

Neutrons for Materials Science

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Budapest, 5th October, 2026

Where science meets matter

BNC



BNC connector
Bayonet Neill–Concelman

BNC

Budapest Neutron Centre



BNC connector
Bayonet Neill–Concelman

Connection to materials science

By neutron research

The Budapest Research Reactor

**is one of the most important
research infrastructures in the
Central European region**

Neutron Research in Hungary

Reactor construction 1957-59

Upgrades: 1986-1992 and 2023-2027

The Reactor main features

Power: 10 MW

Thermal neutron flux: $2.5 \cdot 10^{14}$ n/cm²s

Liquid hydrogen cold source

5 neutron guides, 16 experimental stations



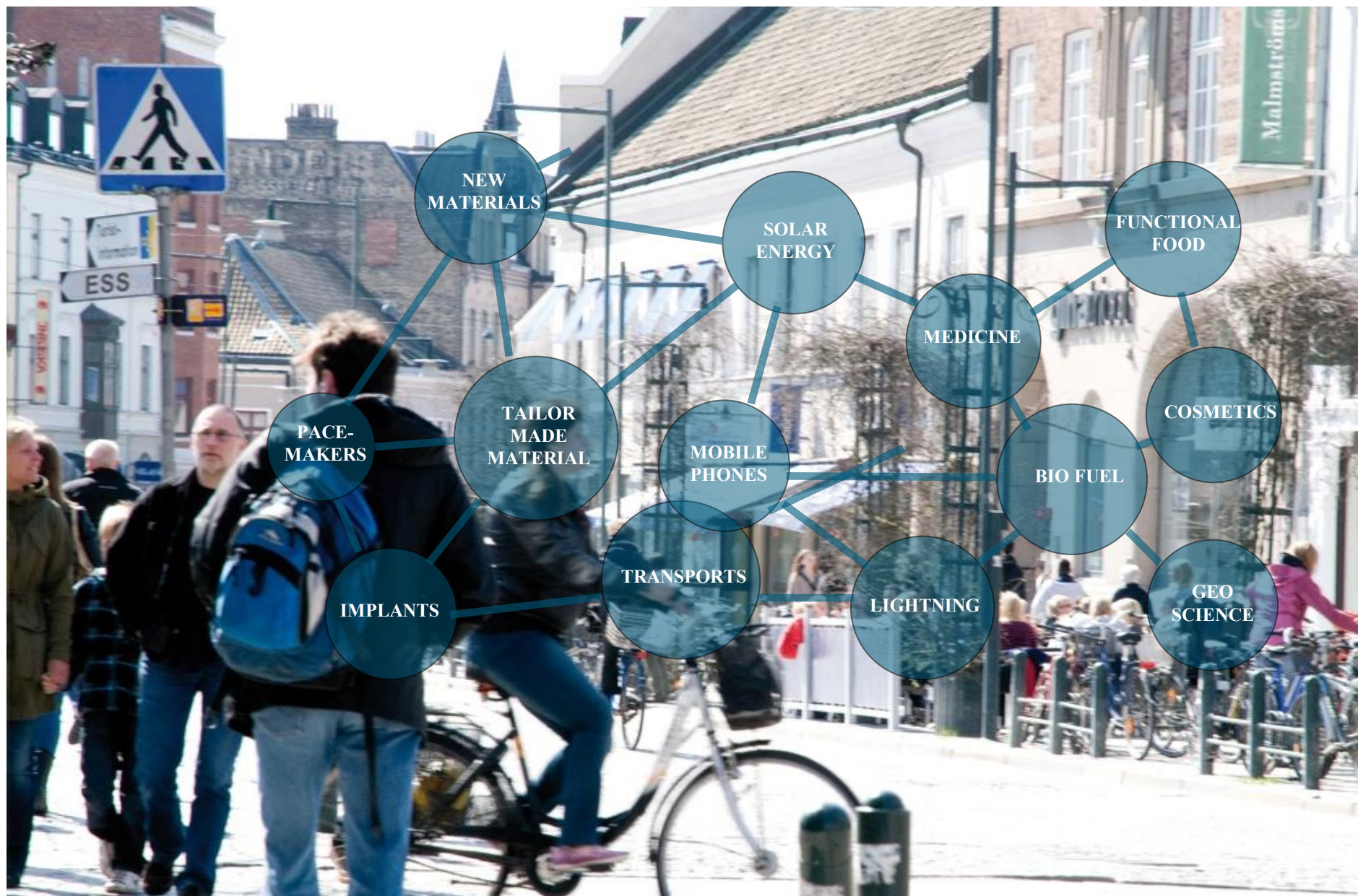
Outline:

The neutron science

**The Budapest
Research Reactor**
is the major hub for neutron
research in Hungary

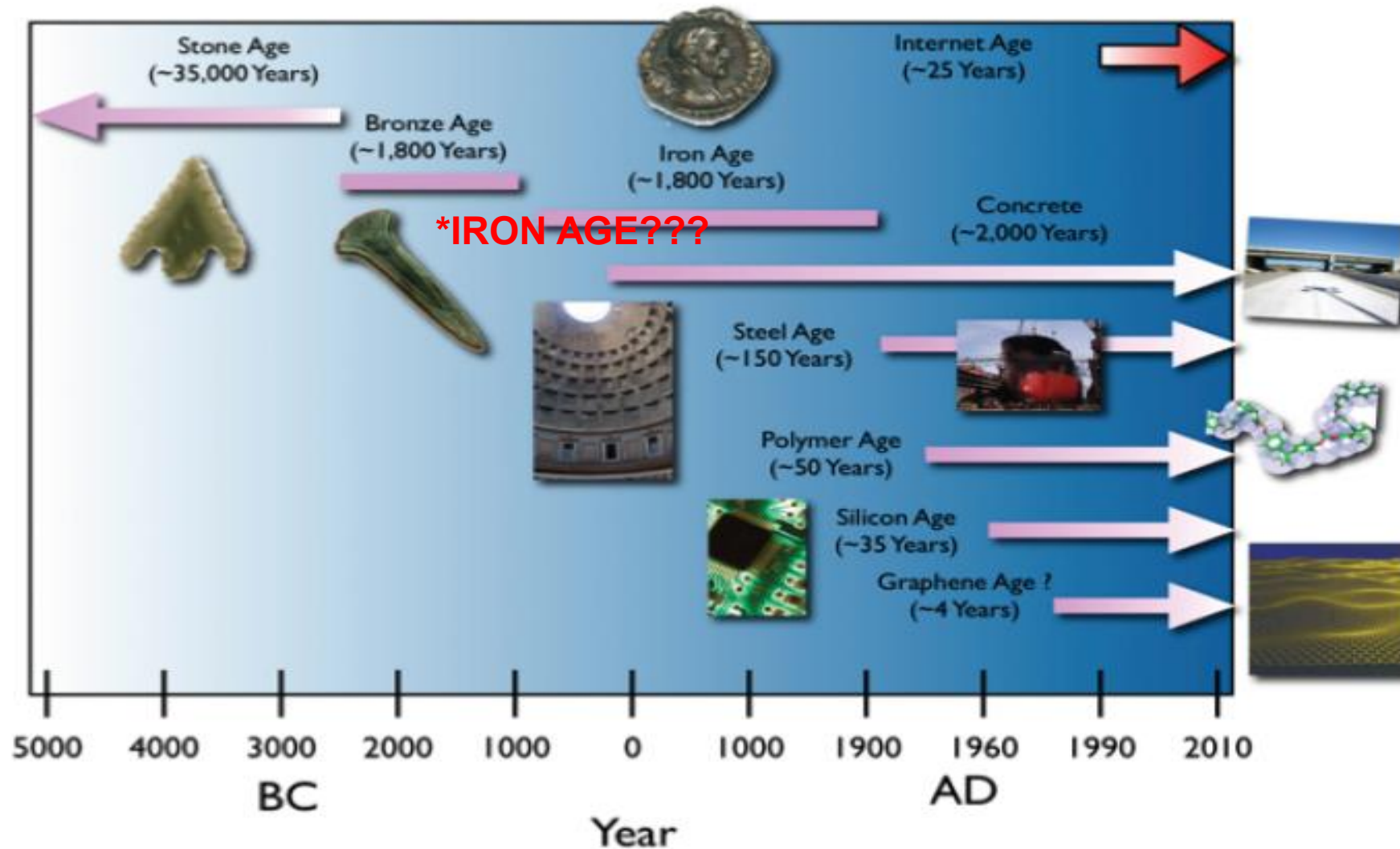
- **Characterisation of the structure of atomic-molecular assemblies**
- **Featuring elemental composition and inside topology of materials**
- **Instrumentation:**
 - Neutron sources – Reactors (ILL, BNC...), Spallation sources (ISIS....)
 - Neutron spectrometers
- **Applications to materials:**

• Industrial components	Functional materials (energy!)
• Biology related systems	Condensed matter physics
• Fundamental physics	Neutron instrumentation



Materials used by mankind

Where science meets matter



Neutron radiation – a useful tool to reveal unique features of materials from macroscopic to atomic scale level.

* Recent new discovery: 5000 years old Egyptian iron pieces made from hammered meteoritic iron, Rosta L Szentmiklósi L, Rehren Th, et al; Proof of the Meteoritic Origin of Mankind's Earliest Iron Artefacts through Neutron and X-ray Analysis, *Hungarian archaeology e-journal* http://www.magyarregeszett.hu/wp-content/uploads/2013/12/Rosta_13

Why neutron experiments are important?

Where science meets matter

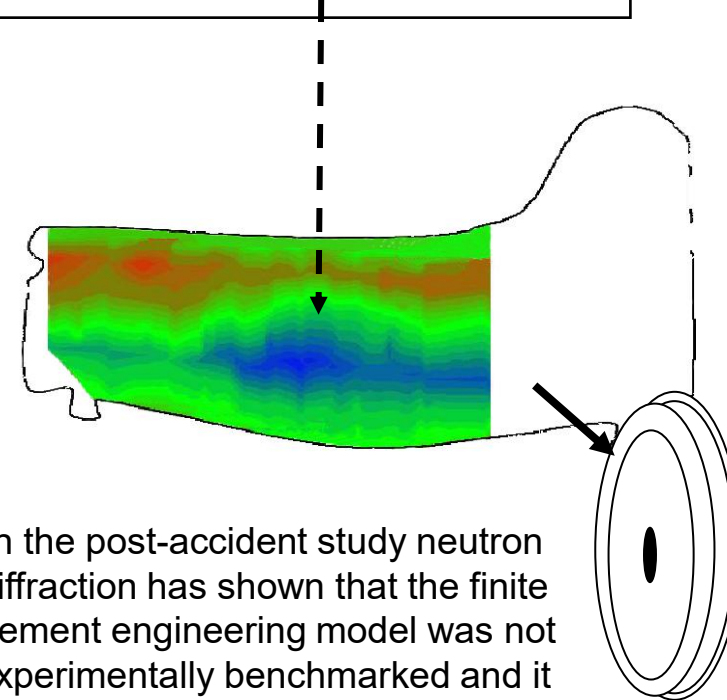
An example: neutrons deliver unique information on **mechanical strain**



ICE accident,
Eschede 1998

Neutrons can see deep inside matter
weak interaction guarantees **large range** and
unambiguous theory

Neutrons see **(tensile) stress** inside
bulky metal parts that caused wheel
failure: standard engineering theory of
plastic deformation stresses in error



In the post-accident study neutron
diffraction has shown that the finite
element engineering model was not
experimentally benchmarked and it
failed (M. Grosse, L. Kőszegi et al.
Journal of Neutron Res. 2001).



