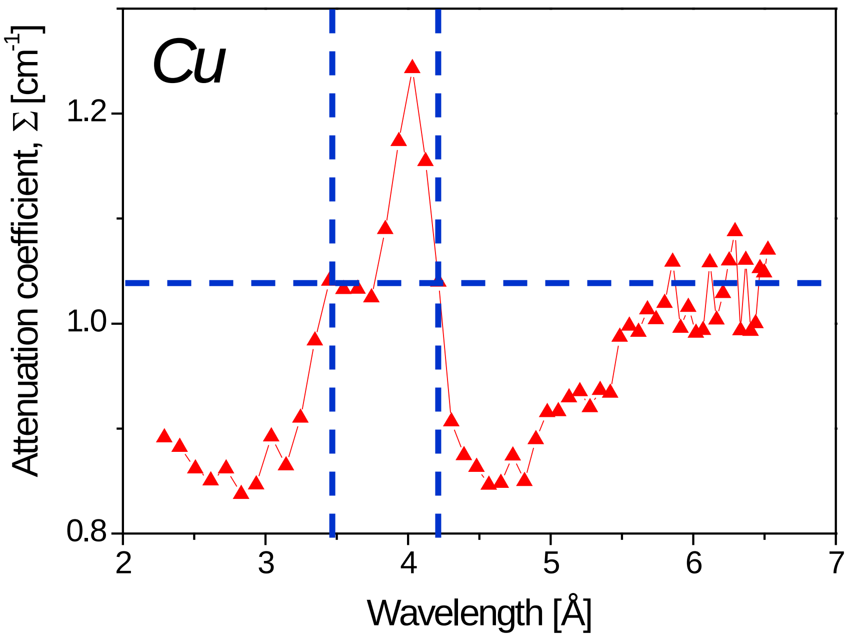
Fe
tabulated
measured
Attenuation coefficient, Σ [cm-1]
Wavelength [Å]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
2
3
4
5
6
7

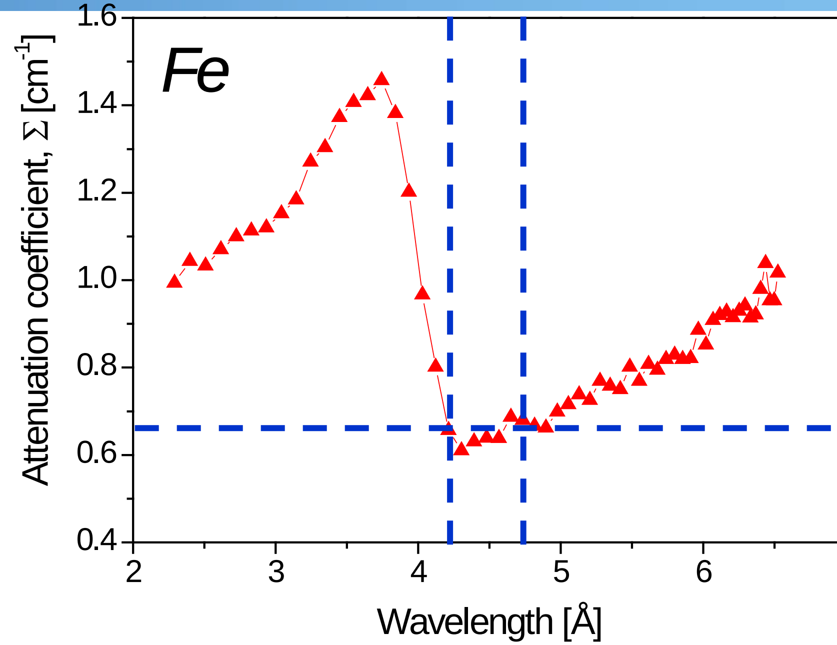

3.14 Å
Al
Steel
Brass
Cu
PE

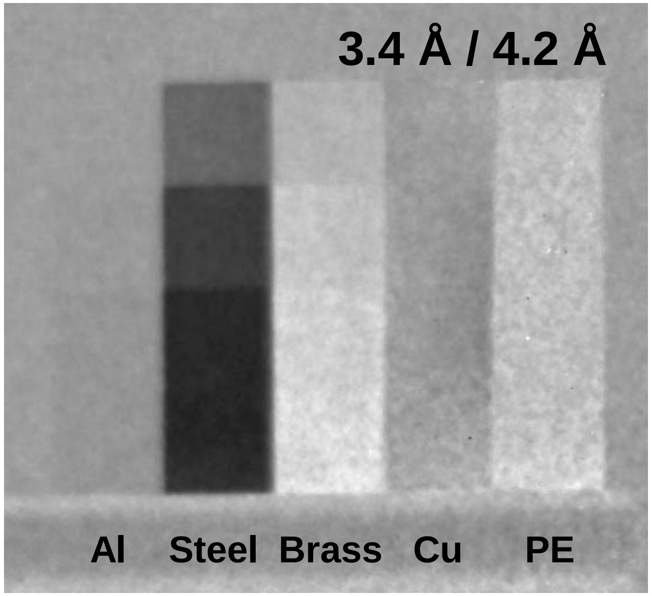

3.74 Å
Al
Steel
Brass
Cu
PE

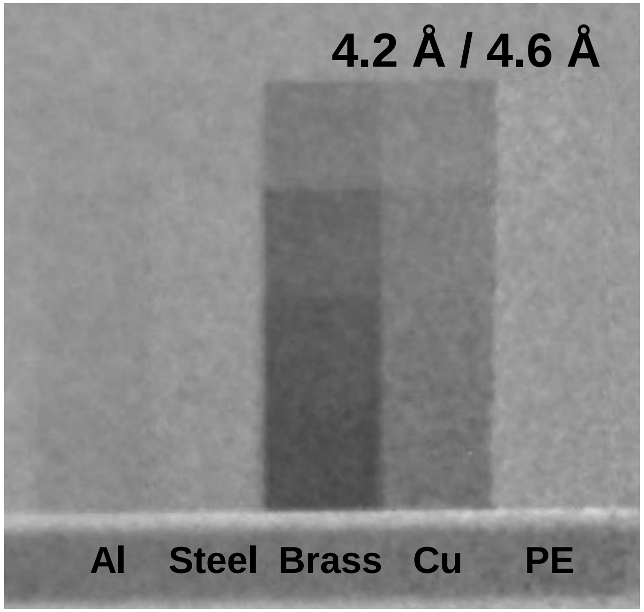

4.30 Å
Al
Steel
Brass
Cu
PE


6.43 Å
Al
Steel
Brass
Cu
PE

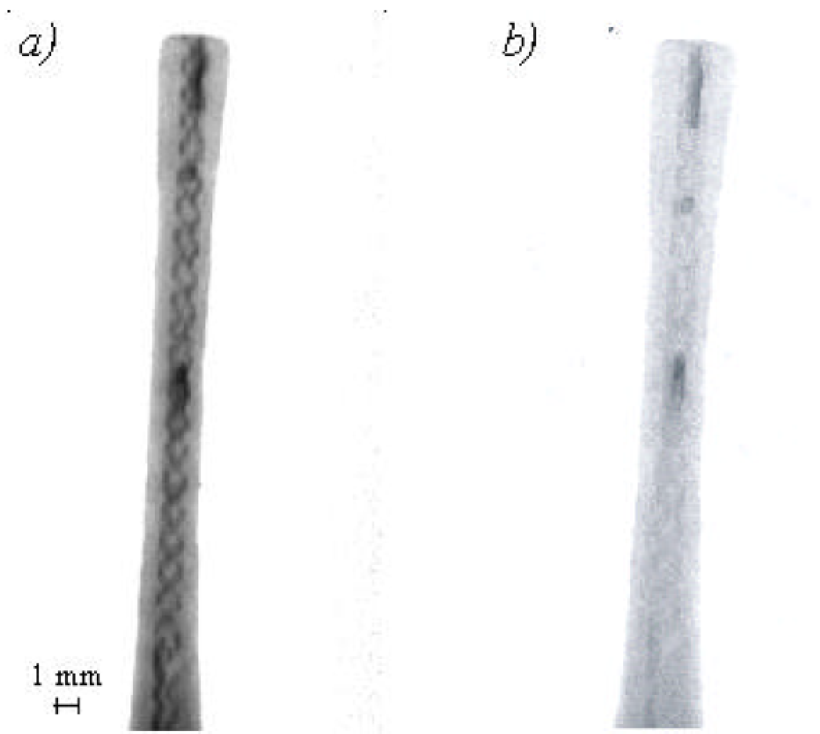

Cu
Attenuation coefficient, Σ [cm-1]
Wavelength [Å]
0.8
1.0
1.2
2
3
4
5
6
7

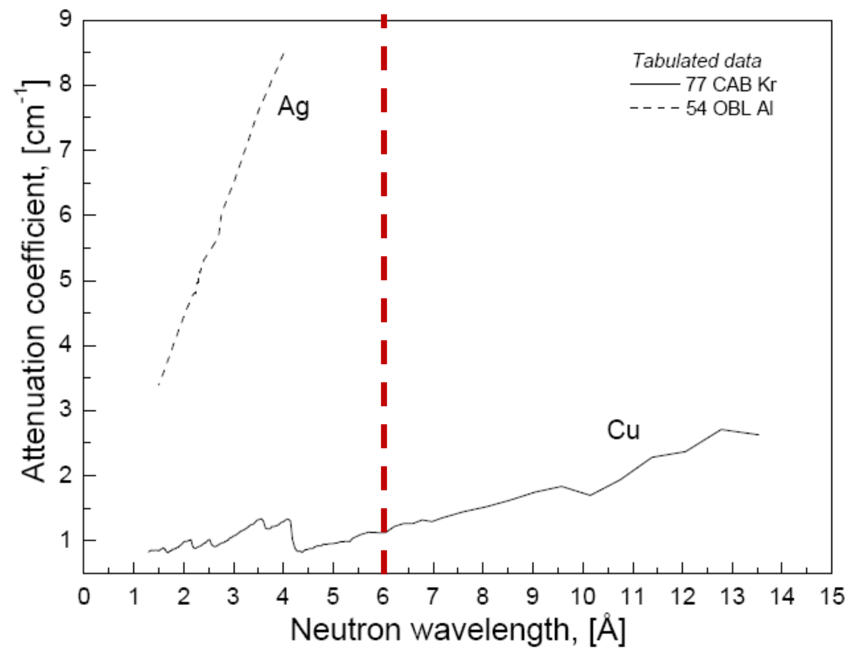

Fe
Attenuation coefficient, Σ [cm-1]
Wavelength [Å]
0.4
0.6
0.8
1.0
1.2
1.4
1.6
2
3
4
5
6
7


3.4 Å / 4.2 Å
Al
Steel
Brass
Cu
PE


4.2 Å / 4.6 Å
Al
Steel
Brass
Cu
PE

Contrast enhancement (Velocity selector)

