

# **Neutrons.**

## **Sources and theory basics.**

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# SNS (Oak Ridge, USA) First neutrons on 28 April 2006!

Today SNS is operating with beam to target.  
Power on target during **January 2008** reached a  
world record of **305 kW**.



View of J-PARC  
in May 2007



Site; Tokai, Ibaraki  
150km to the north  
from Tokyo

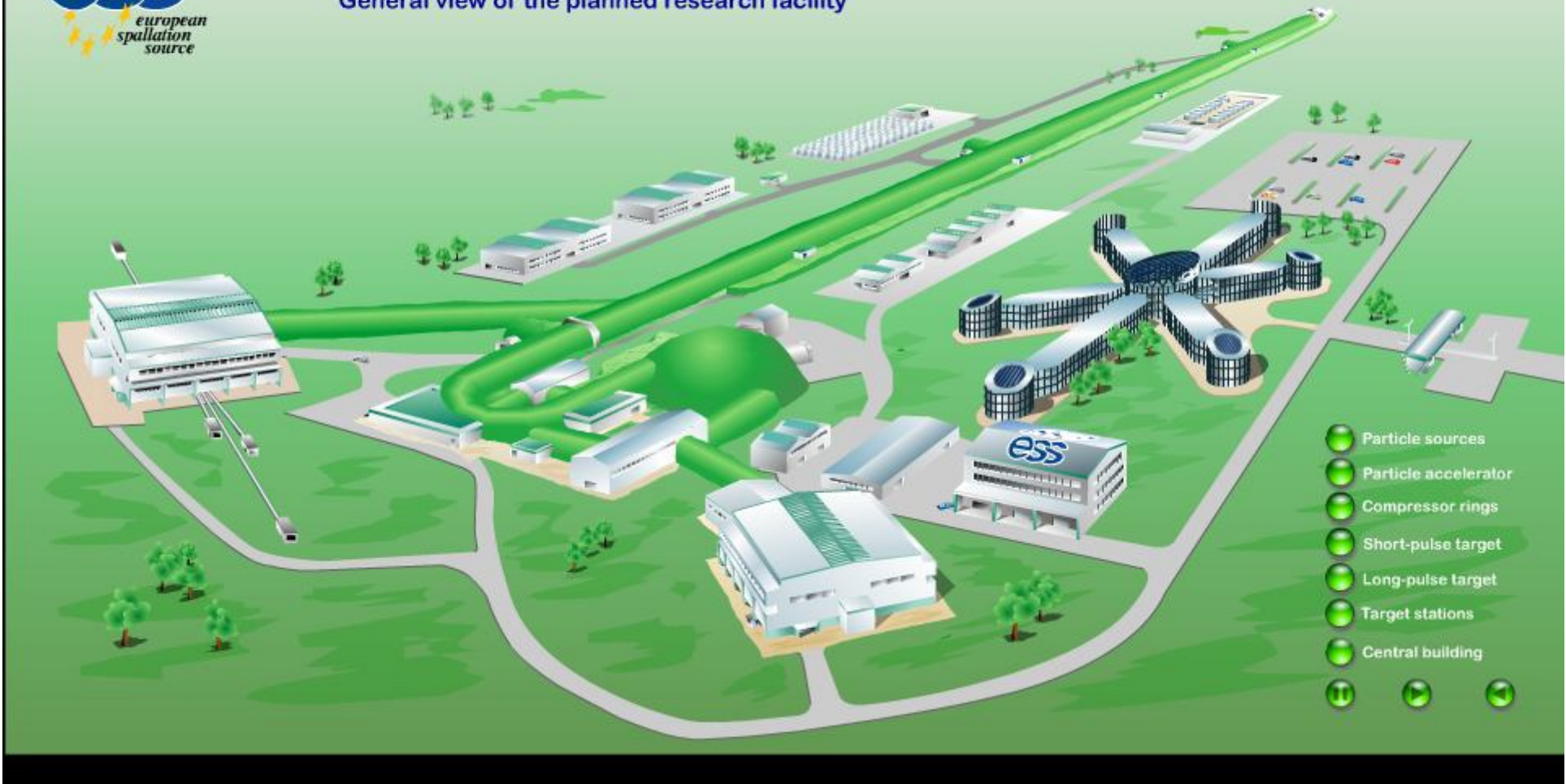
The first neutrons from liquid mercury target  
30 May 2008!