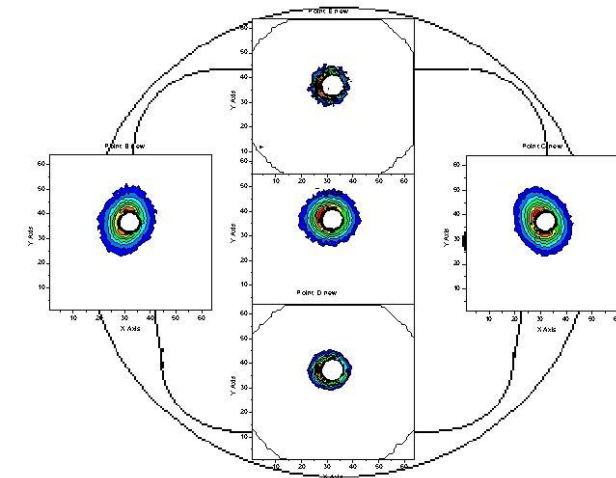
A train
wheel
study at
ISIS (2014)



Life-time investigation of Ferrari engine pistons



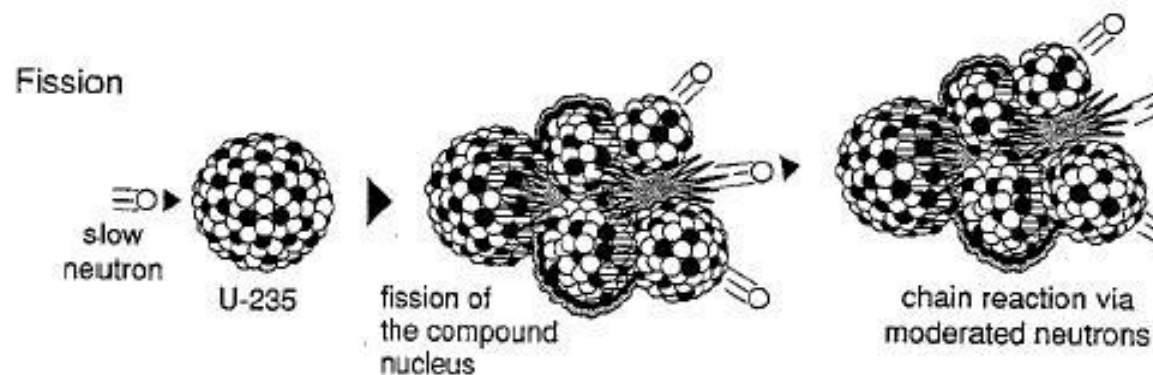
Small angle neutron scattering study of the nanoscale defect structure in Al-alloy pistons at different stages of usage. Anisotropic distribution and highly geometry dependent growth of precipitates was revealed.



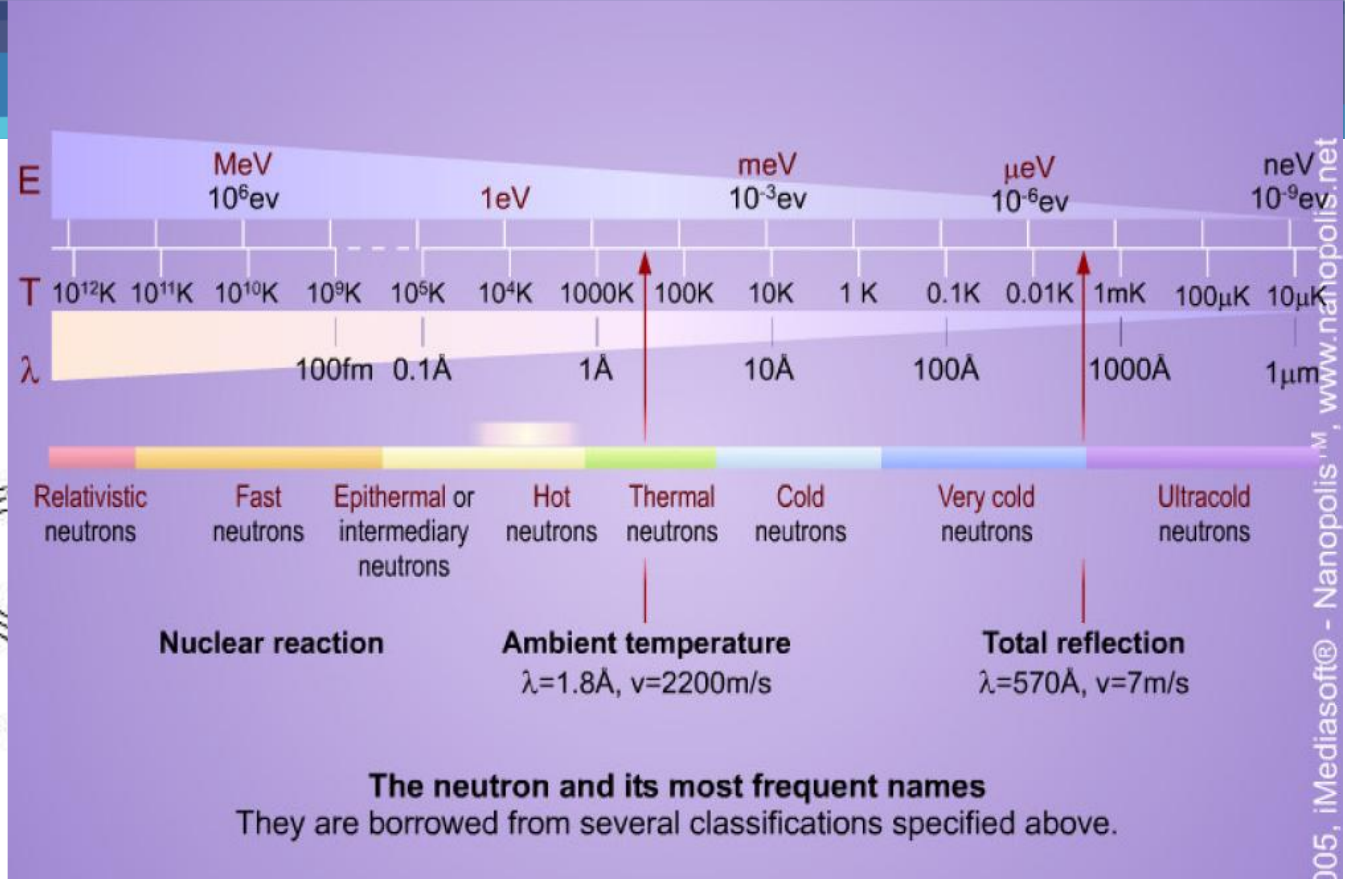
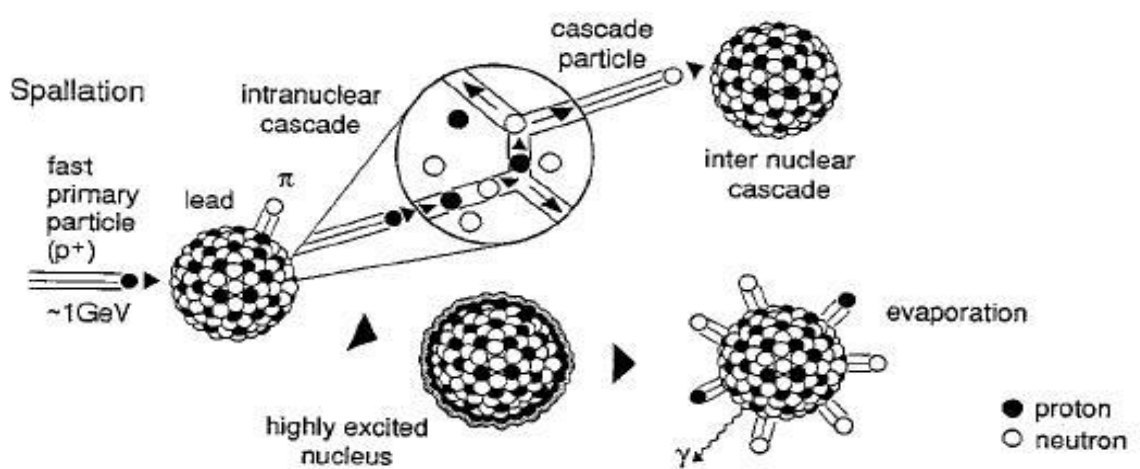
Modifications of the technology based on the nanoscale defect analysis enabled to double the life-time and increase the engine power.

To produce beams of free neutrons the most suitable used processes are:

- **nuclear fission in research reactors**



- **spallation using high-energy proton accelerators**



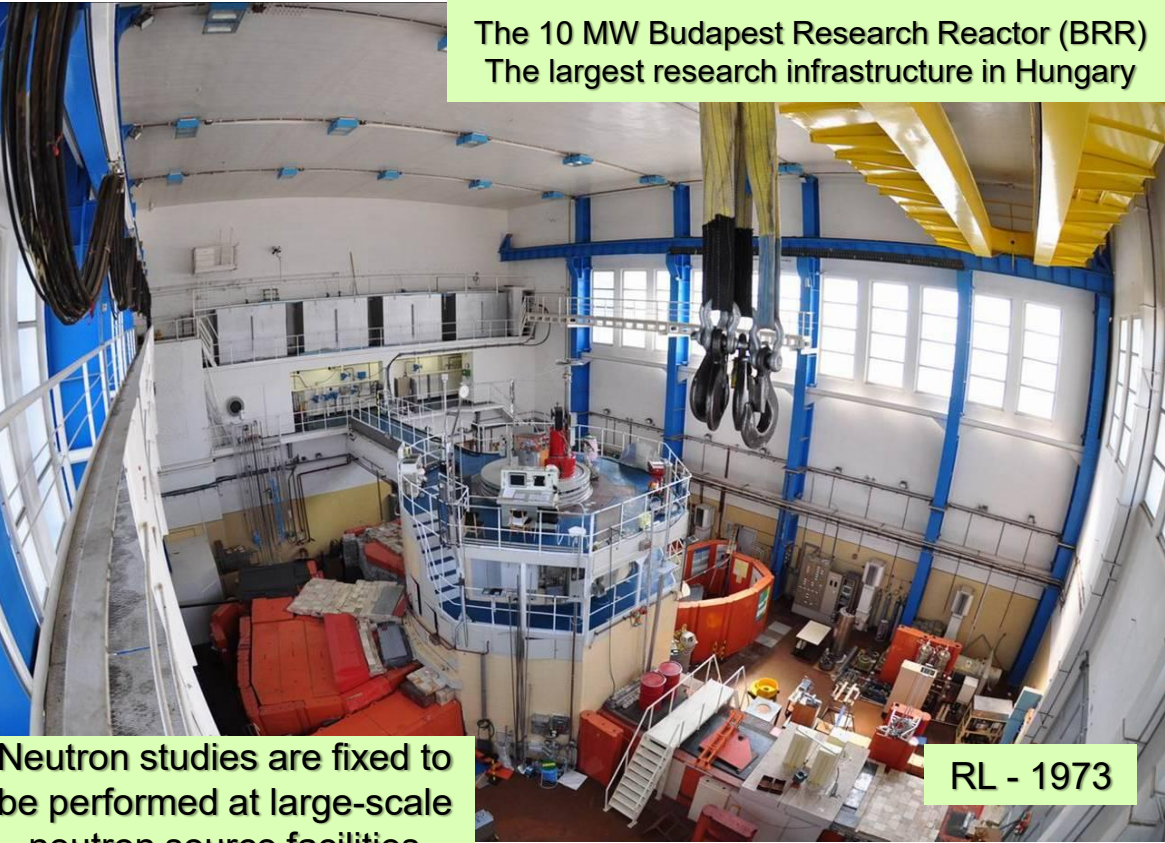
- **nuclear reactions with low-energy proton accelerator**

Bombarding of target material such as **lithium or beryllium** with low or medium energy protons or deuterons in the range of 2 to 50 MeV produces neutrons by specific nuclear knock-out or stripping reactions. The neutron yield depends on the energy of the incident particles. At lower energies it is around 10–2 per proton (or per deuteron) with a heat release of around 1,000 MeV per neutron.

The neutron

Intense neutron beams are produced in **nuclear research reactors** (e.g. BRR) or accelerator-based **spallation neutron sources** (e.g. ISIS). Today, in Europe 6 neutron centers provide access to about 100 various neutron spectrometers for materials research, to serve ~6000 users. The Budapest Neutron Centre operates 16 experimental stations.