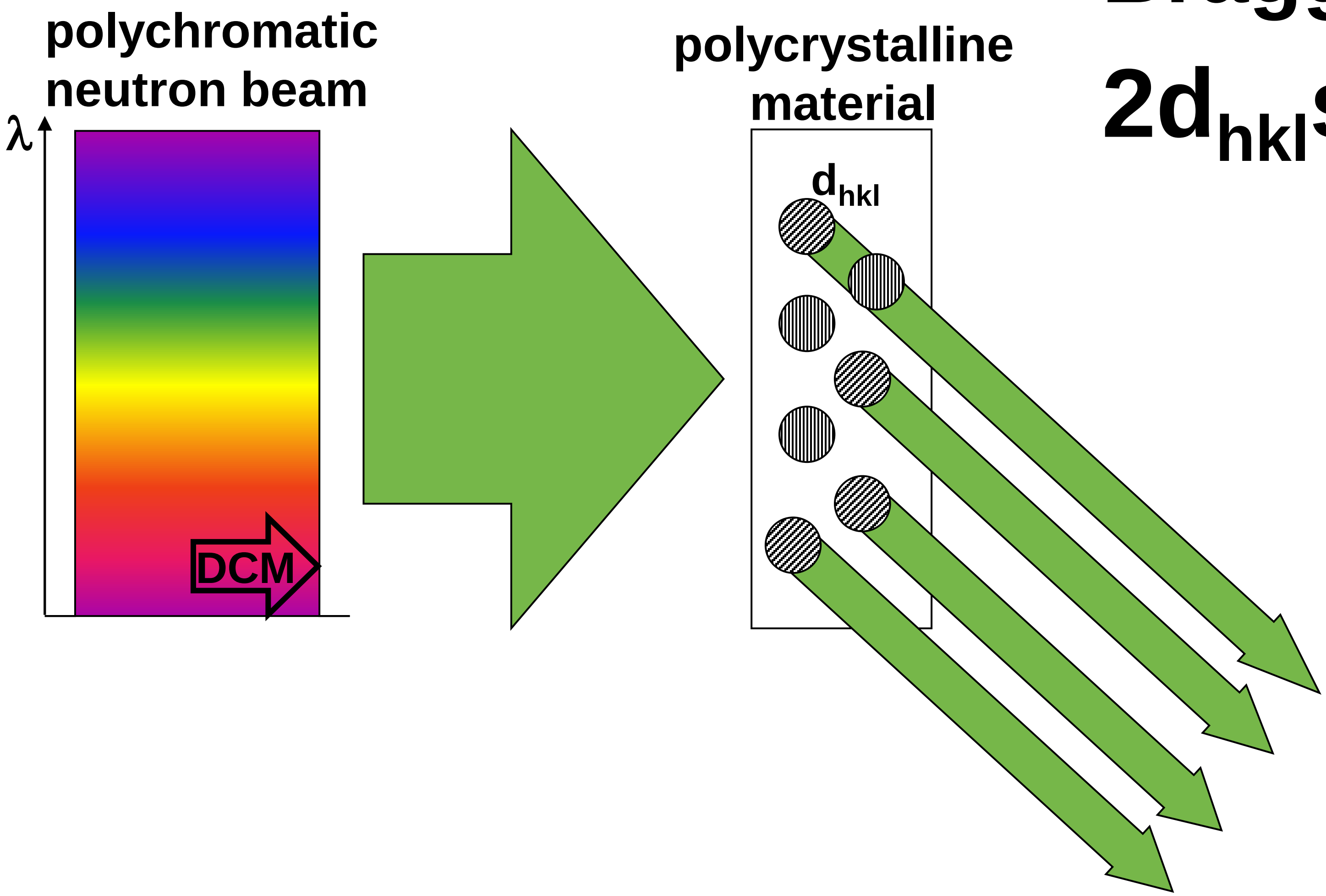




Radiographs of an ancient roman brooch taken with a) energy selective neutron radiography – 6 Å and b) standard thermal neutron radiography technique – NEUTRA (Courtesy of the Museum Aventicum, Switzerland).

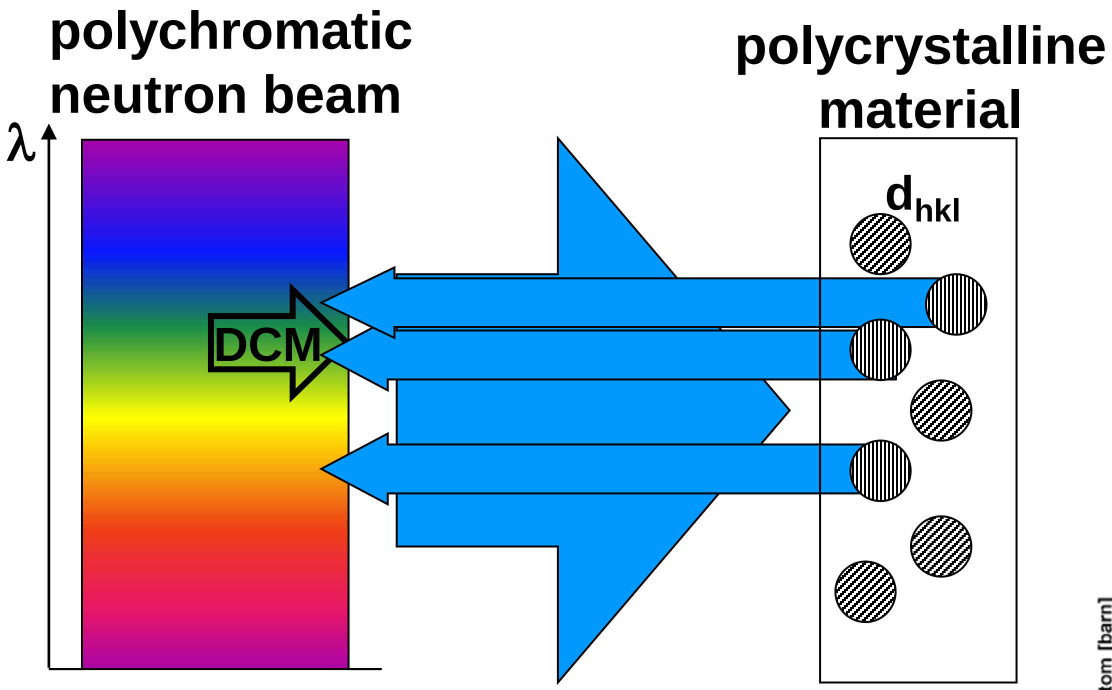
Kardjilov, N., et al.
***Nuclear Instruments and Methods in Physics Research Section A* 501.2-3 (2003): 536-546.**

Coherent scattering – Bragg edges



Bragg‘s law

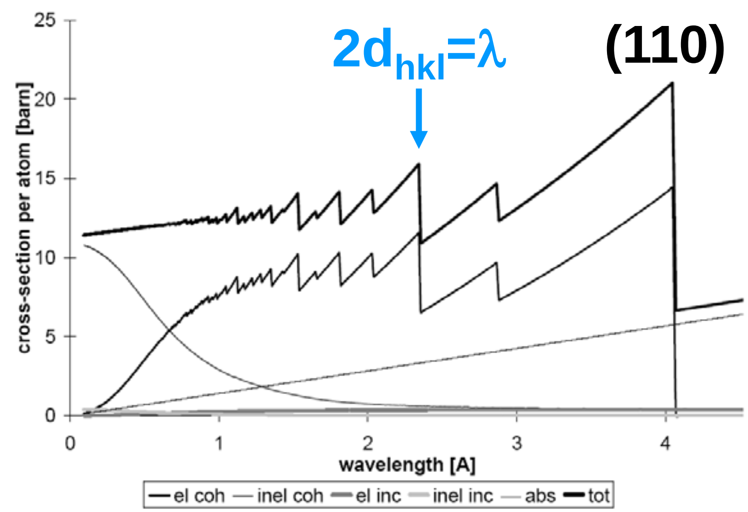
$$2d_{hkl}\sin\theta=\lambda$$



Bragg's law

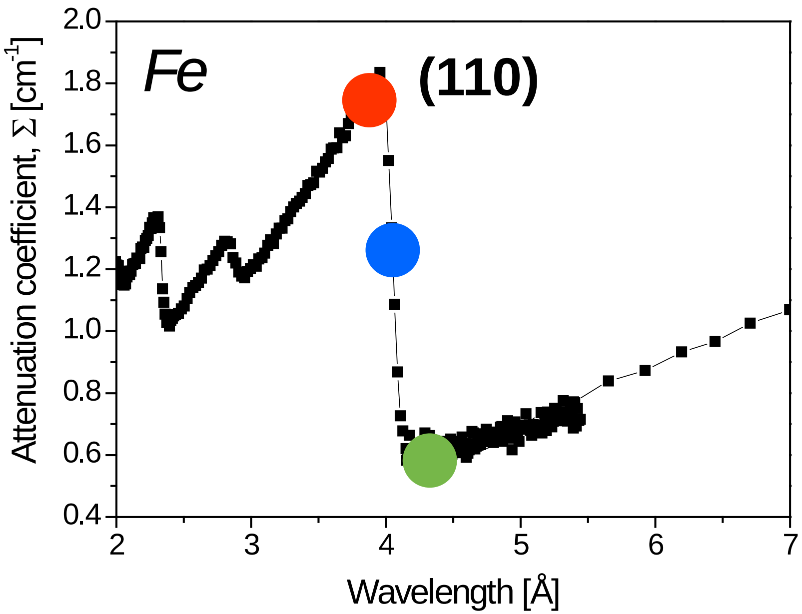
$$2d_{hkl}\sin 90° = \lambda$$

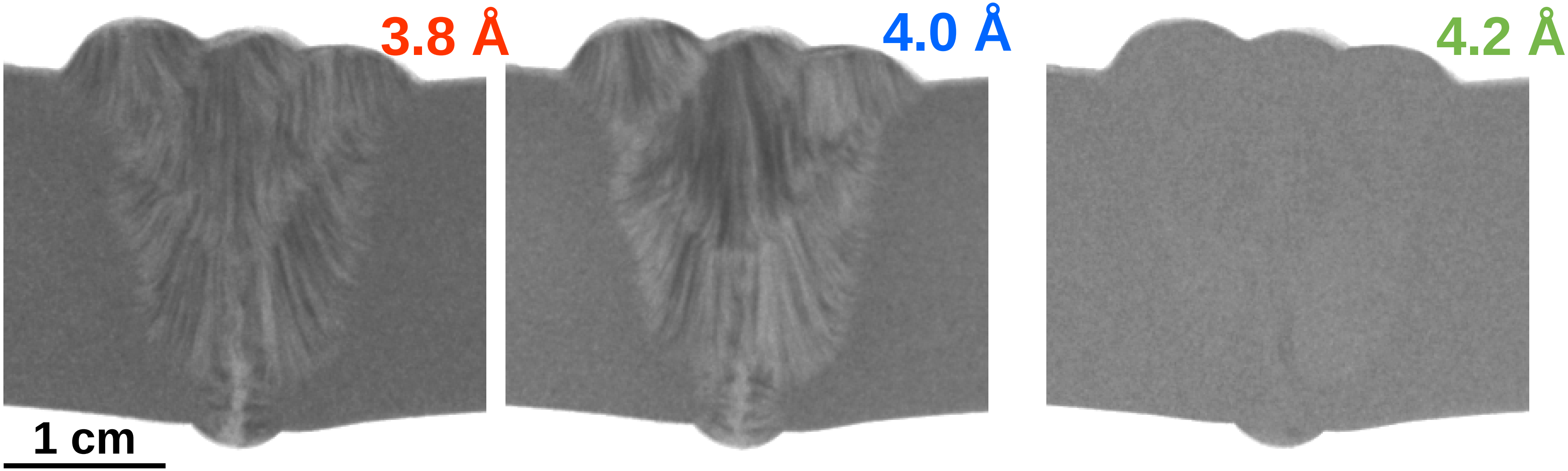
Cross-sections of iron per ator



Energy-selective radiography

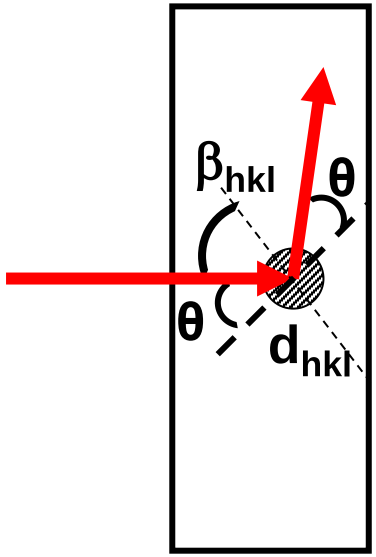
Welded joint (photo)