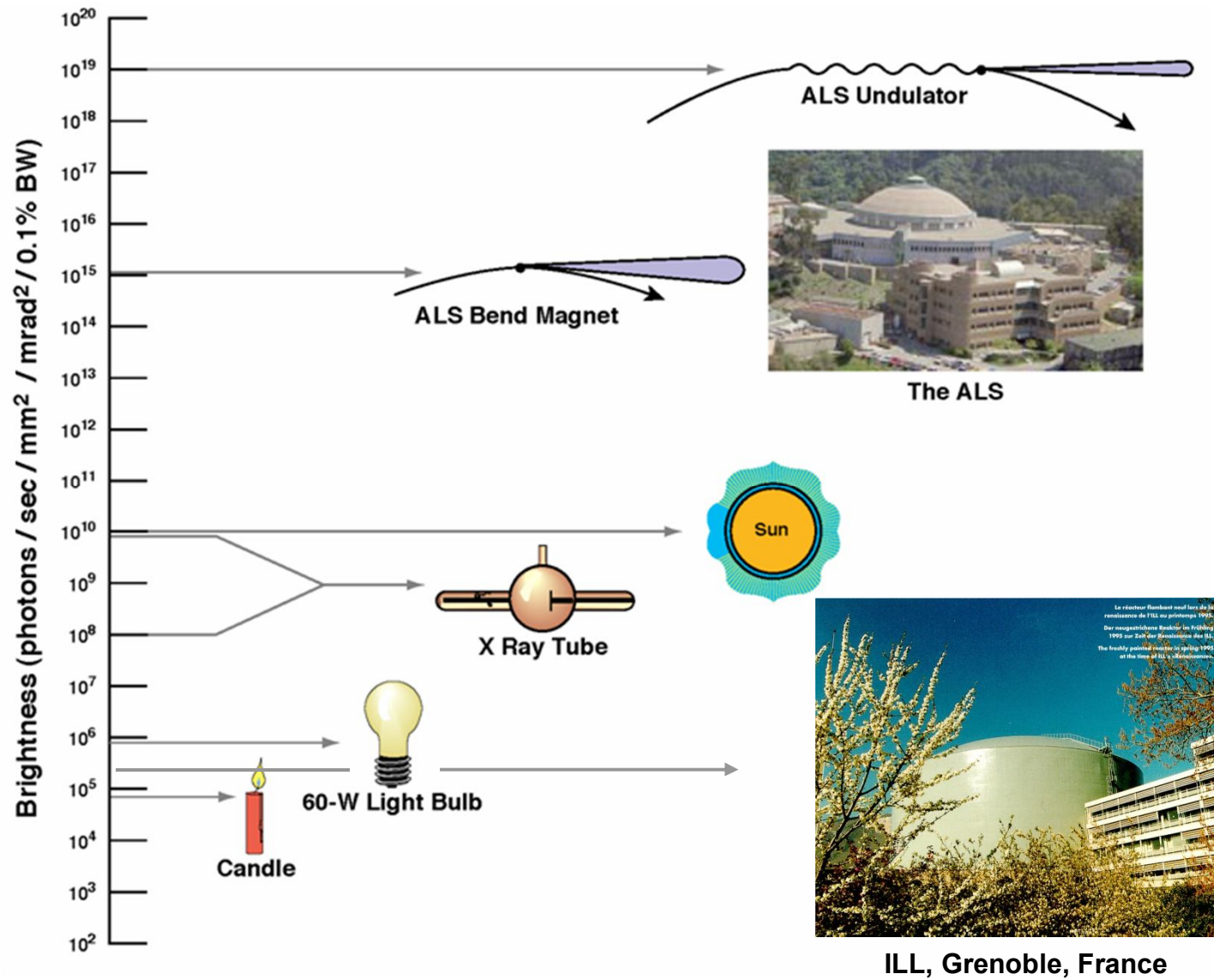
# The European Spallation Source



European Spallation Source (ESS) – A scientific project for the future  
General view of the planned research facility



# Brightness comparison of different radiation sources



# Neutron as a particle

According to quark theory, neutron consists of two down (d) and one up (u) quarks.