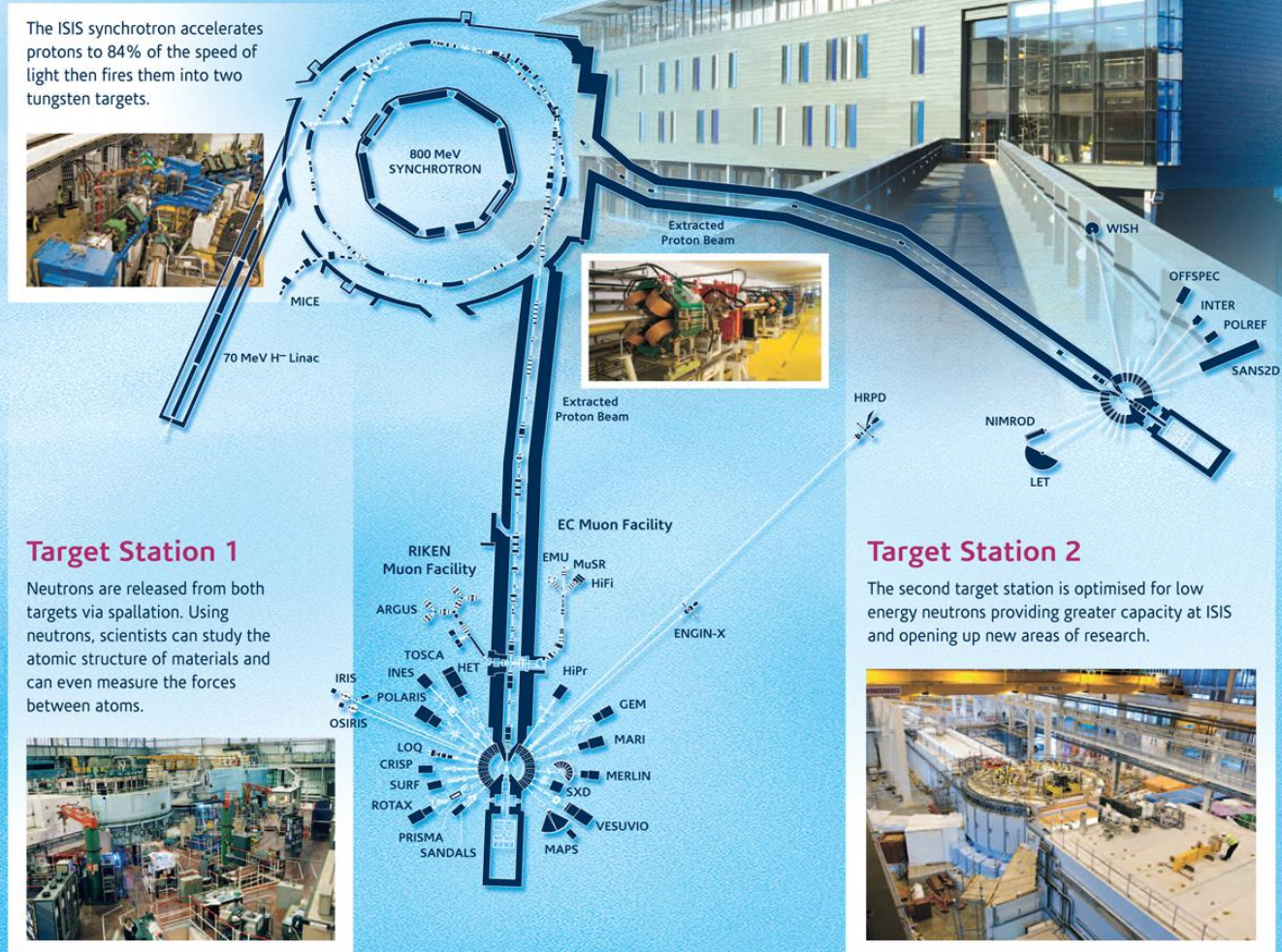
The 10 MW Budapest Research Reactor (BRR)
The largest research infrastructure in Hungary



Neutron studies are fixed to be performed at large-scale neutron source facilities

RL - 1973

ISIS is a high power accelerator that fires high energy protons into two targets to release neutrons for experiments.



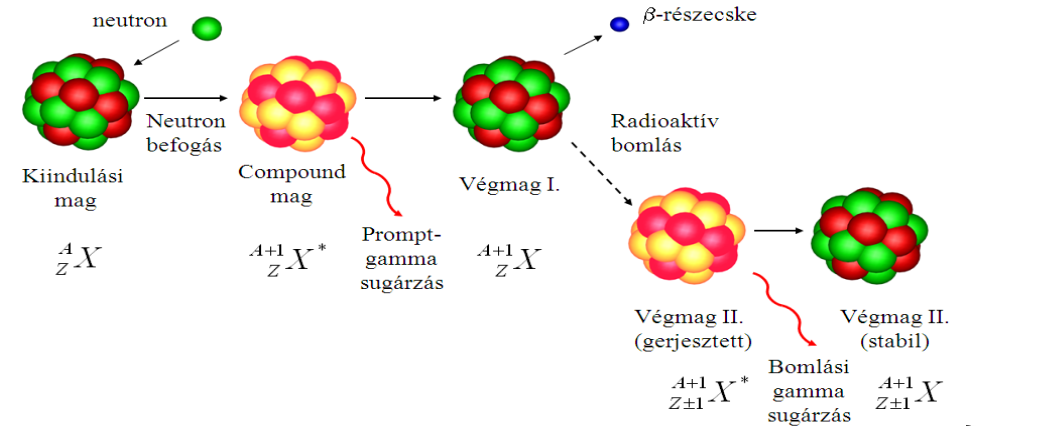
These instruments are using thermal/cold neutrons. While, some few hot/forró neutrons are used for materials modification.

Three major ways/techniques to get information with neutrons on materials properties and internal topology of objects

1. Absorption of neutrons by nuclear reaction with atoms of studied materials

Radiative capture – (n,γ) reaction

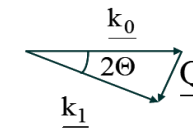
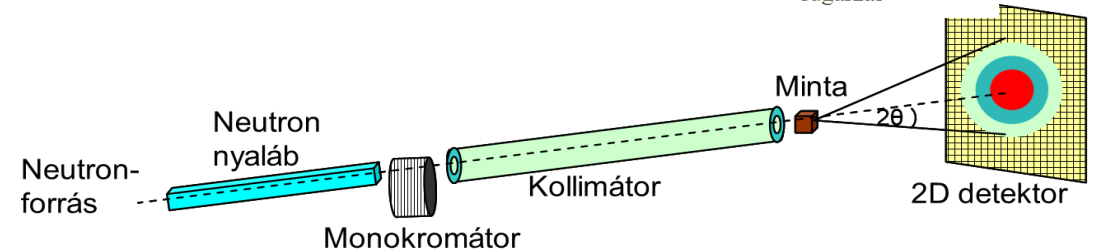
Determination of elemental composition of materials



2. Weak interaction with atoms – changing in the trajectory and velocity of neutrons passing through solid or liquid materials

Neutron Scattering (elastic or inelastic)

Measuring intensity variation of scattered neutrons from the sample reveal information on microstructure



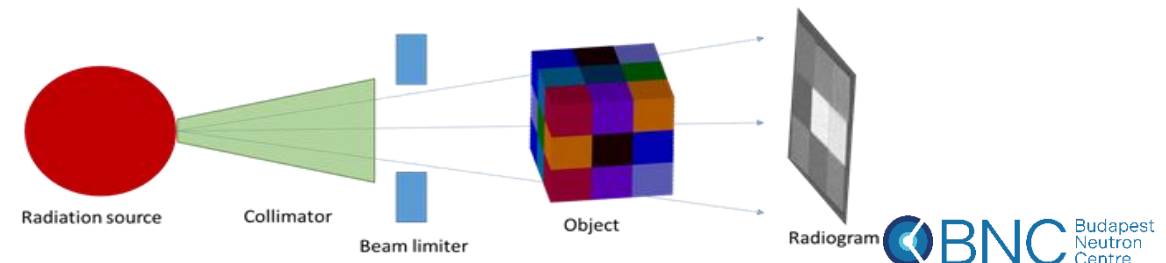
$$\underline{Q} = \underline{k}_1 - \underline{k}_0$$

$$|\underline{k}_1| = |\underline{k}_0| \quad k = \frac{2\pi}{\lambda}$$

$$Q = \frac{4\pi}{\lambda} \sin \Theta$$

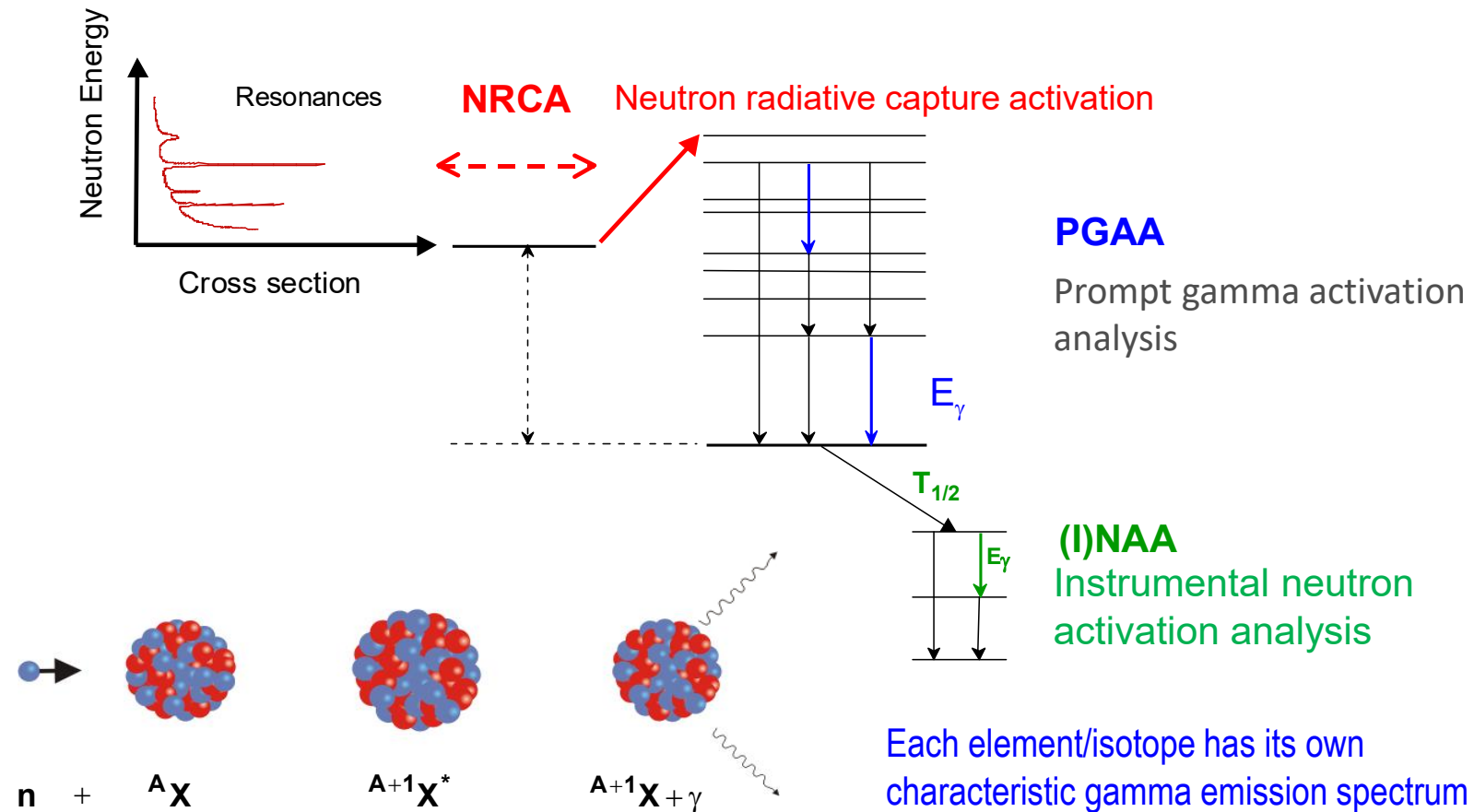
3. Imaging by passing neutron beams through objects
- ### Neutron radiography and tomography