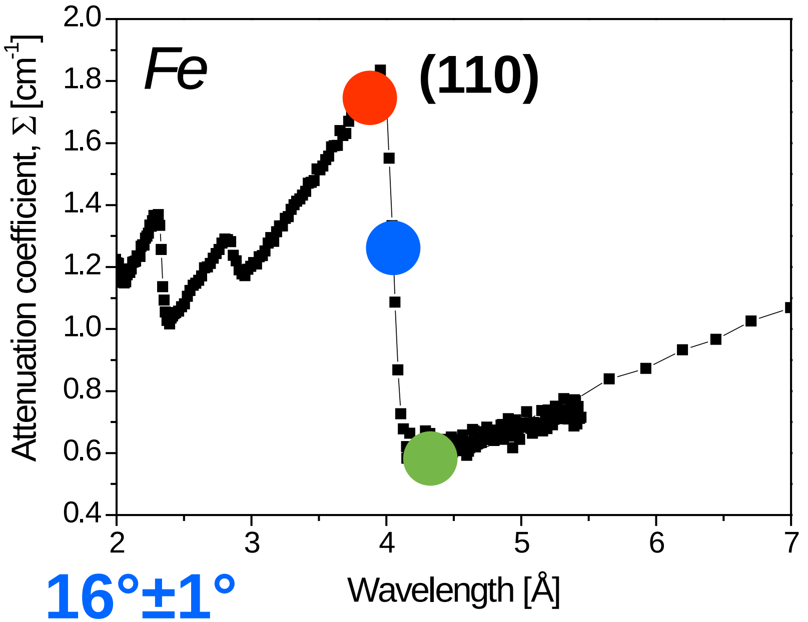


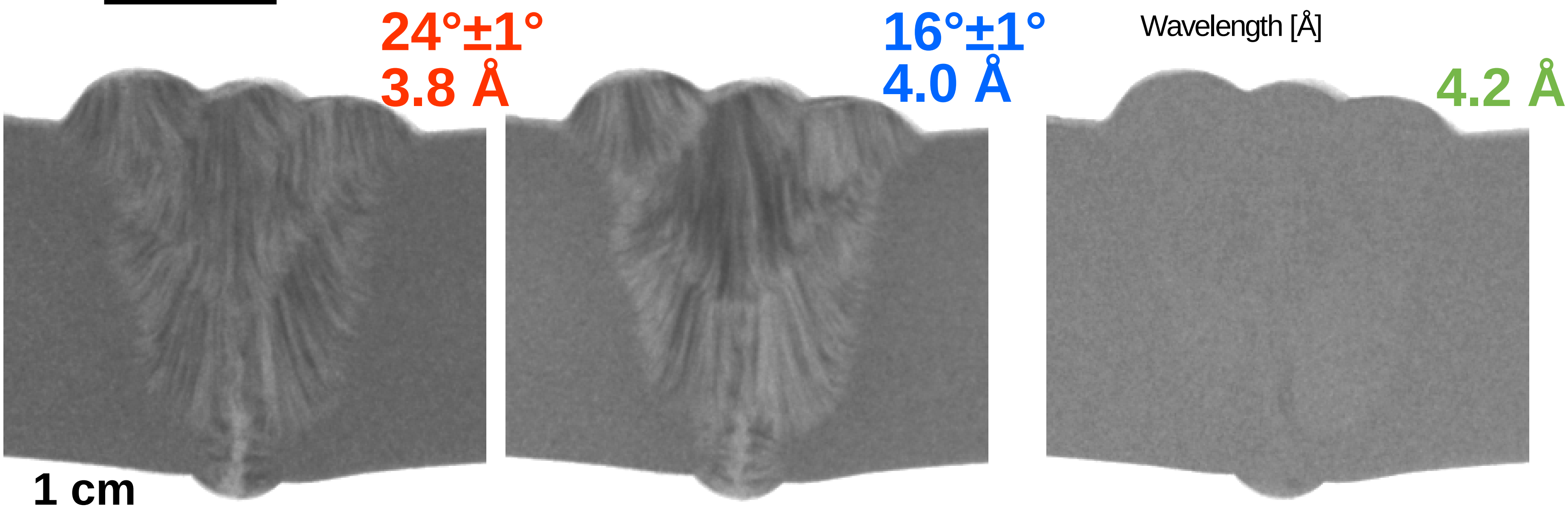
Lehmann, E. H., et al. *Nuclear Instruments and Methods in Physics Research Section A:* 603.3 (2009): 429-438.

Energy-selective radiography



$$\beta_{hkl} = \frac{\pi}{2} - \arcsin\left(\frac{\lambda}{2d_{hkl}}\right)$$

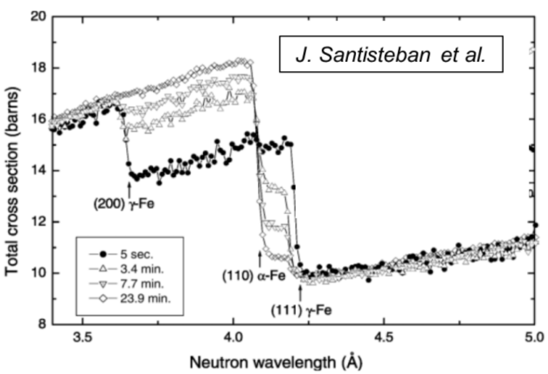


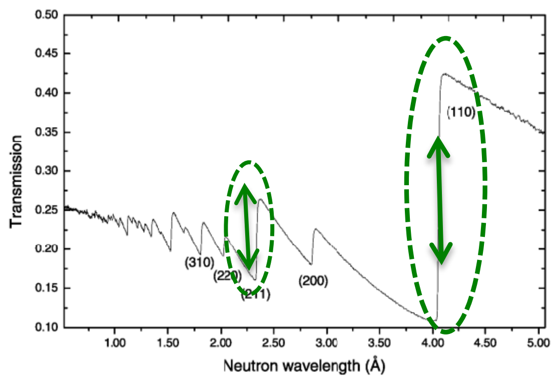


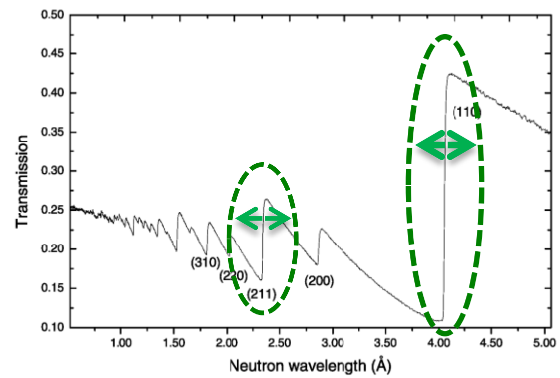
Lehmann, E. H., et al. *Nuclear Instruments and Methods in Physics Research Section A:* 603.3 (2009): 429-438.

Neutron "Bragg Edge" Imaging: Applications

- **Record transmitted neutron beam energy resolved (TOF, tunable monochromator)**
- ***hkl* lattice spacing is probed in the direction of incoming beam and is "averaged" through thickness**
  - **Phase**
  - **Texture**
  - **Strain**