Transforms invisible radiation into visible images



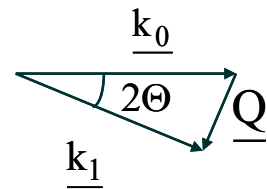
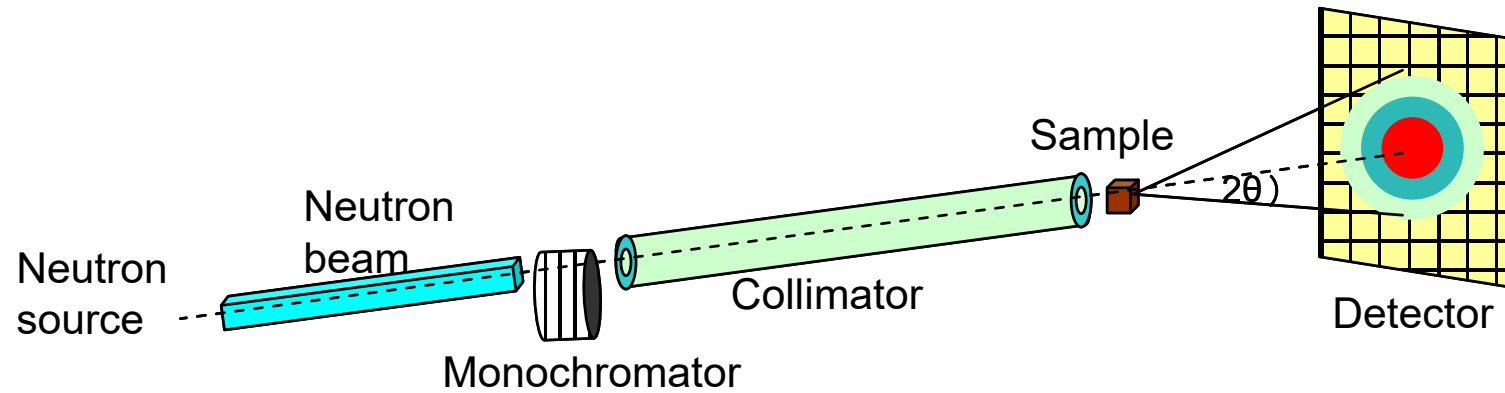
1. Radiative capture

(n, γ) reaction: captured neutrons induce emission of gamma rays



Determination of **elemental composition** of materials

2. Neutron scattering



$$\underline{Q} = \underline{k}_1 - \underline{k}_0$$
$$|\underline{k}_1| = |\underline{k}_0| \quad k = \frac{2\pi}{\lambda}$$
$$Q = \frac{4\pi}{\lambda} \sin \Theta$$

Measuring intensity variation of scattered neutrons from the sample reveal **information on microstructure**

3. Radiography

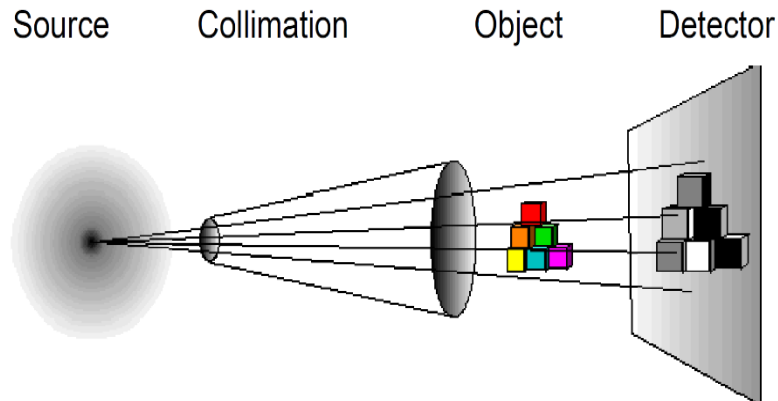
- Radiography = „Drawing with radiation”
- Radiography is a direct imaging technique, where the visual representation of an object is obtained nondestructively by detecting the modification of an incident beam as it passes through the matter
- Neutrons penetrate deep into bulk materials (metals, alloys, stones etc.)
- **Transforms invisible radiation into visible images**



X-ray radiography

Röntgen

Neutrons and X-rays complement each other



Transmission of neutron or X-ray beam through an object provides a contrast image in the detector



X-rays have high penetration through soft/organic matter

Neutrons penetrates rather thick metal/hard matter objects

Neutron spectrometers

Basic requirements:

- 1 A good spectrometer should deliver a *high flux* of neutrons with a *good collimation* at the sample position.
- 2 As much as possible scattered neutrons should be detected, with adequate angular and energy resolution.

Additional advantages:

- * low background
- * wide accessible q and *energy* range
- * versatile sample environment

There are about 10-15 different kinds of neutron beam instruments.

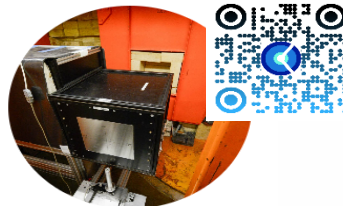
Examples

Wide angle neutron diffractometer

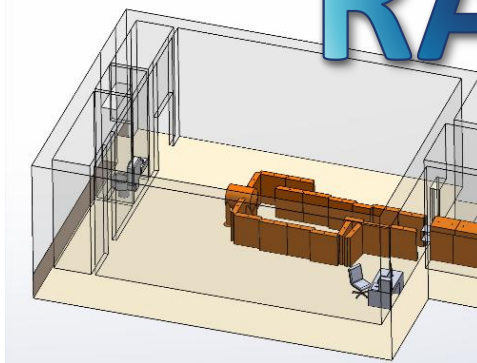
Small-angle scattering diffractometer/reflectometer

Imaging stations

- **Name:** RAD – Static/dynamic white-beam-neutron and X-ray imaging station
- **Technique:** Objects in the beam produce attenuation-based contrast on the scintillation screens
- **Range of investigated features:** 2D and/or 3D macroscopical morphological, structural and real-time process information via static and/or dynamic imaging
- **Penetration depth:** cm's
- **Typical size of the sample:** some or several cm's
- **Measurable materials:** Natural and engineered objects (Hydrogen-containing materials)
- **Contact:** rad@bnc.hu



RAD



- **Name:** TOF-ND General Purpose Time-of-flight Neutron Diffractometer
- **Technique:** time-of-flight neutron diffraction
- **Range of investigated features:** $d=0.7-3.5 \text{ \AA}$
- **Penetration depth:** mm's – cm's
- **Typical size of the sample:** 1-10 cm or parts of larger objects
- **Measurable materials:** solids (powder or bulk) and liquids
- **Contact:** tof@bnc.hu



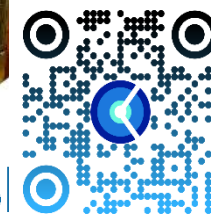
TOF-ND

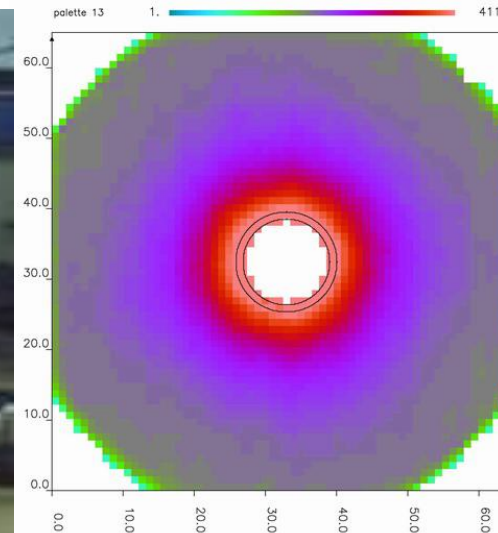
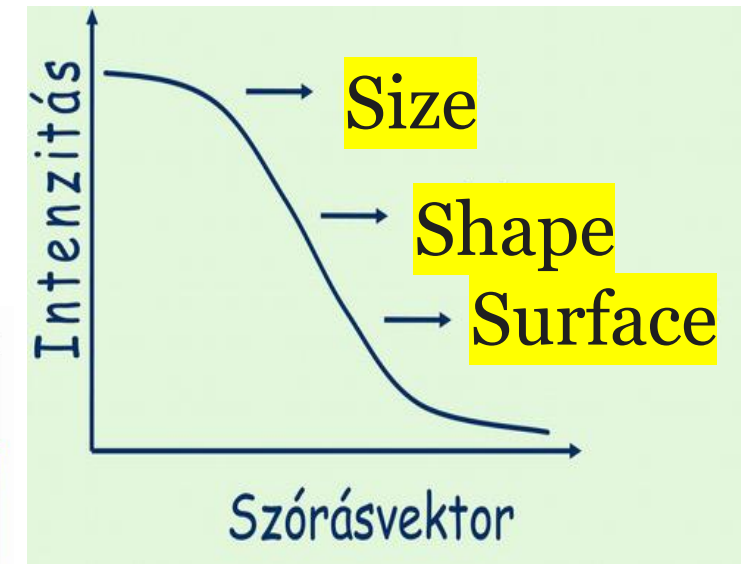
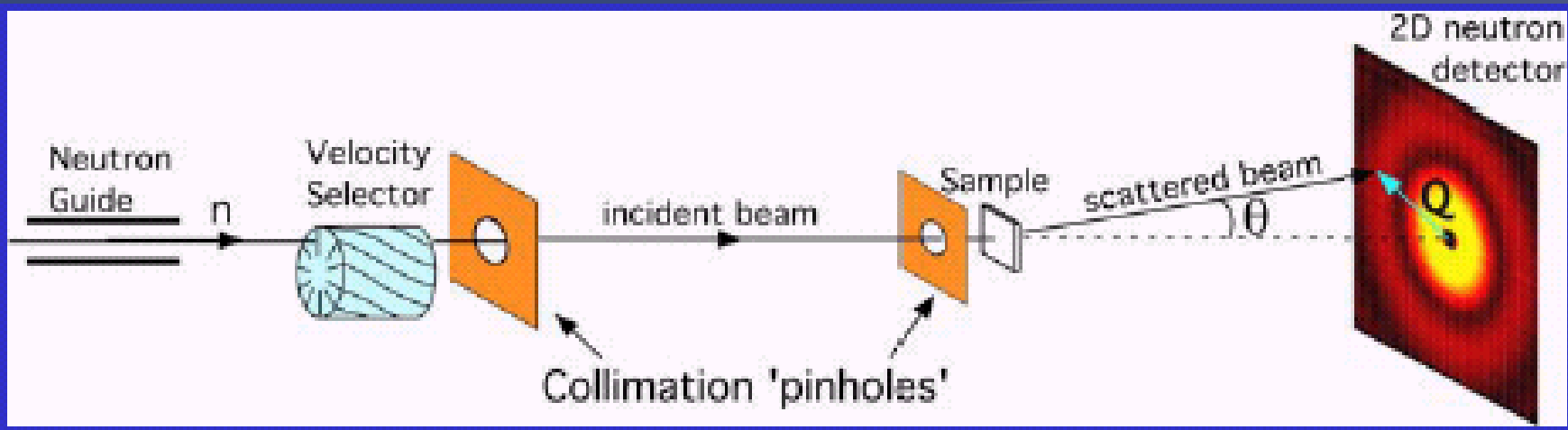


- **Name:** Yellow Submarine SANS instrument
- **Technique:** small angle neutron scattering
- **Range of investigated features:** structure in the size range 0.5 – 200 nm
- **Penetration depth:** 5 mm
- **Typical size of sample:** 2 – 20 mm
- **Measurable materials:** solid and liquid samples
- **Contact:** sans@bnc.hu