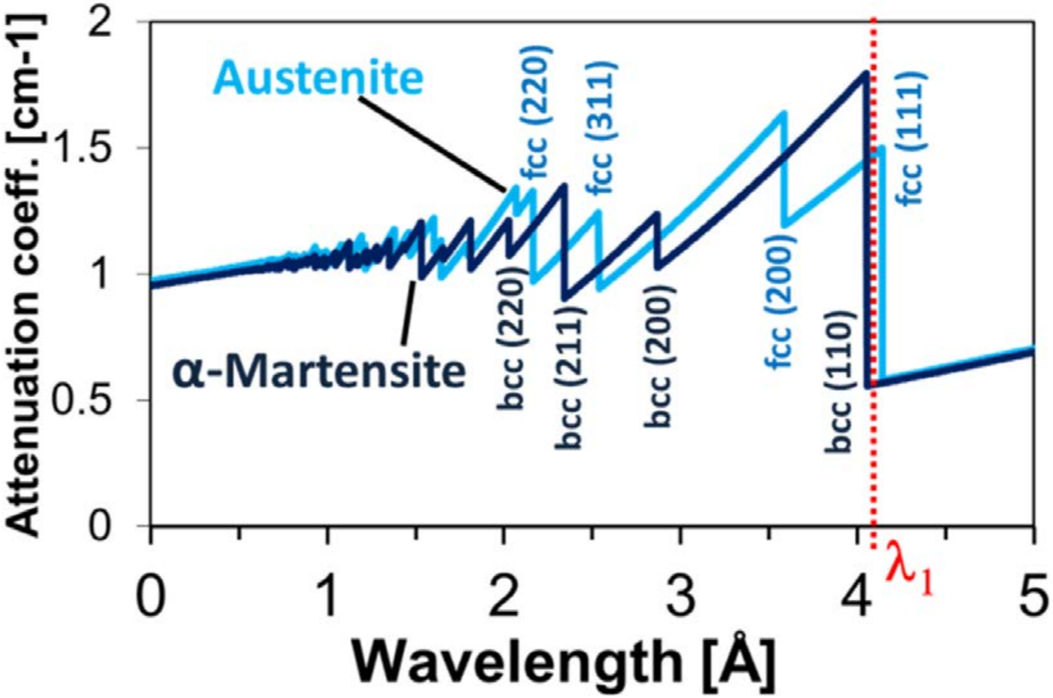


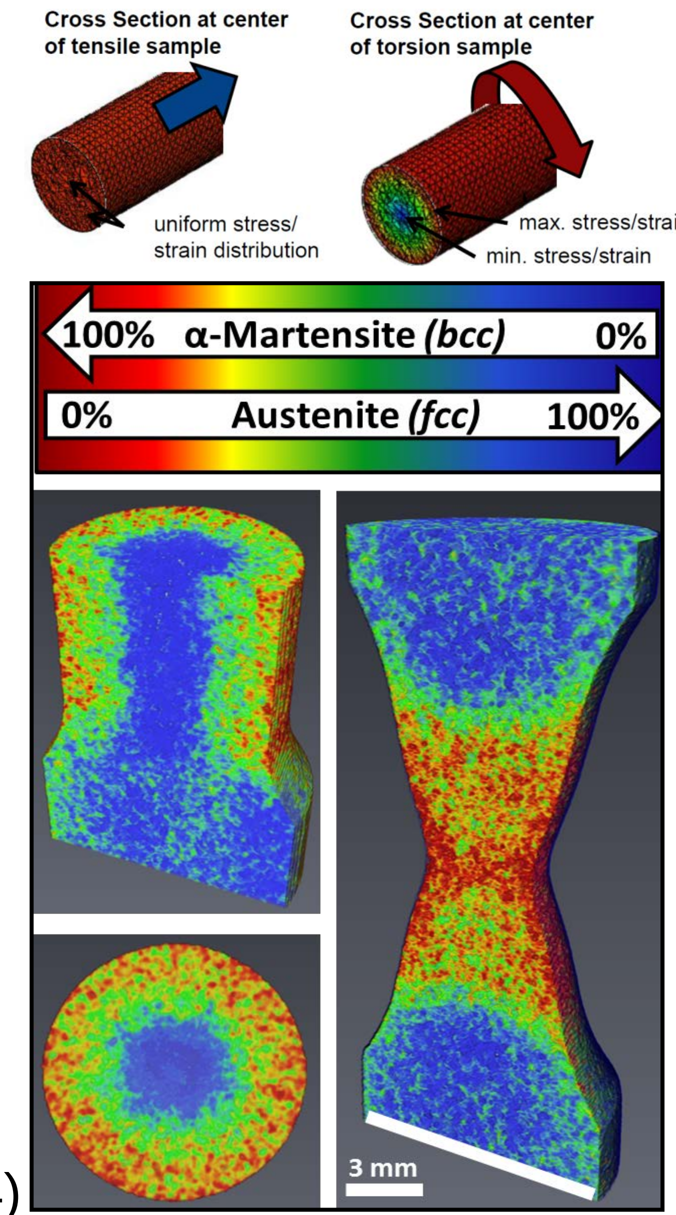


- Strain resolution of ~ 100με ($\Delta d_{hkl}/d_{hkl} \sim 1\cdot 10^{-4}$) desirable for engineering applications *(E.g.: for iron this corresponds to bragg peak shift of: $2\cdot\Delta d_{110} \sim 4\cdot 10^{-4}$Å)*

Diffraction Contrast

3D Phase mapping in metals

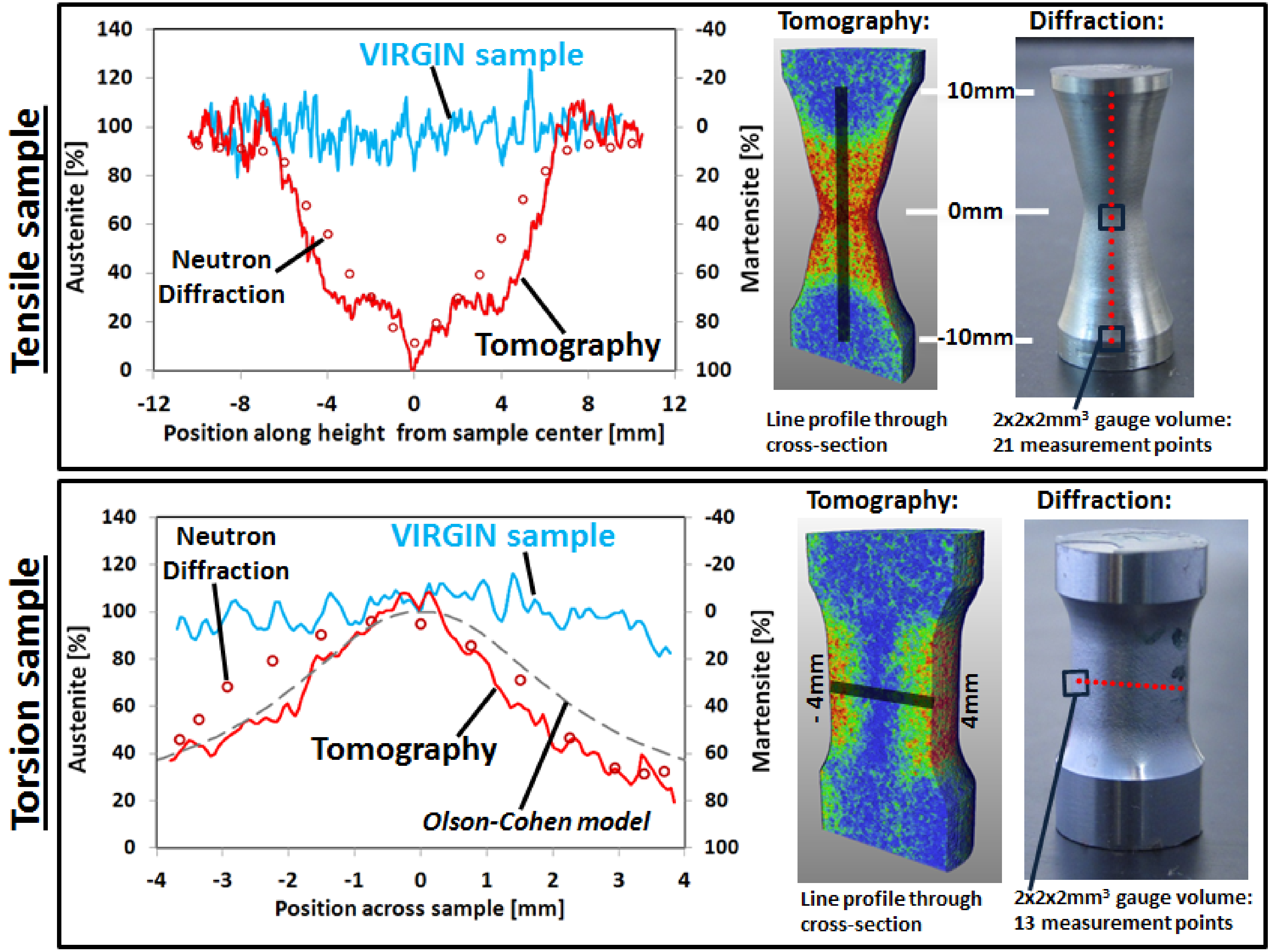




Energy-selective neutron tomography of TRIP-steel

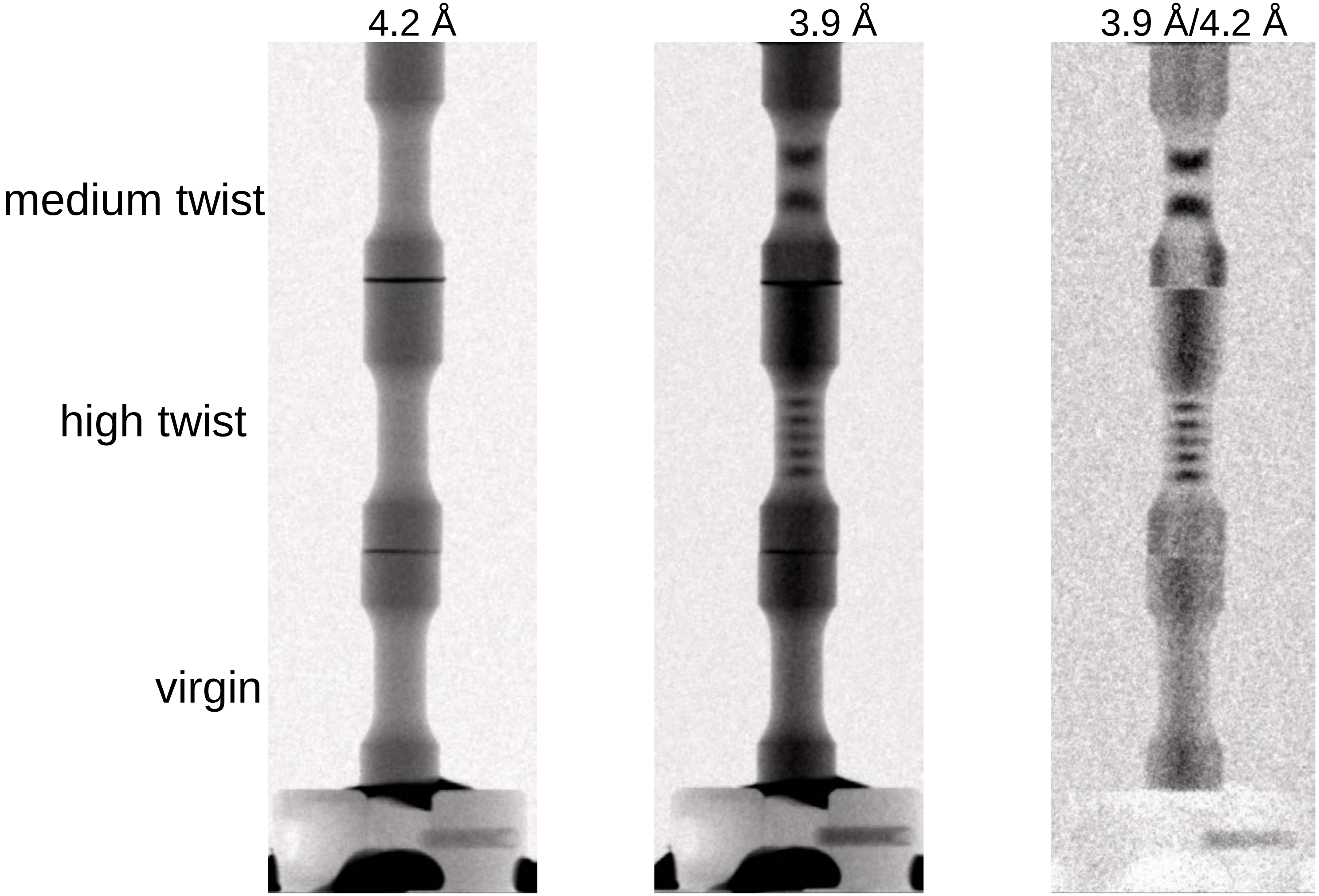
R. Woracek et al., **Advanced Materials** 26 (2014)

Diffraction Contrast



Diffraction Contrast

- Different set of torsion samples: Strong texture
- Difficult to study phase transformation in such samples for both imaging & diffraction methods (dominated by texture effect)