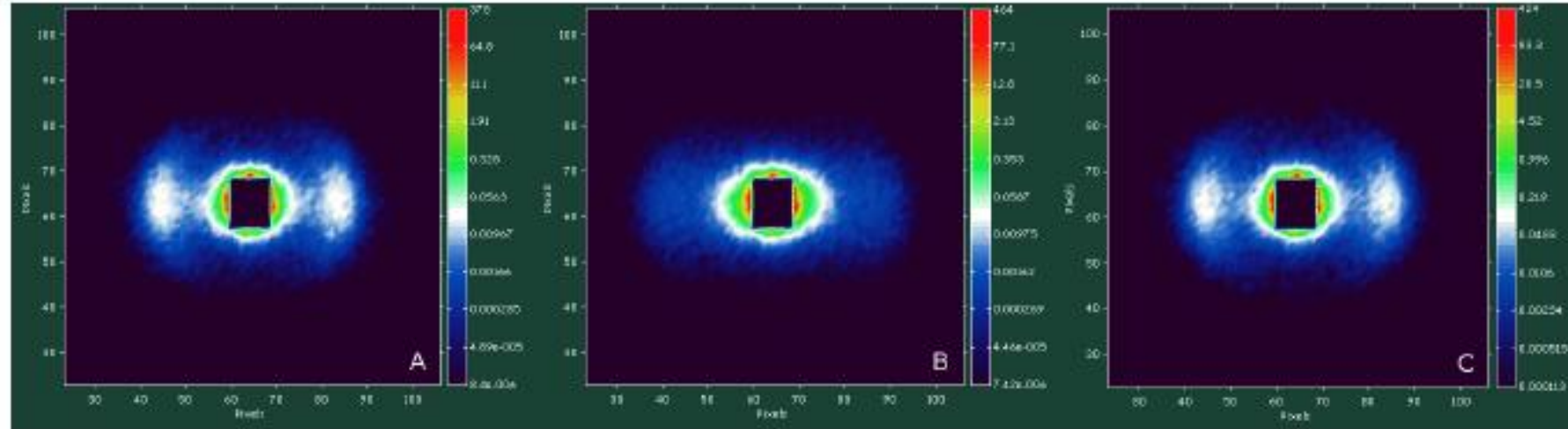
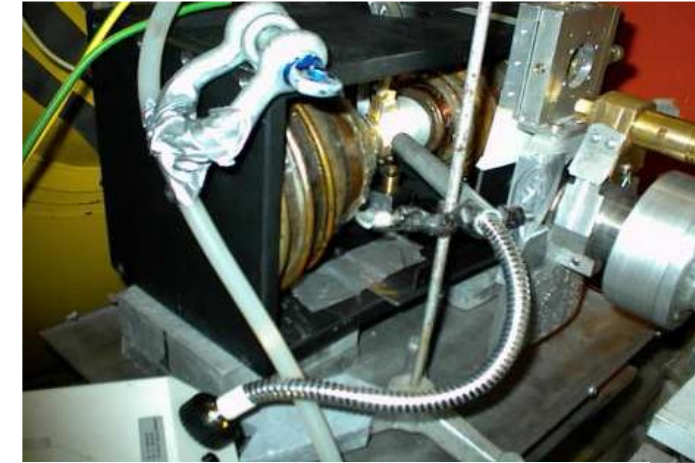
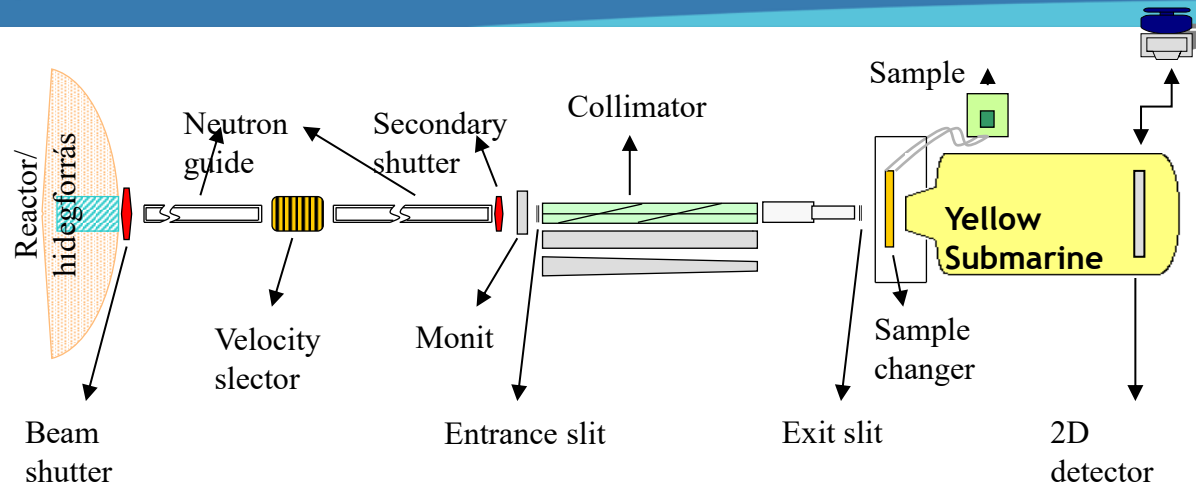
YS-SANS





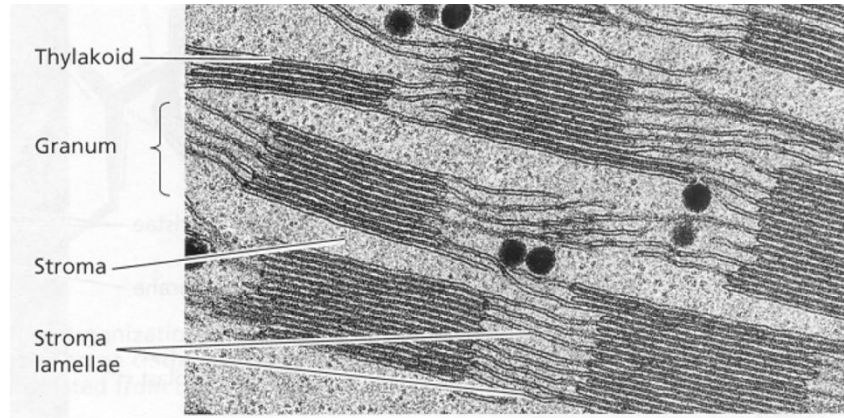
Nanoscale information from the scattering object:

- size, size-distribution
- shape (sphere, cylinder)
- correlation between the particles
- global surface of the scattering media
- orientation
- magnetic structure

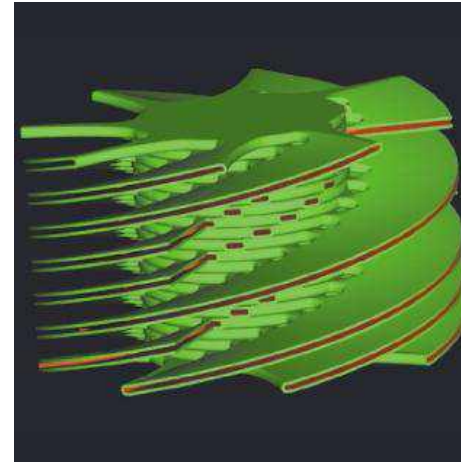


Small angle scattering instrument at the Budapest Research Reactor. The photo shows the sample environment for a biology experiment: the photosynthetic behaviour of green plants is investigated as a function of the membrane structure (laser illumination of the magnetic field aligned, temperature controlled spinach extract). Below are the 2D spectra of scattered neutrons from membrane layers at various stages of illumination.

Photosynthetic membranes – the effect of illumination

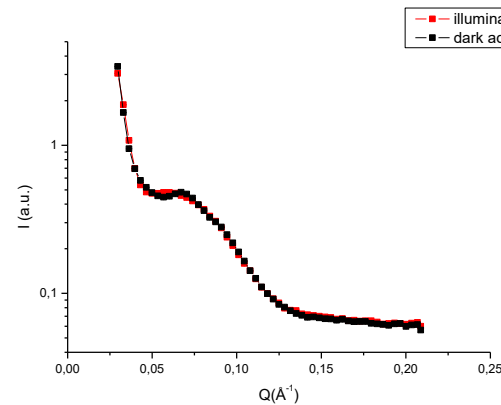


Thin section e-micrograph granal thylakoid membranes



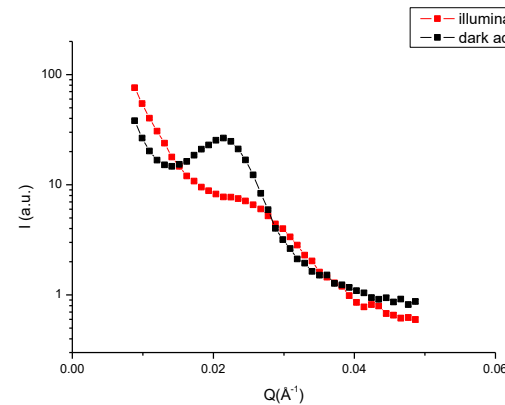
Computerized 3D model:
Membrane assembly.

Granum-
stroma
thylakoid
membrane
assembly of
higher plants

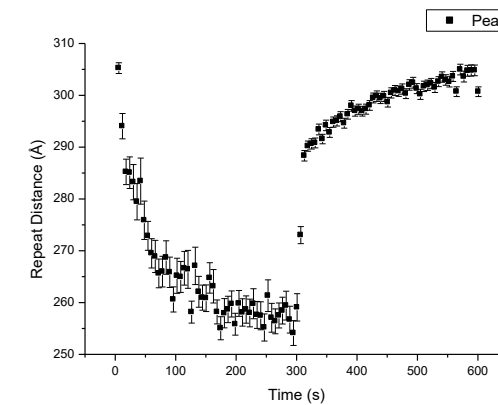


Effect of illumination (white light, $1700 \mu\text{mol photons m}^{-2}\text{s}^{-1}$) on the SANS of granum thylakoids.

Herdean A., Teardo E., Nilsson A.K., Pfeil B.E., Johansson O.N., Ünneper R., Nagy G., Zsiros O., Dana S., Solymosi K., Garab Gy., Szabó I., Spetea C., Lundin B. A voltage-dependent chloride channel fine-tunes photosynthesis in plants. *Nature Comm.* 2016, 7: 11654.



Effect of illumination ($1700 \mu\text{mol photons m}^{-2}\text{s}^{-1}$) on the SANS of stroma thylakoids.



The shift in the peak position for the stroma thylakoids was determined by curve fitting, and plotted as a function of time during the illumination.

PSD – Neutron diffractometer



Cu(111) crystal monochromator
 $\lambda = 1.07 \text{ \AA}$; $2\theta = 8-115^\circ$;
 $Q = 0.45-10 \text{ \AA}^{-1}$

Sample: 2-4g powder
Measuring time: 3-8h
Vanadium can, $\varnothing: 5 \text{ \AA} \& 8 \text{ mm}$

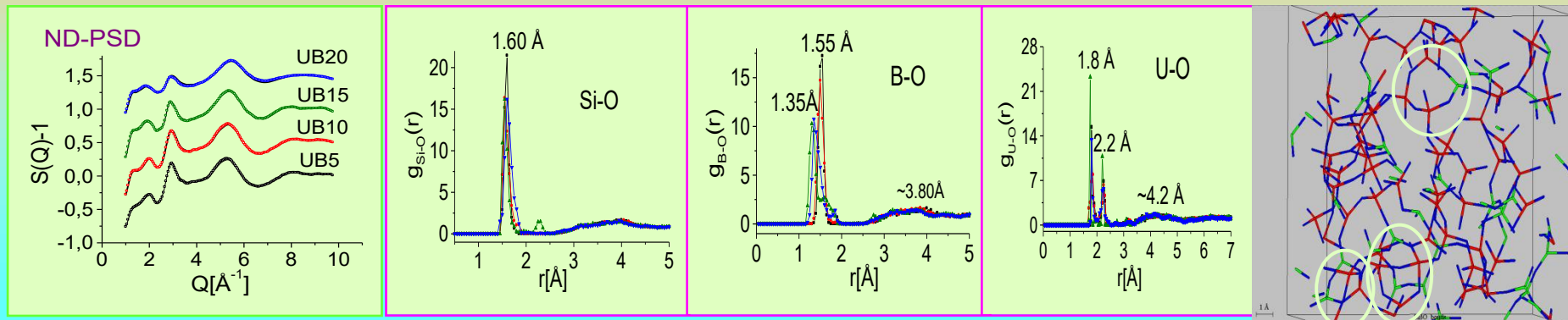
<http://www.bnc.hu>
contact: Margit FÁBIÁN
fabian@szfki.hu

Atomic structure of amorphous and crystalline materials:

- ✓ Borosilicate-, chalcogenide and rare-earth oxide glasses
- ✓ $\text{YAl}_3(\text{BO}_3)_4$ (YAB) substituted with Er^{3+} , Yb^{3+} , Y^{3+} , manganites, perovskites and hexaferrites

Uranium loaded borosilicate glasses:

70wt% $[\text{SiO}_2(60-x)\text{B}_2\text{O}_3(x)\text{Na}_2\text{O}(25\%)\text{BaO}(5\%)\text{ZrO}_2(5\%)] + 30\text{wt}\%\text{UO}_3$, $x=5-20\text{mol}$,: UB5 UB10 UB15 B20

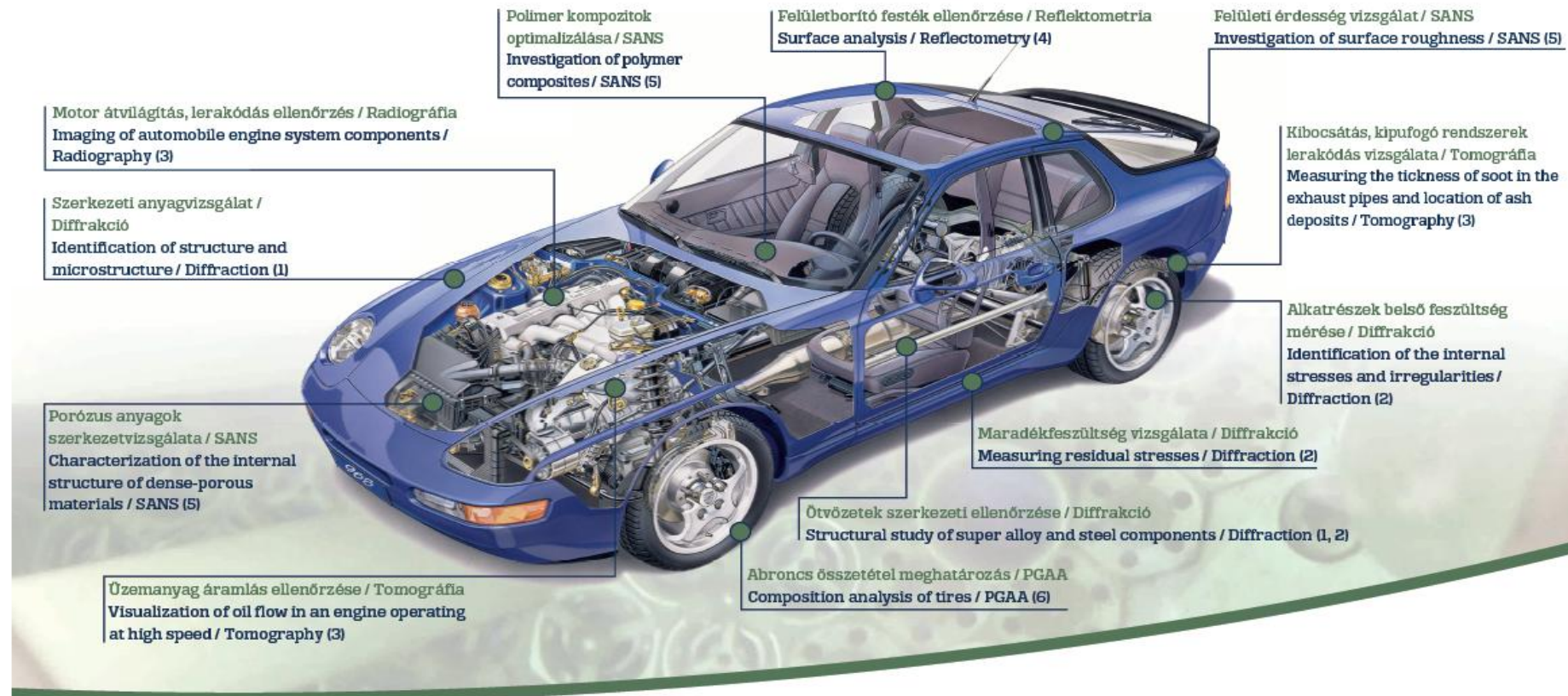


BUDAPEST NEUTRON CENTRUM

**OTTHON VAGYUNK
AZ AUTÓIPARBAN!**



**NEUTRONS FOR
BUILDING A CAR!**



(1) PSD
Neutron
pordiffrakto-
meter
Powder
diffractometer



(2) MTEST
Diffraktométer
Diffractometer



(3) RAD
Neutron
radiográfia
és tomográfia
Thermal-
neutron and
X-ray imaging



(4) GINA
Polarizált
neutron
reflektométer
Neutron
reflectometer
with polarization
option



(5) SANS
Kisszögű szórás
spektrométer
Small angle
neutron
scattering
diffractometer



(6) PGAA
Prompt-gamma
aktivációs
analízis
Promp-gamma
activation
analysis

The Budapest Neutron Centre for EASI-STRESS (H2020 EU project)

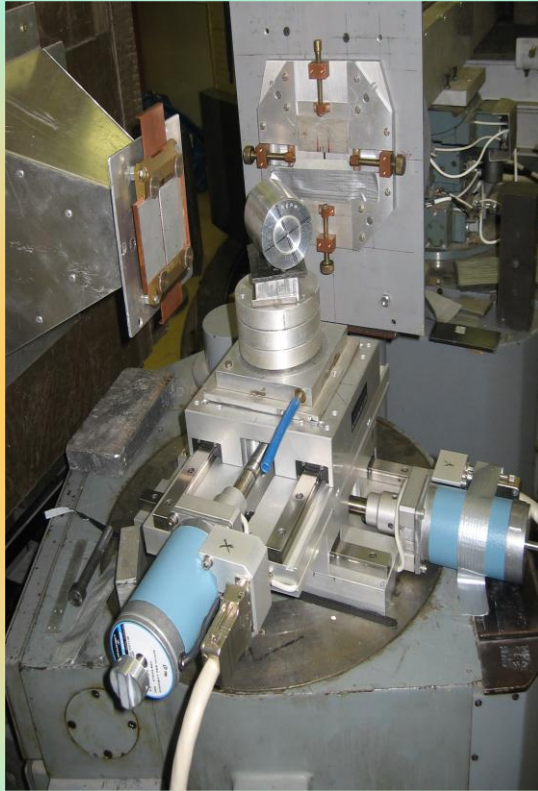


Figure 1/a

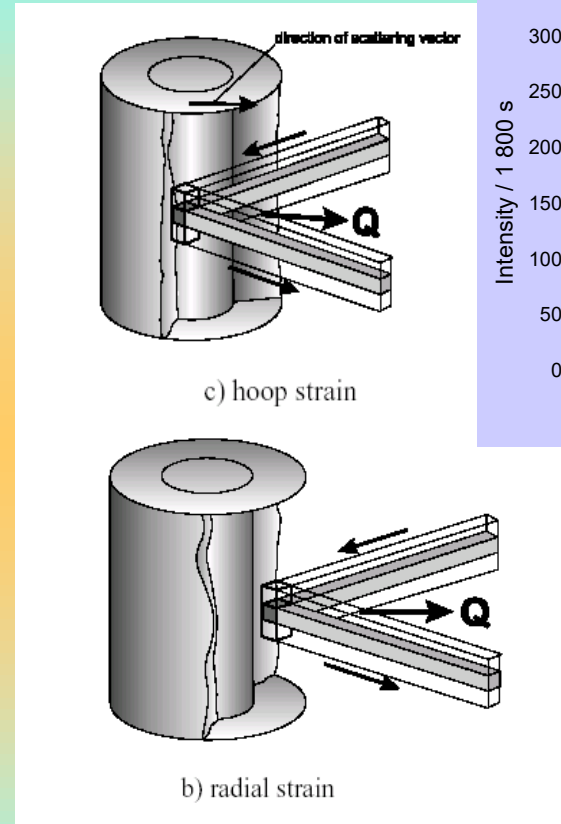
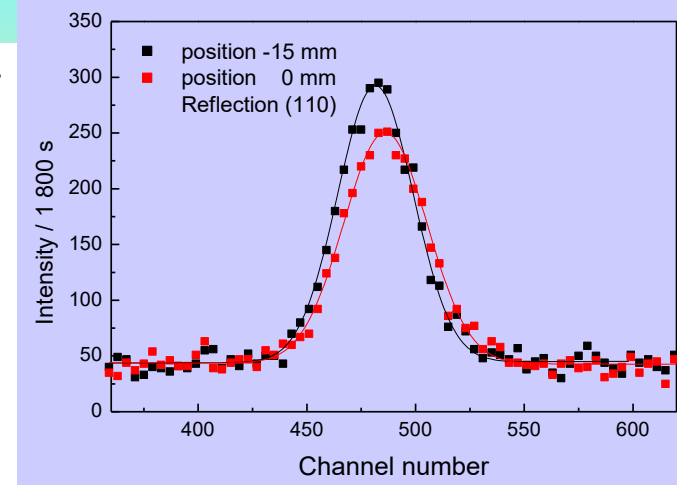
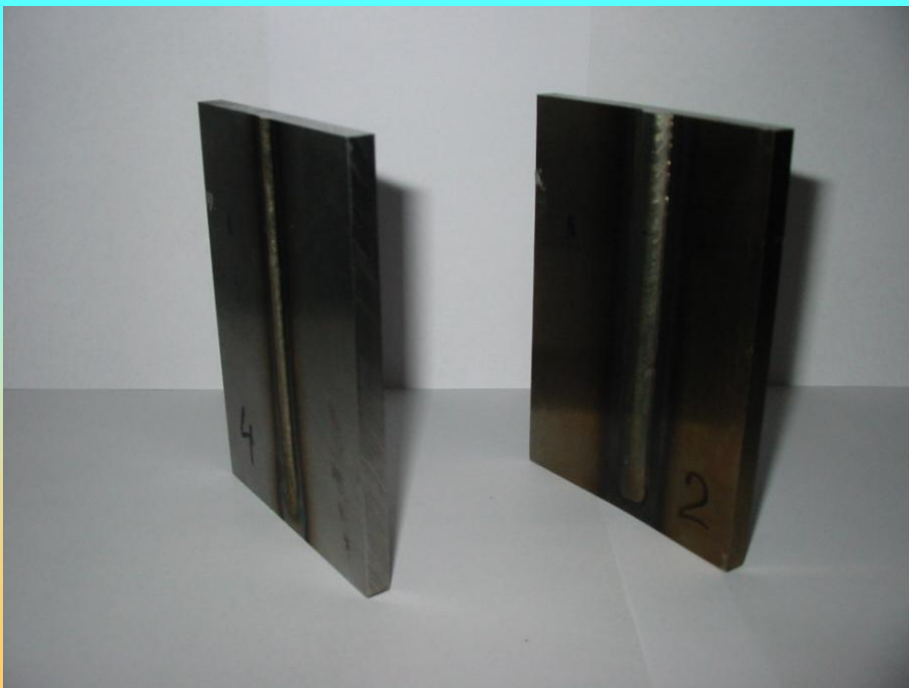