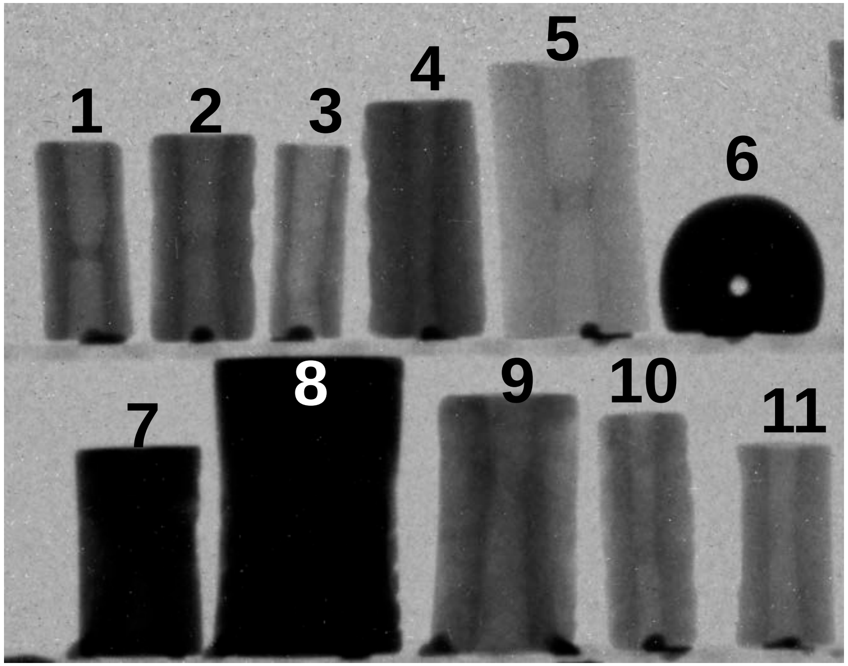
Diffraction Contrast

Mesopotamian Seals (from c. 2000 - 1600 BC)

(Theo Krispijn, *NINO Institute*, Dirk Visser, *Delft University of Techn*ology, Holland)

Photo

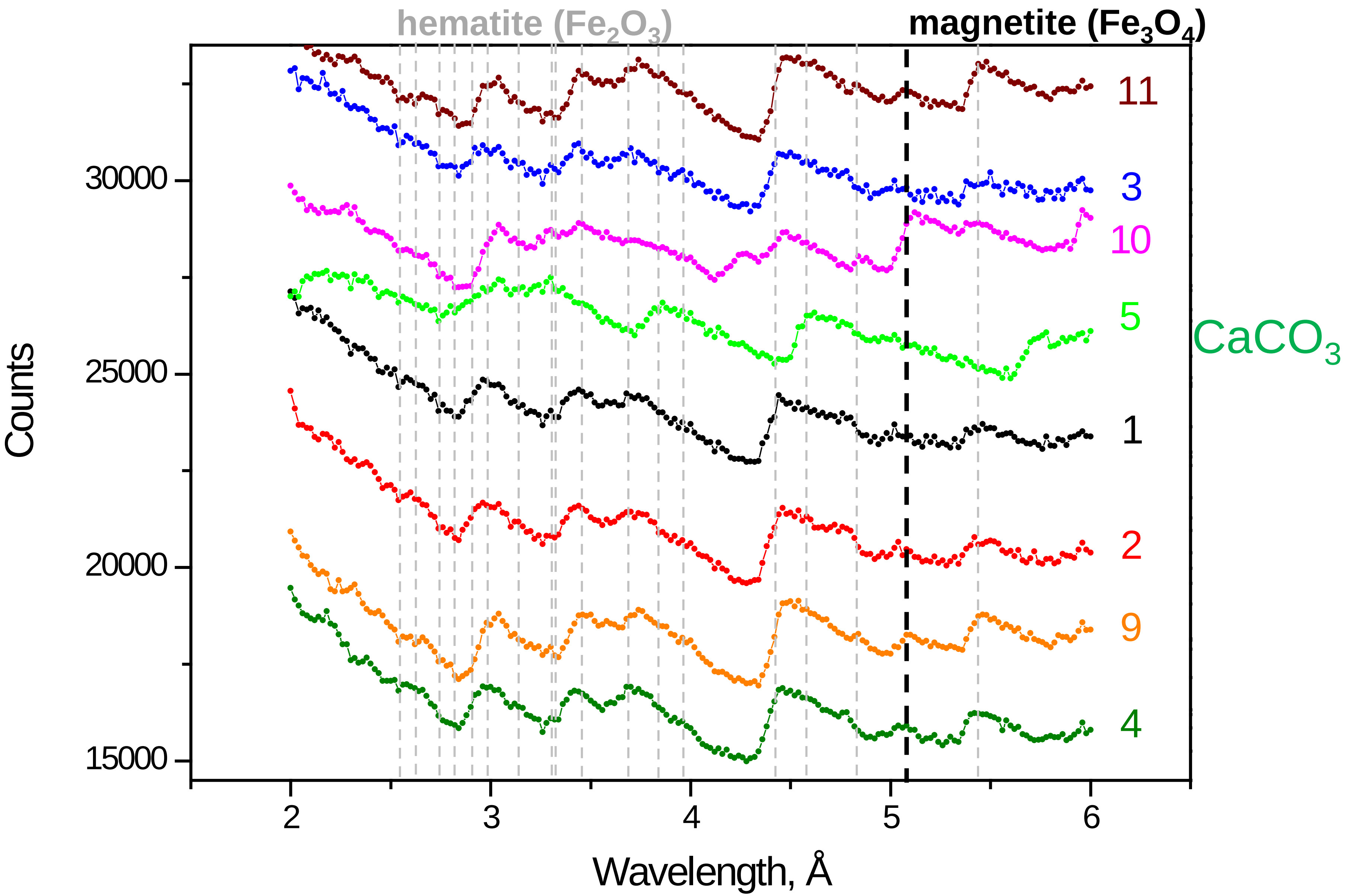
Neutron radiography



1 cm

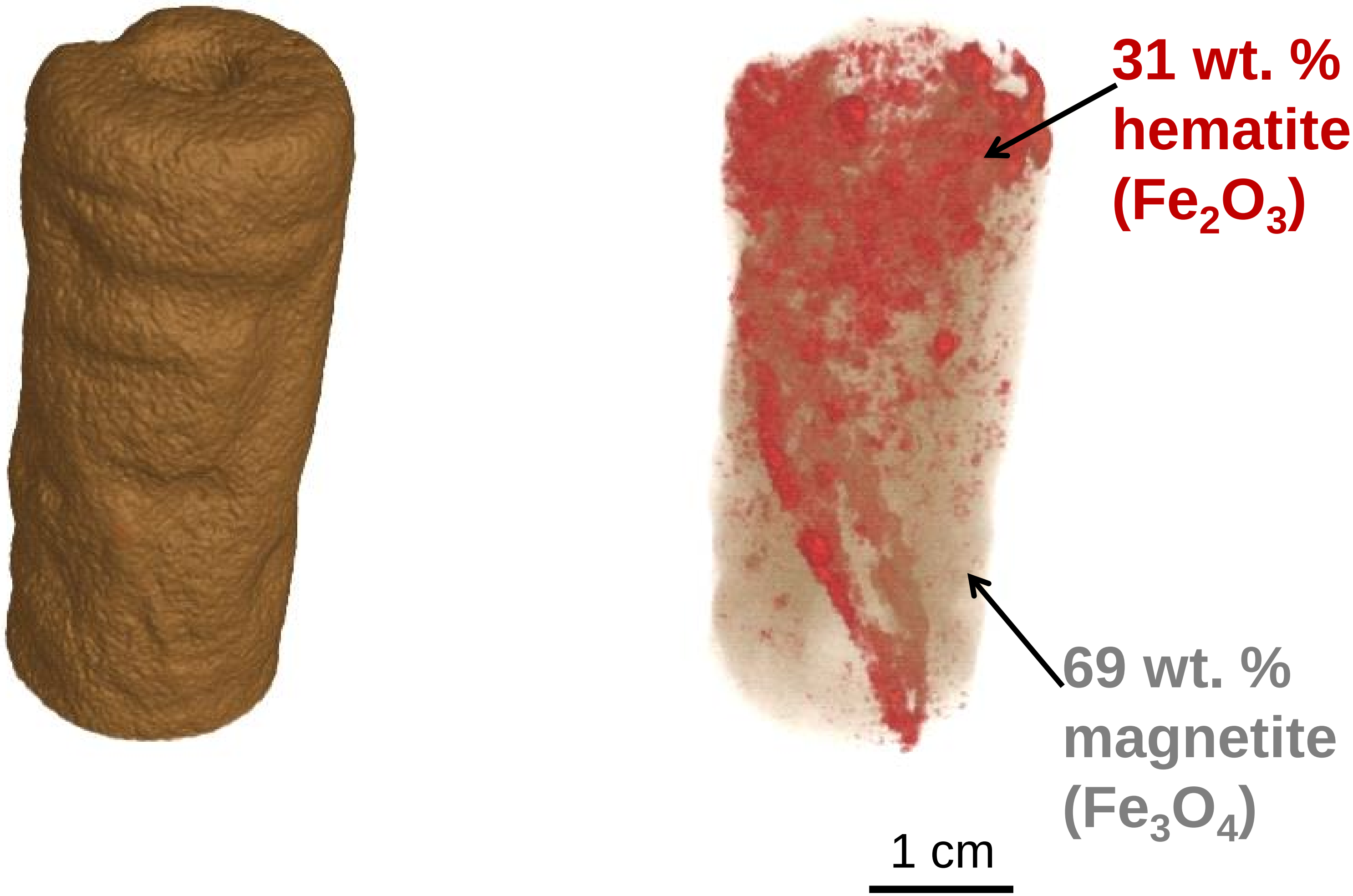
The De Liagre-Böhl collection of the Dutch Institute for the Near East (NINO) houses about 150 seals, 13 of which were visually identified as hematite. The seals were acquired in Iraq at the beginning of the last century.

Diffraction Contrast



Diffraction Contrast

Seal Nr. DLB 67 (De Liagre-Böhl collection)



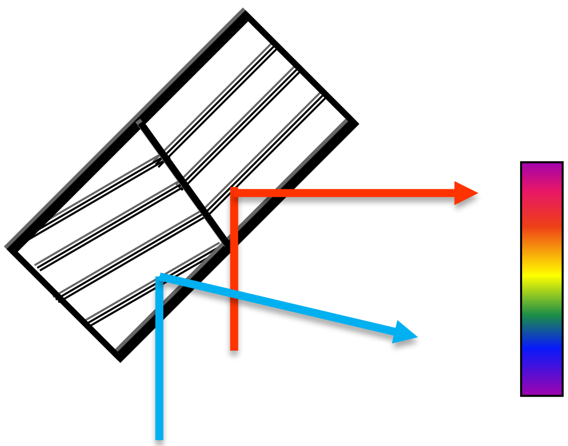
Wavelength gradient

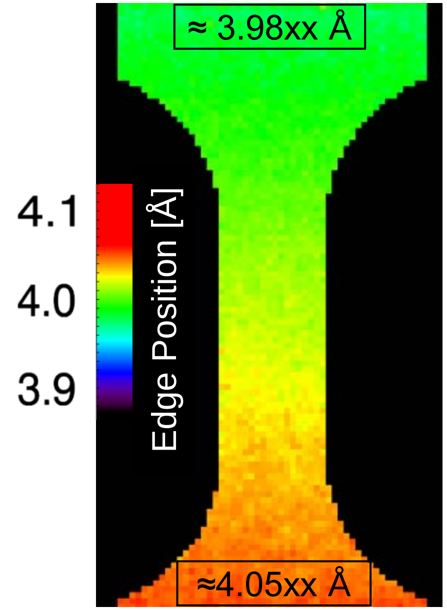
Advantages:

- good energy resolution (1 – 10 %)
- constant neutron flux
- no need for vacuum and cooling instalations