Figure 1/b



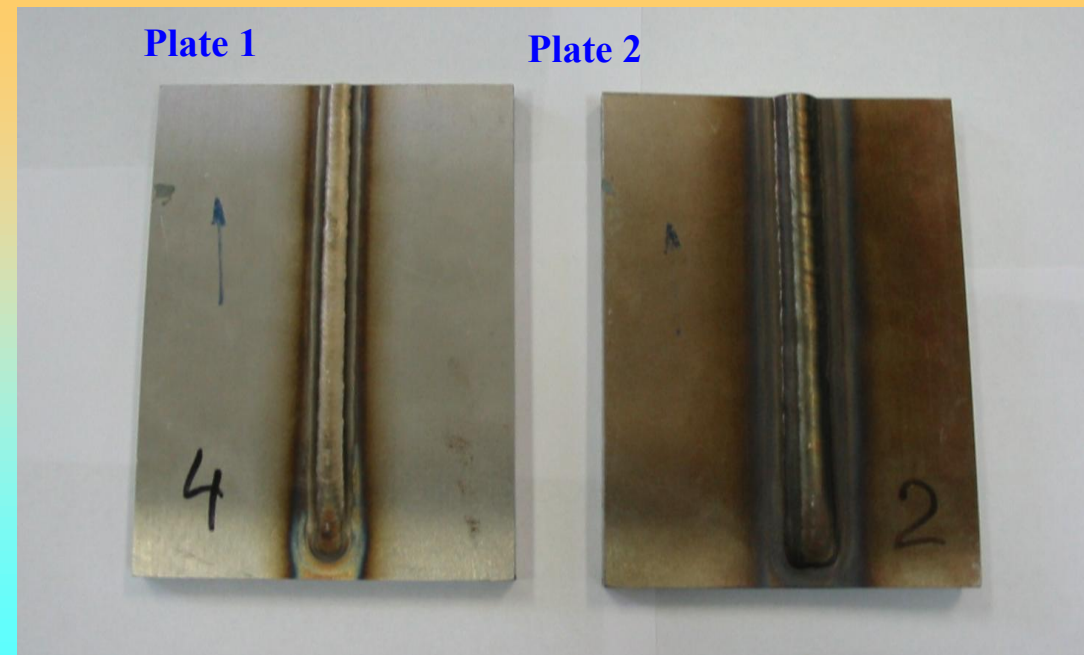
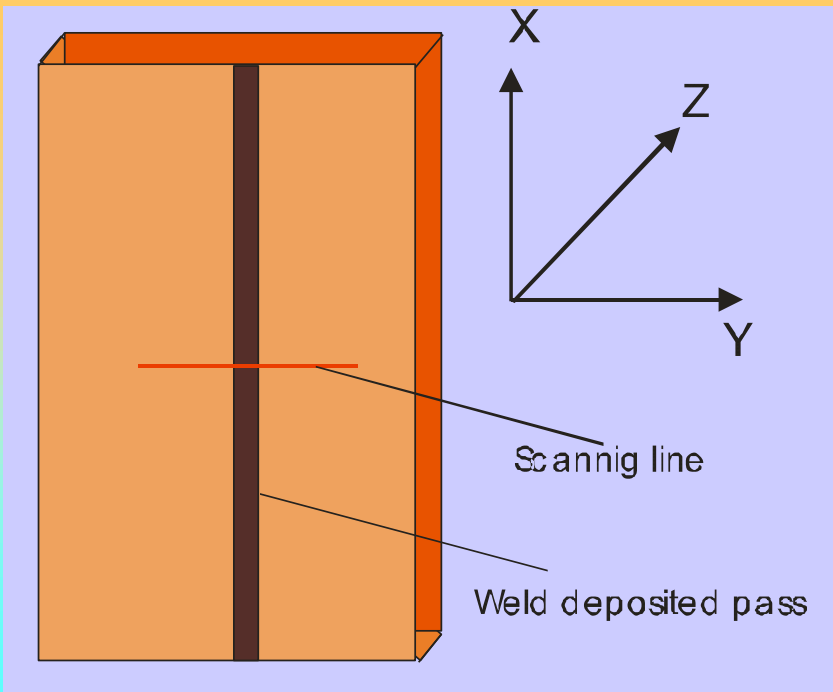
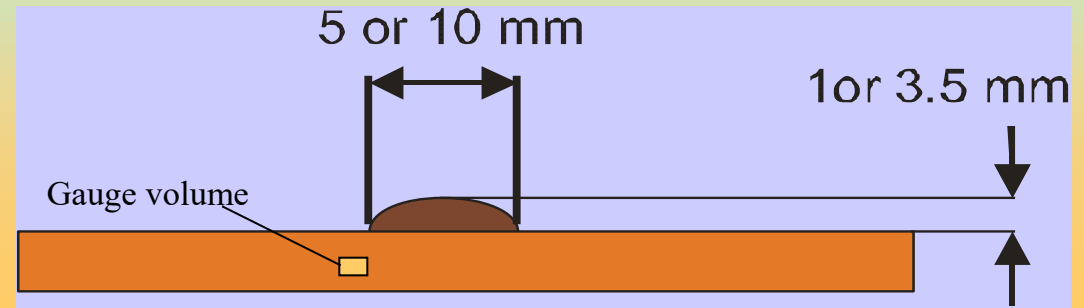
ATHOS is an instrument at BNC cold neutron guide with high flexibility and a relatively big sample table for investigation of industrial samples.

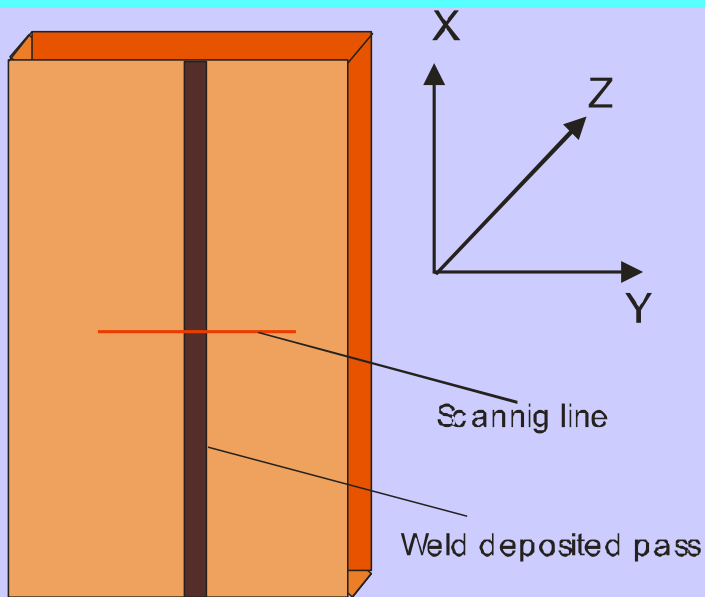
Figure 1/a shows the experimental setup, and scheme for measuring radial and hoop stresses are shown in the Fig1/ b. For stress measurement we used the 111 reflection using a gauge volume determined by the incident beam 20x3mm (HxW) and by the outgoing beam 20x3mm (HxW) at the detector direction. At the 111 reflection we used the wavelength of 0.33 nm giving us the 90 deg scattering angle.



Hegesztési varrat

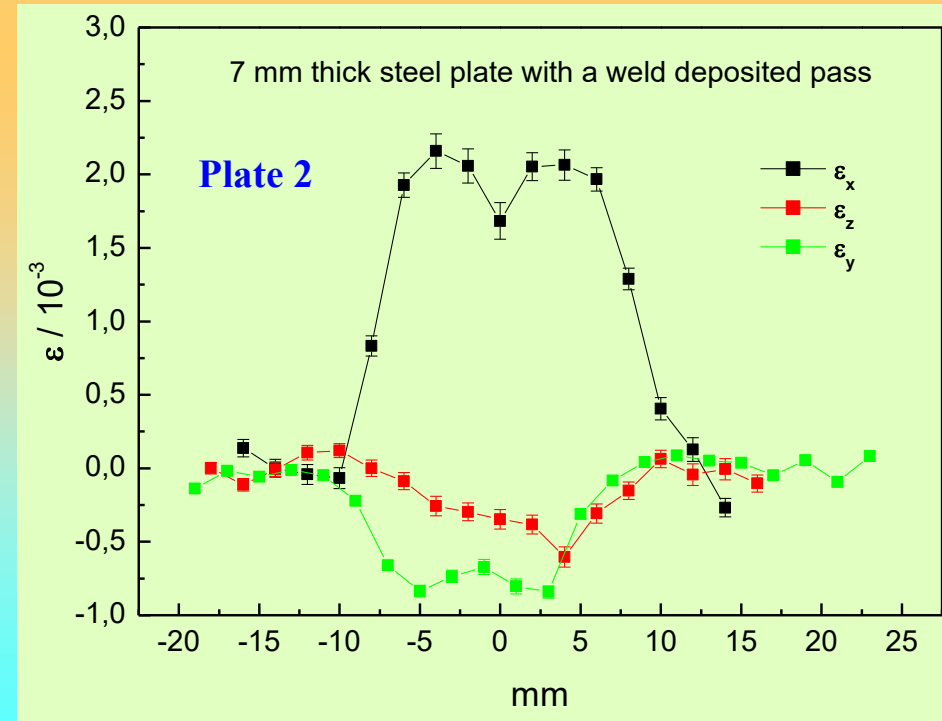
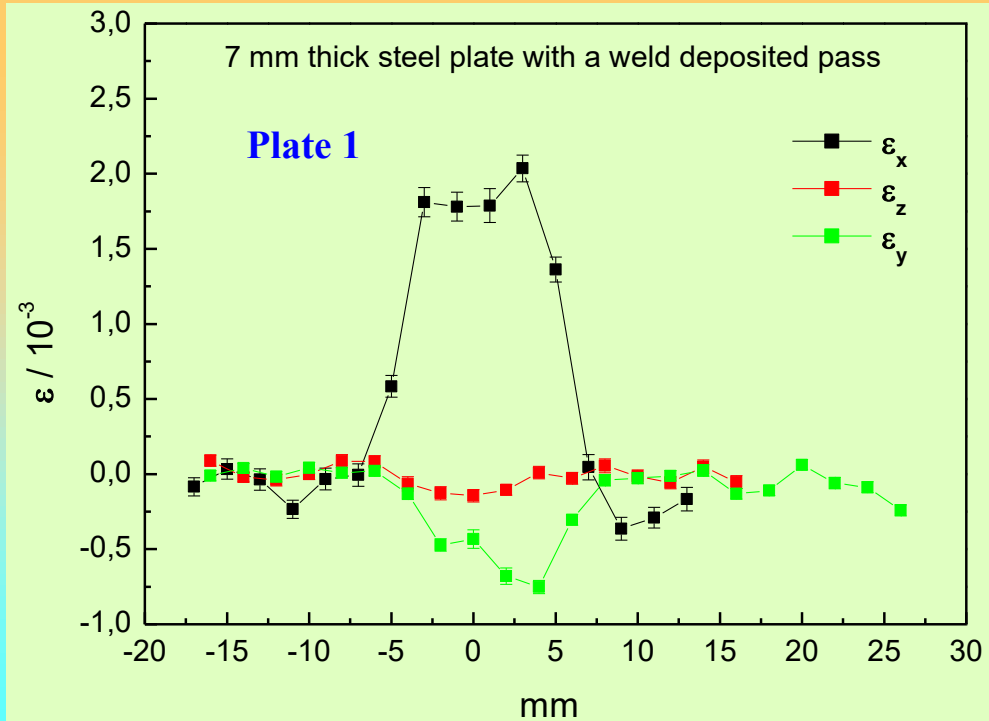
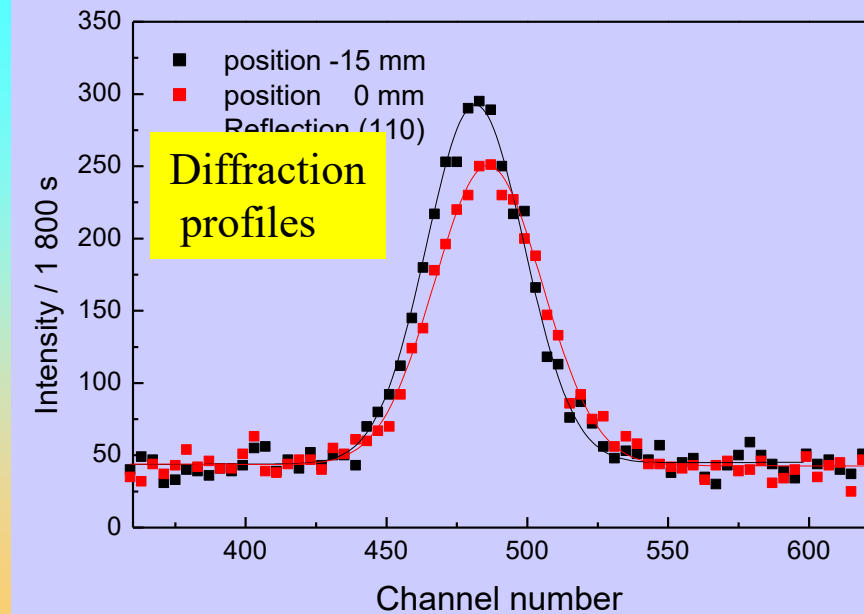
7 mm vastag lemez: 15Ch2MFA,
Kötőanyag: Inconel 52, két minta
különböző varratszélességgel