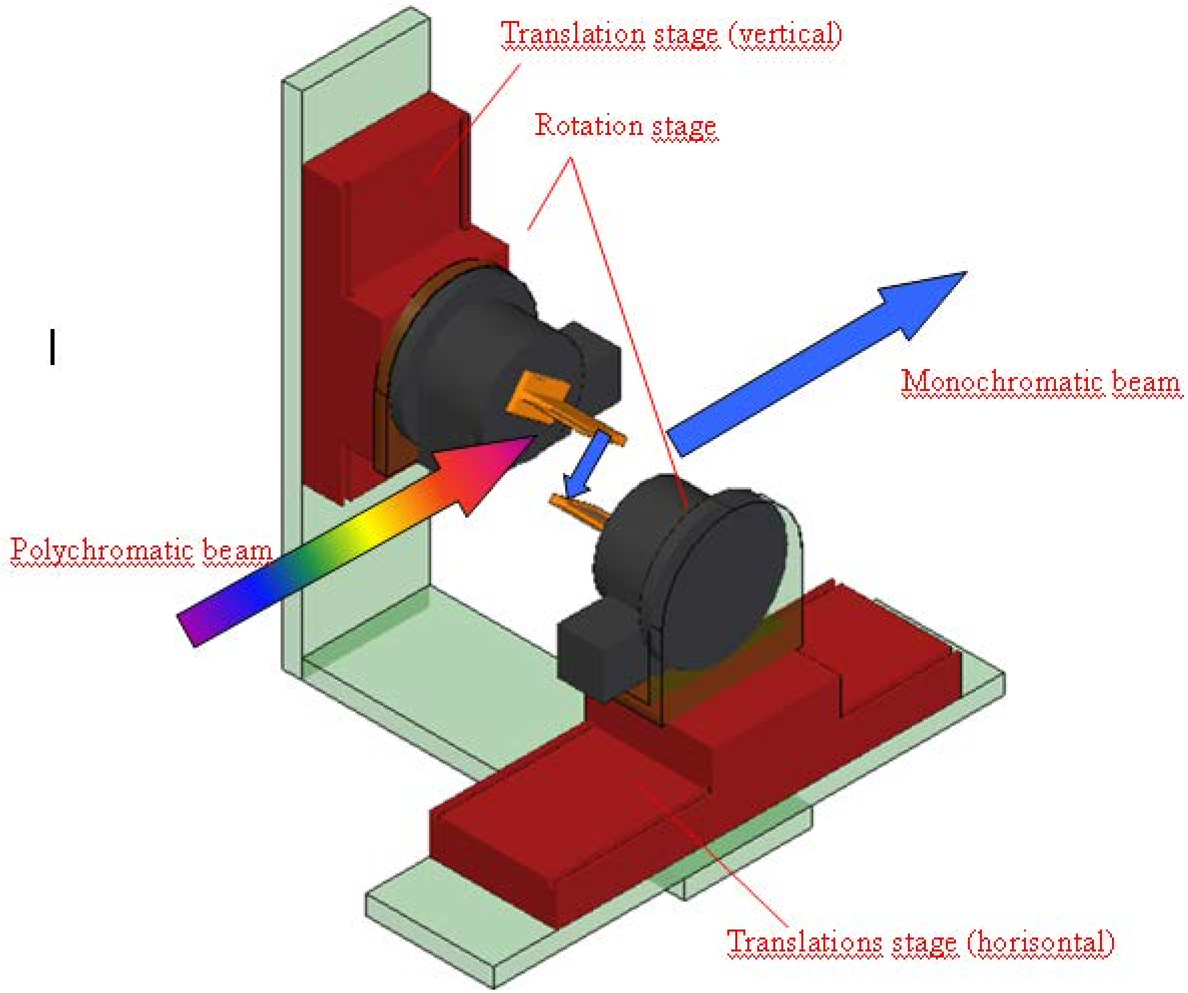
Disadvantages:

- mechanical instability
- wavelength gradient



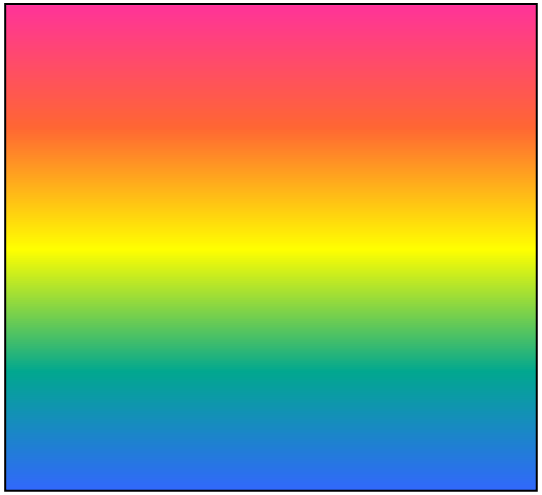


Wavelength gradient



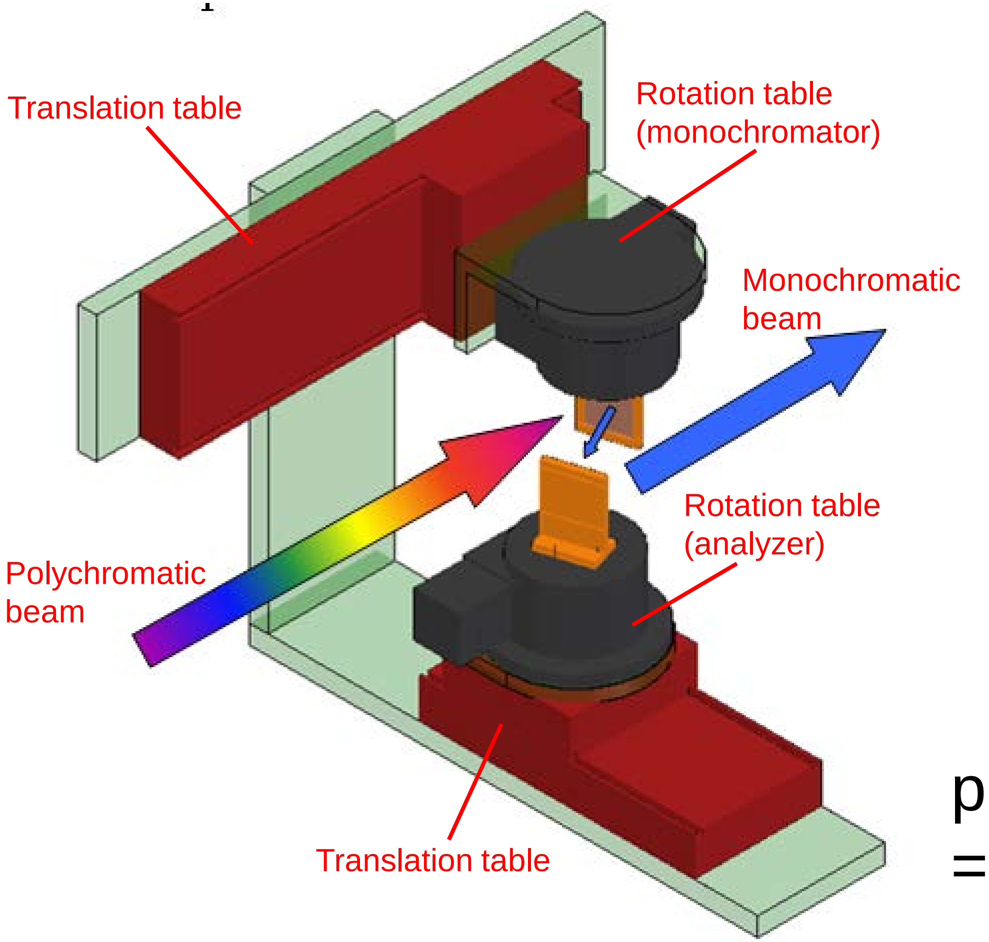
I

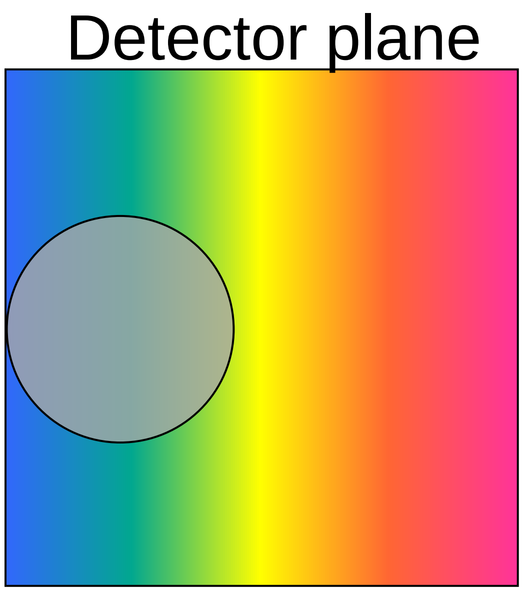
Detector plane



Wavelength gradient: ~ 0.006Å/cm

Wavelength gradient

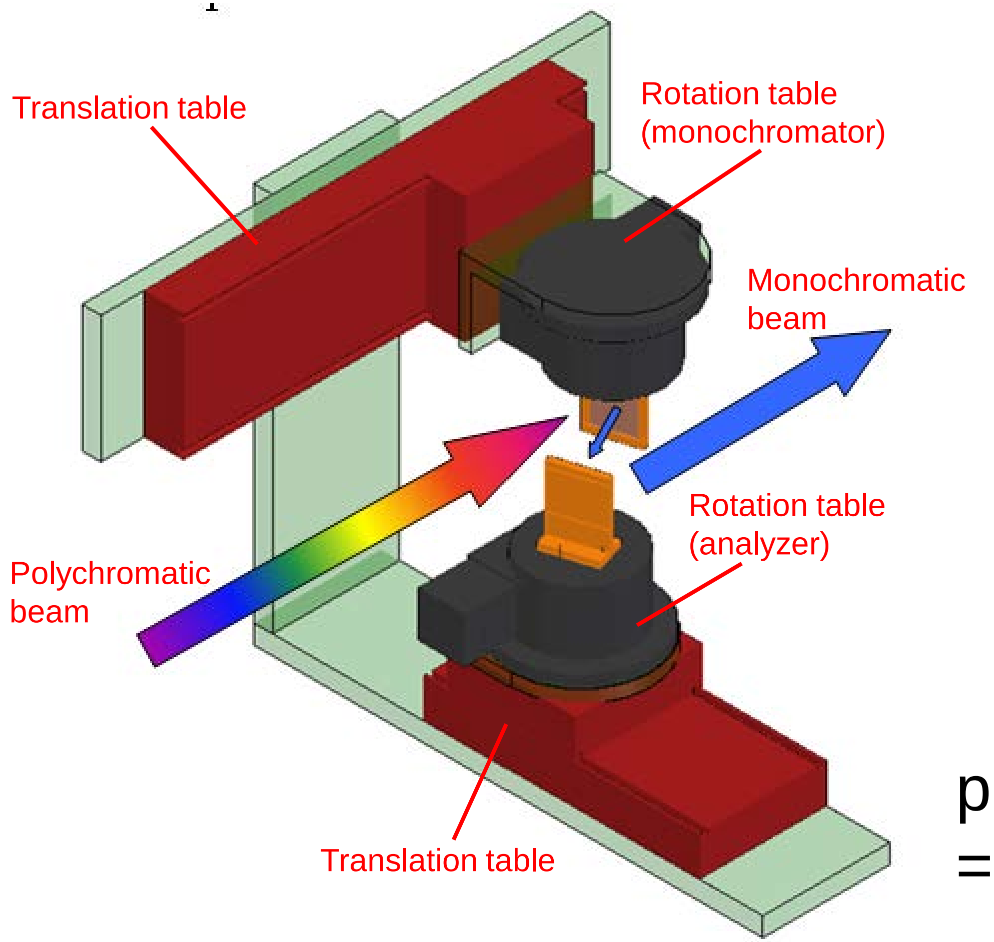


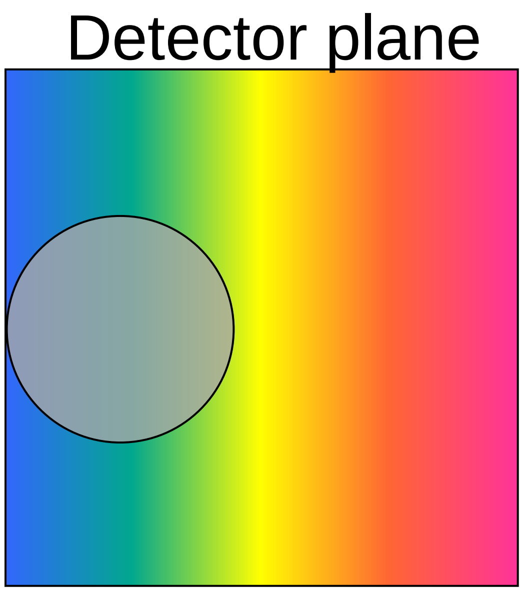


pixel size: 100 µm = 0.001 cm
=> 0.00006Å / pixel

Wavelength gradient: ~ 0.006Å/cm

Wavelength gradient





pixel size: 100 µm = 0.001 cm
=> 0.00006Å / pixel

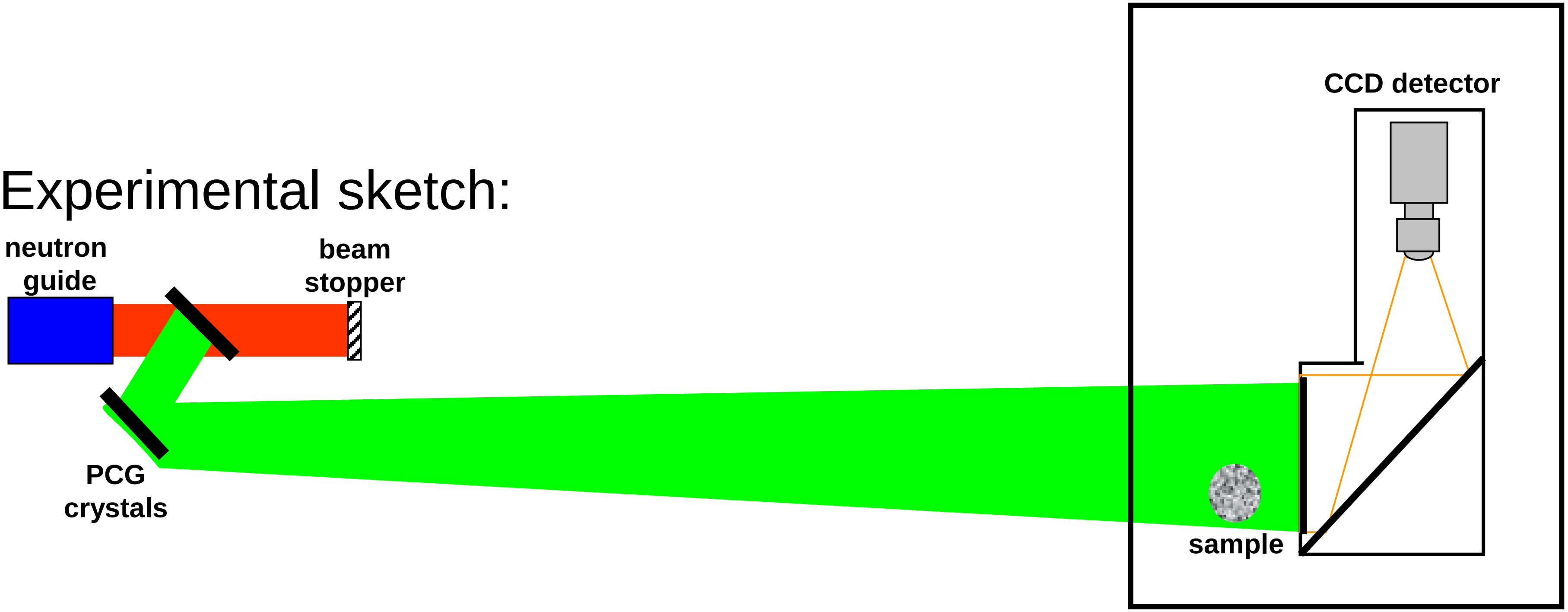
Wavelength gradient: ~ 0.006Å/cm

Wavelength gradient

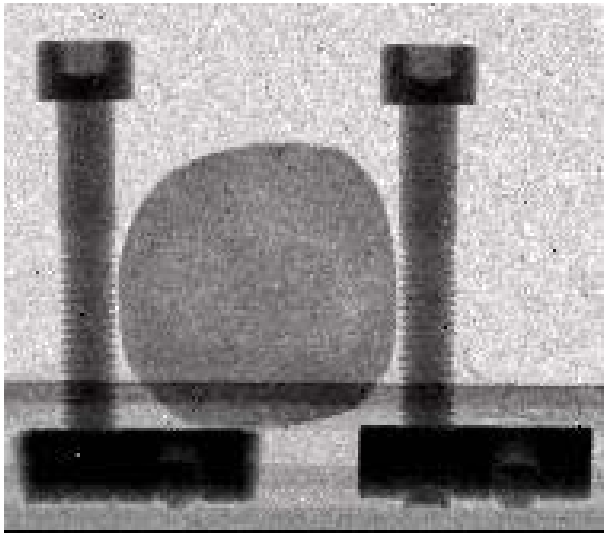
Maximal translation path: 300 mm
Variable scan speed: 0.01 – 200 mm/s
Position accuracy: ± 0.02 / 300 mm

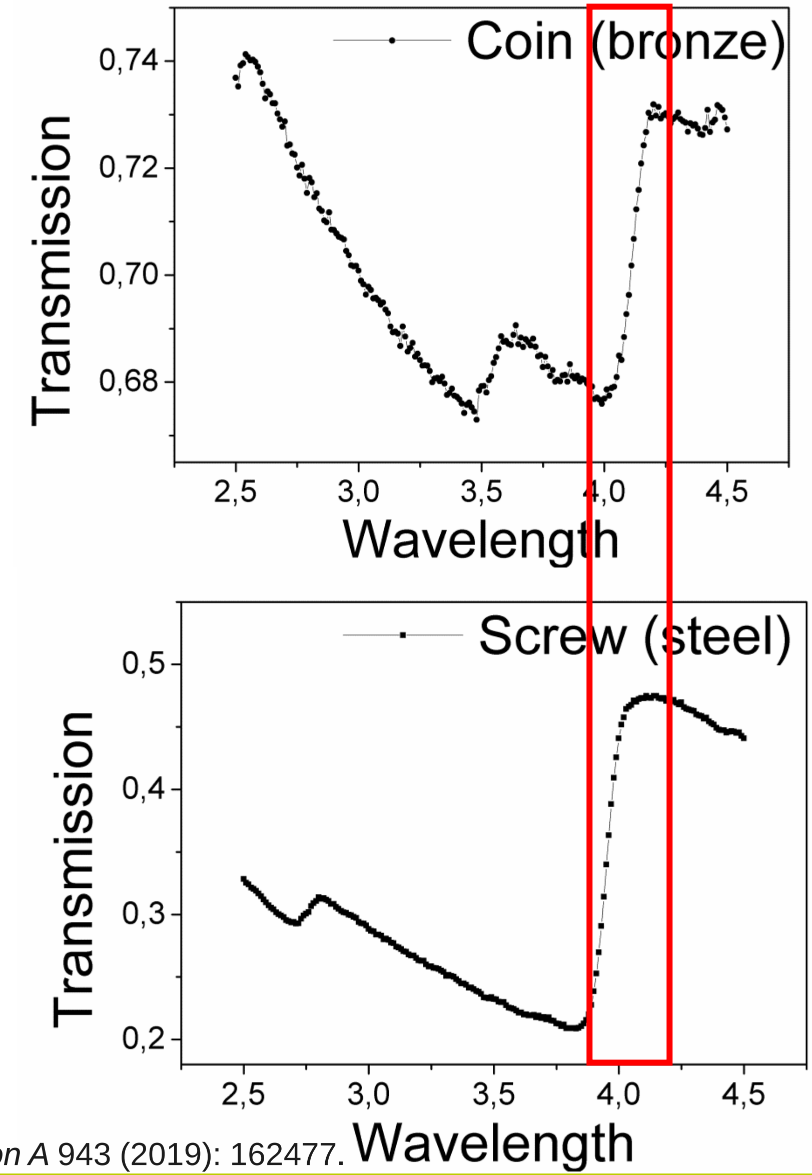
Maximal sample width: 200 mm

Experimental sketch:



Wavelength gradient





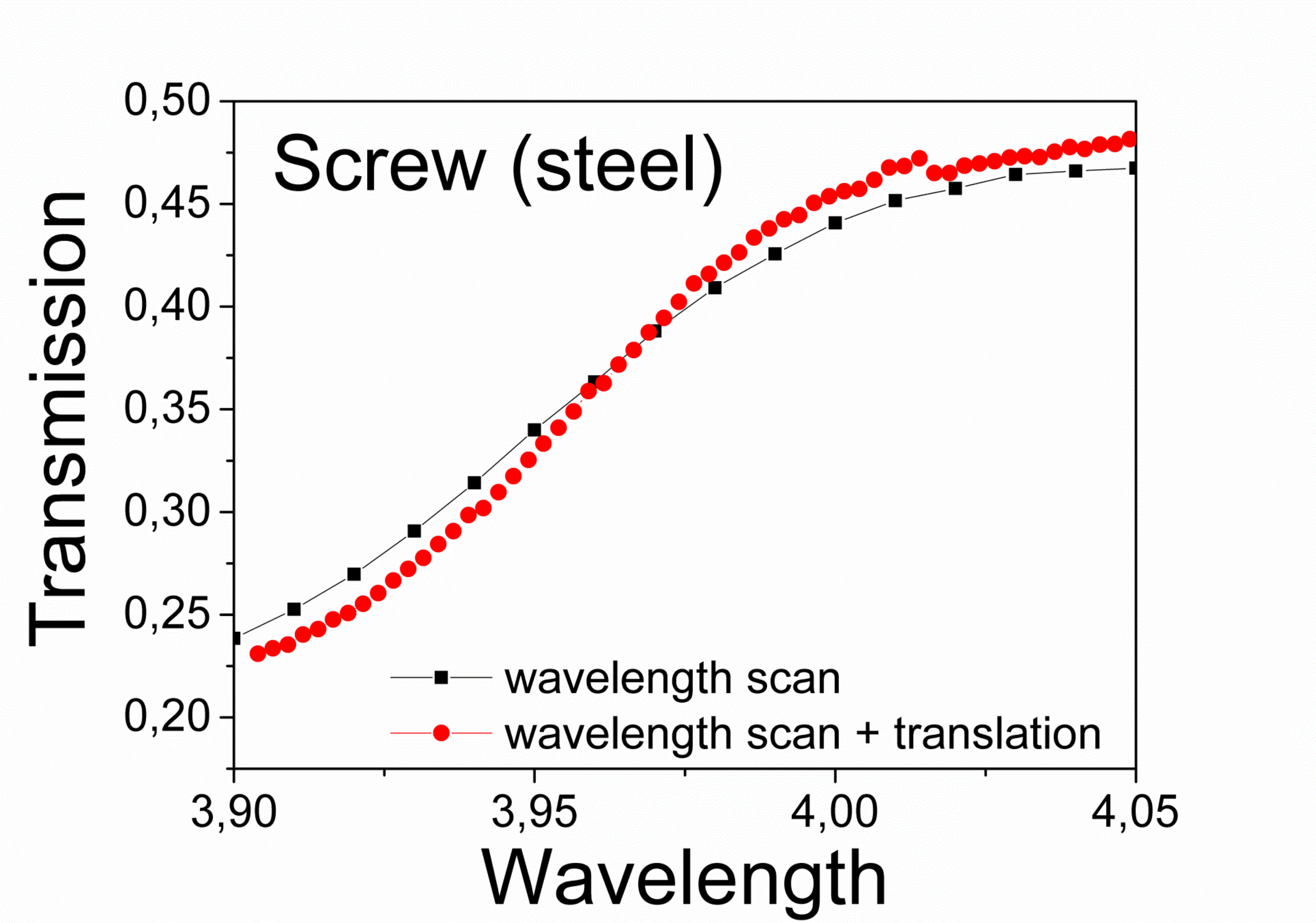
Wavelength scan:
2.5 Å – 4.5 Å, step 0.01 Å

Exposure time:
200 s / image

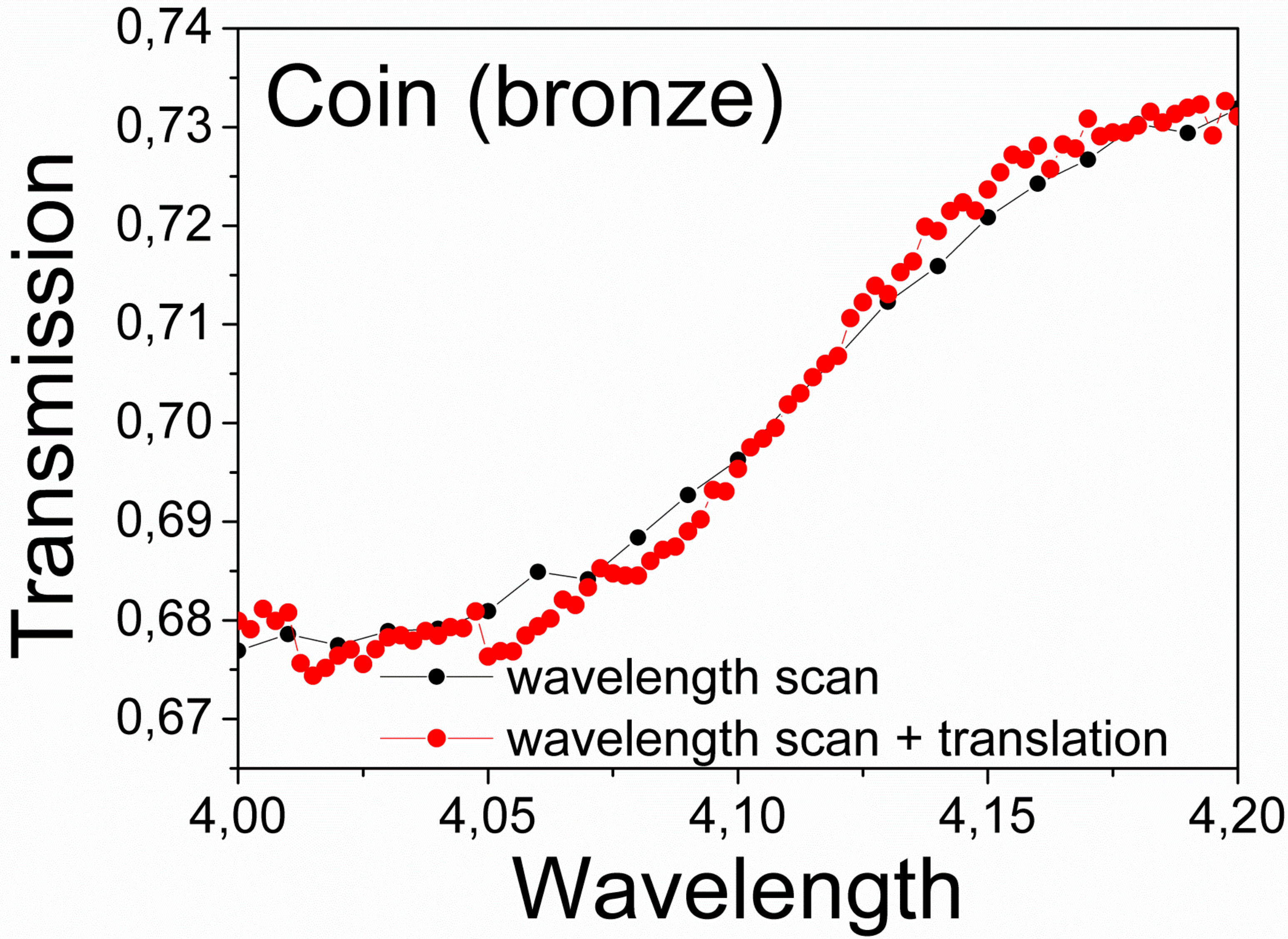
Total: ~ 23 h

Al-Falahat, A. M., et al.
Nuclear Instruments and Methods in Physics Research Section A 943 (2019): 162477.

Wavelength gradient

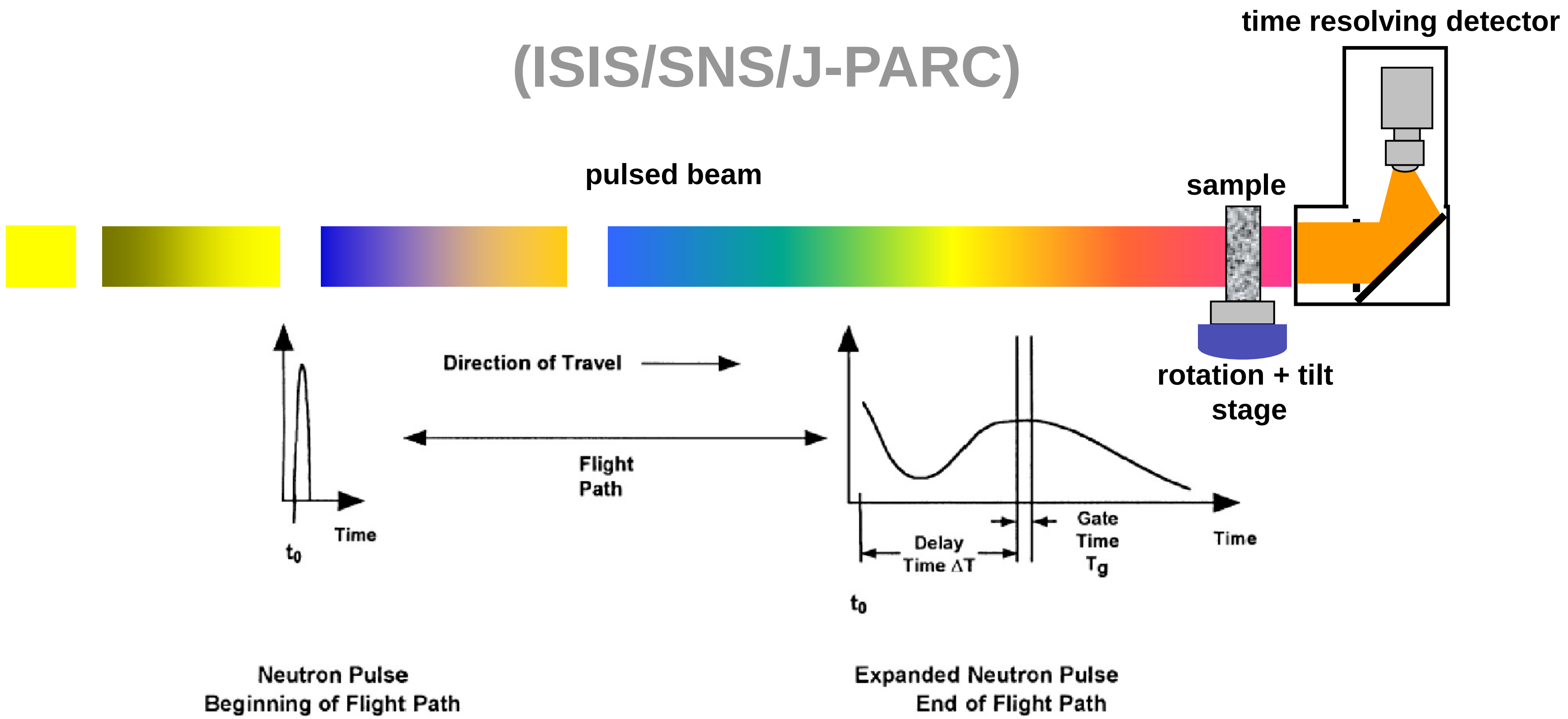


Wavelength gradient



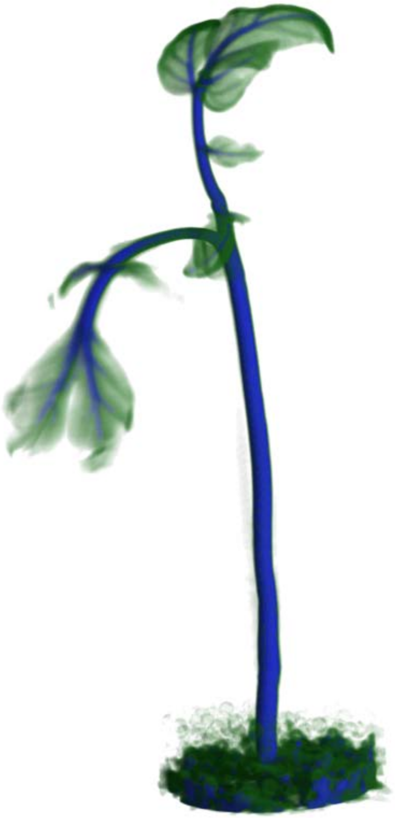
Beam monochromatization

(ISIS/SNS/J-PARC)



Time of flight

Resolution (Δλ/λ): ~ 0.1% - 1 %
Excelent resolution
Extreme long exposure times



Thank you !