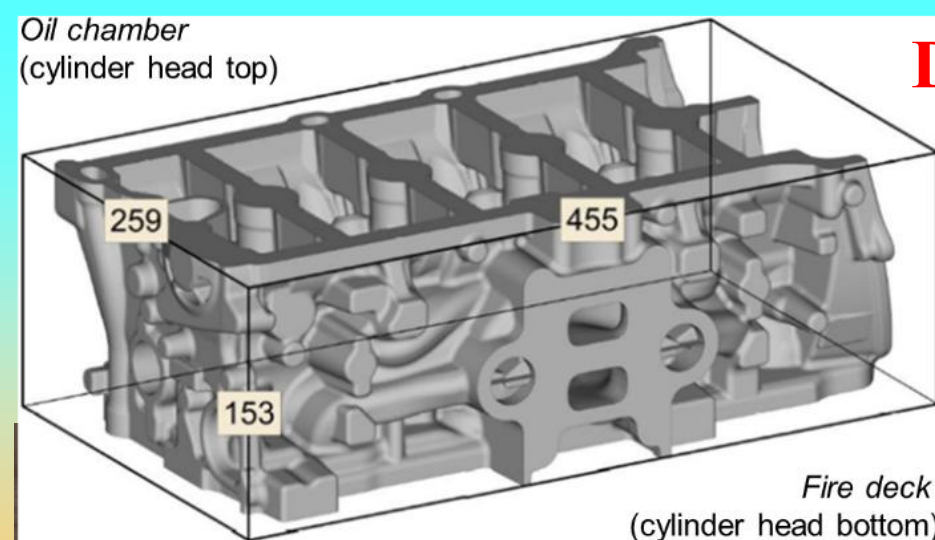


A neutrodiffrakciós kísérlet eredményei

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} = \frac{\Delta d_{hkl}}{d_{0,hkl}} = -\cot \Theta \cdot \Delta \Theta$$



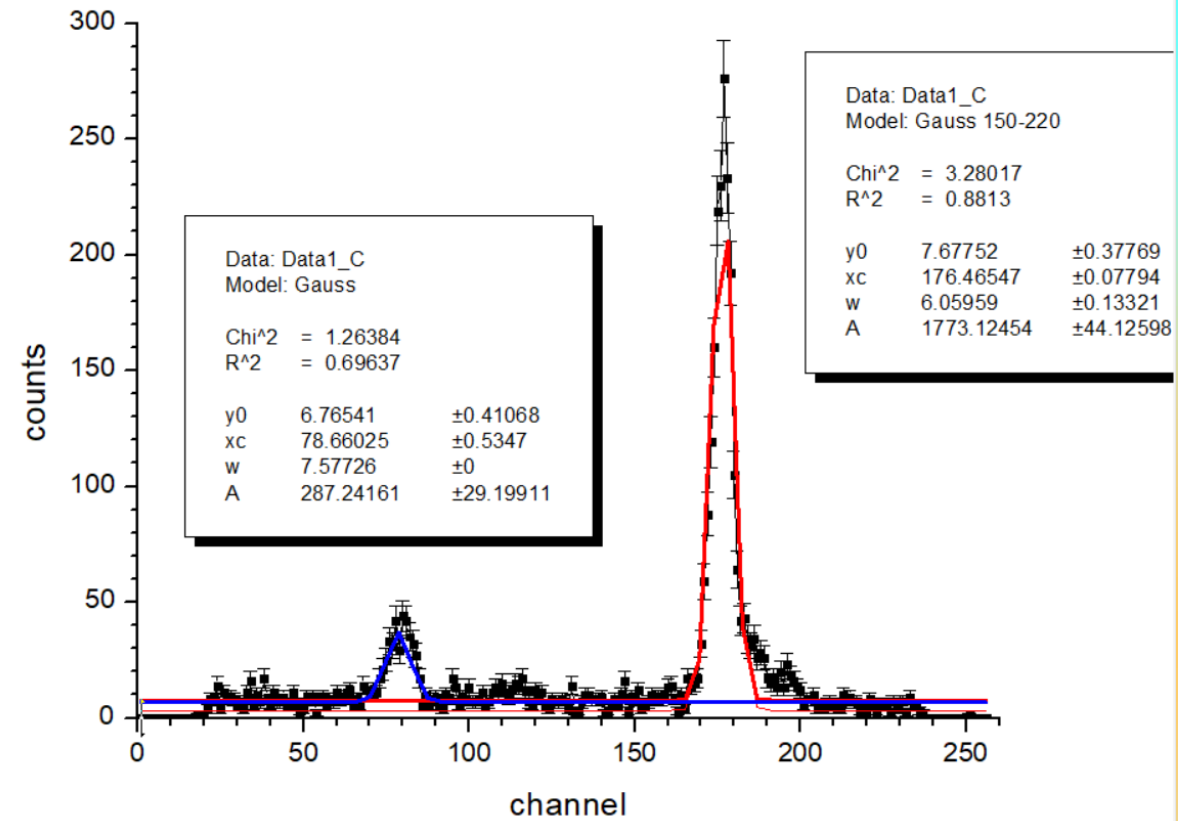
Oil chamber
(cylinder head top)



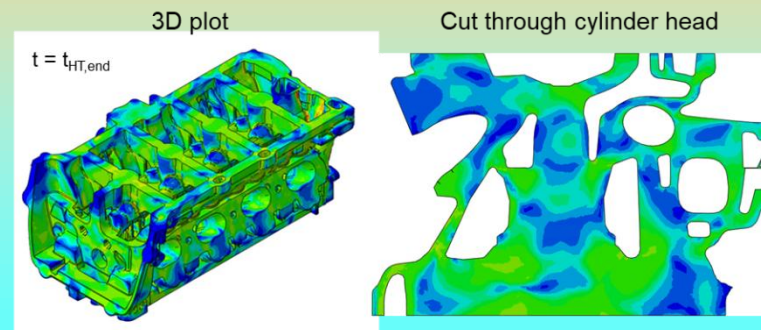
**Diesel-motor
hengerfeje**

**NEMAK-AUDI
Al-ötvözet**

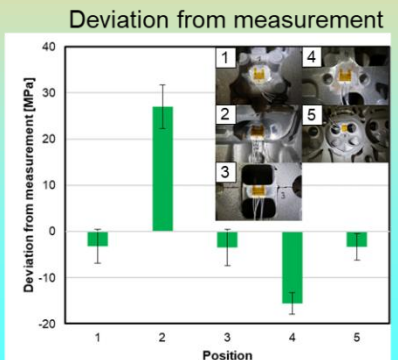
Fire deck
(cylinder head bottom)



(a)



(b)



Radiography

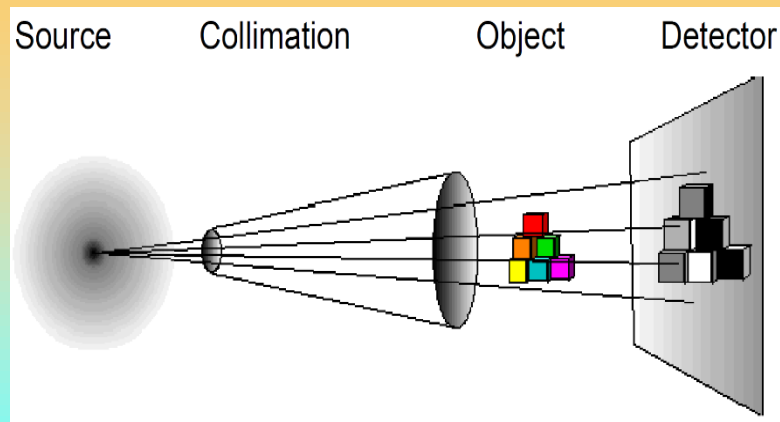
- Radiography = „Drawing with radiation”
- Radiography is a direct imaging technique, where the visual representation of an object is obtained nondestructively by detecting the modification of an incident beam as it passes through the matter
- Neutrons penetrate deep into bulk materials (metals, alloys, stones etc.)
- **Transforms invisible radiation into visible images**



X-ray radiography

Röntgen

Neutrons and X-rays complement each other



Transmission of neutron or X-ray beam through an object provides a contrast image in the detector

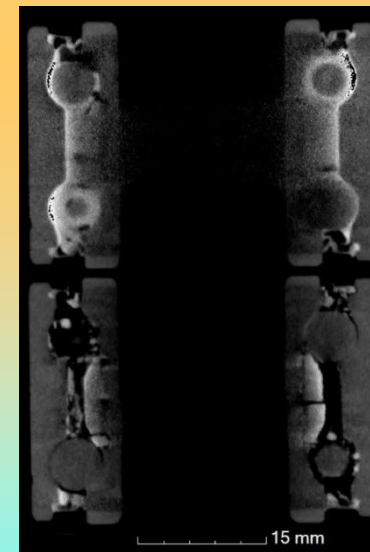
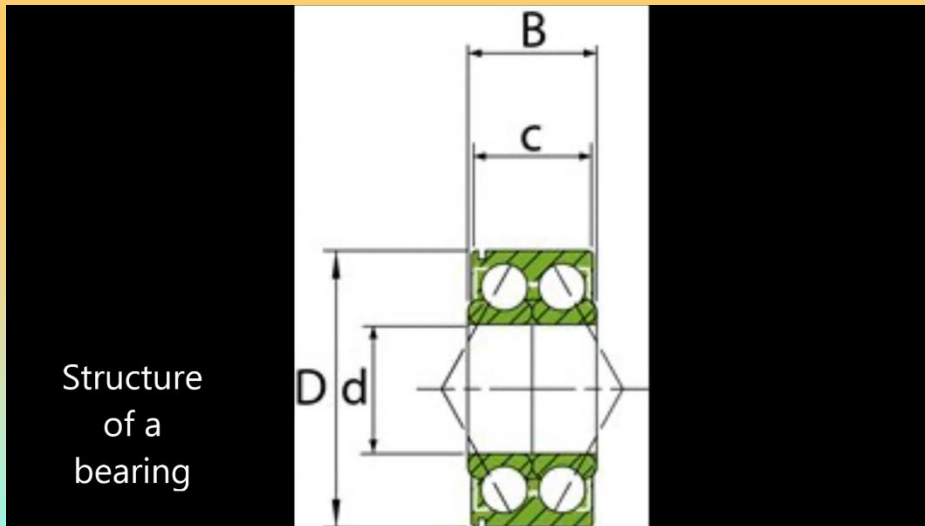
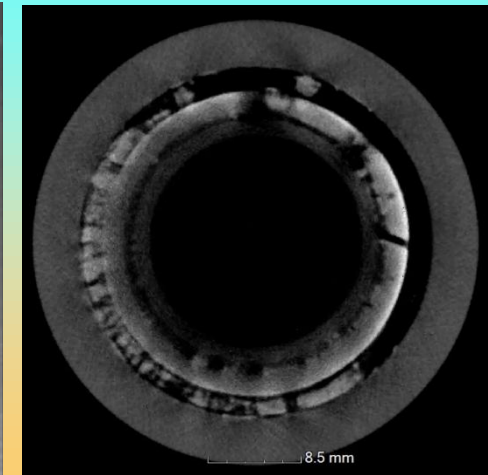
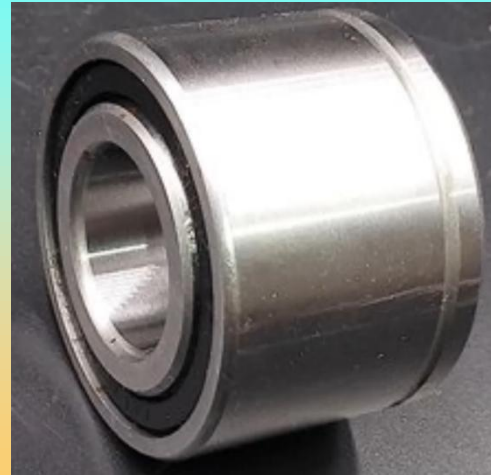


X-rays have high penetration through soft/organic matter

Neutrons penetrates rather thick metal/hard matter objects

Minőség-ellenőrzés – meghibásodott golyóscsapágó vizsgálata

- 100Cr6 high-carbon chromium steel, organic grease -> problem for X-rays
- Unexpected damage observed during use of a double row bearing, due to insufficient lubrication
- Before taking it apart for further studies (e.g. diffraction), the exact geometry can be recorded
- Collaborator: Rogante Engineering Office, Italy



A neutrontomográfia adatok függőleges és vízszintes metszetei, valamint 3D ábrázolása. Figyeljük meg az alsó alkatrészt átszövő repedéshálózatot és a golyók körüli kenőanyag hiányát