Quarks	Charge / e	Mass / $m_e$
'down' d	- 1/3	600
'up' u	+ 2/3	600

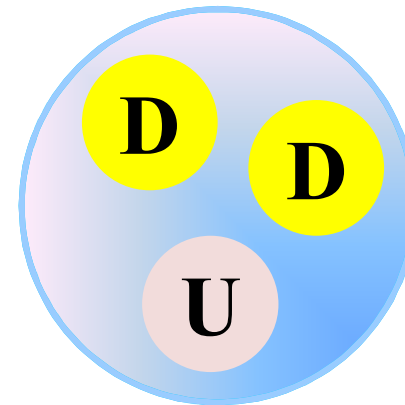
## Neutron

mass  $m_n = 1.175 \times 10^{-27}$  кг

el. charge = 0; спин =  $\frac{1}{2}$

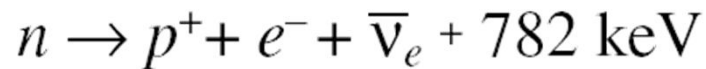
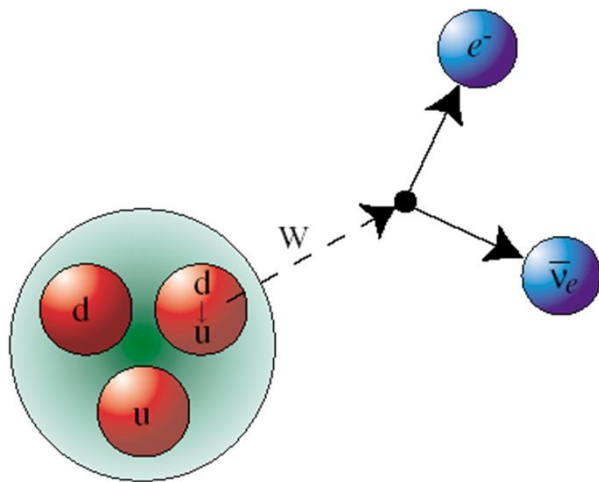
magnetic dipole moment  $\mu_n = -1.913 \mu_N$ , where

nuclear magneton  $\mu_N = eh/4\pi m_p = 5.051 \times 10^{-27}$  JT<sup>-1</sup>



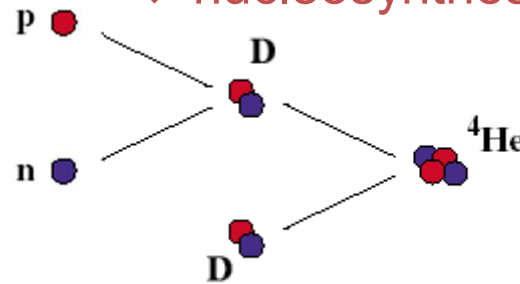
# Neutron as a particle

## Neutron Beta Decay



Why it is important to know precisely the neutron life-time?

- ❖ verification of Standard model: matrix element  $V_{ud}$
- ❖ parameters of weak interactions
- ❖ nucleosynthesis during the Big Bang



$$\tau_n = 885.7 \pm 1.0 \text{ sec}$$

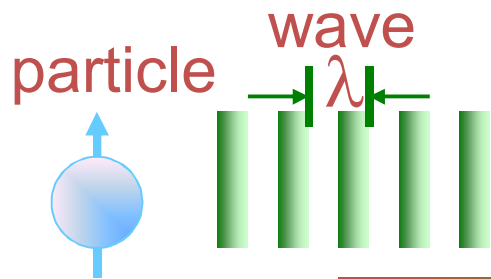
# Neutron as a particle and a wave

Neutron possesses properties of both particle and a wave:

$$E = m_n v^2 / 2 = k_B T = (h k / 2\pi)^2 / 2m_n; \quad k = 2\pi / \lambda = m_n v / (h / 2\pi)$$

$$\lambda \text{ (nm)} = 395.6 / v \text{ (m/s)}$$

$$E \text{ (meV)} = 0.02072 k^2 \text{ (k in nm}^{-1}\text{)}$$



$$1 \text{ meV} = 8.066 \text{ cm}^{-1} = 11.6 \text{ K} = 1.6 \times 10^{-22} \text{ J}$$



**Ultra-cold**

**cold**

**thermal**

**hot**

Energy (meV)	<0.0001	0.001 - 10	5 - 100	100 - 500
Wavelength (Å)	~ 900	4 - 300	1 - 4	0.4 - 1
Temperature (K)	~ 0.001	0.01 - 120	60 - 1000	1000 - 6000

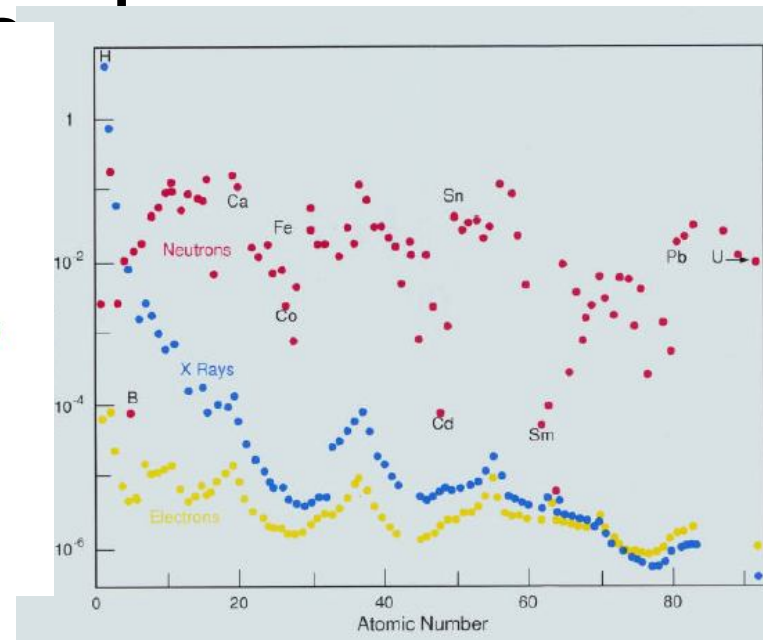
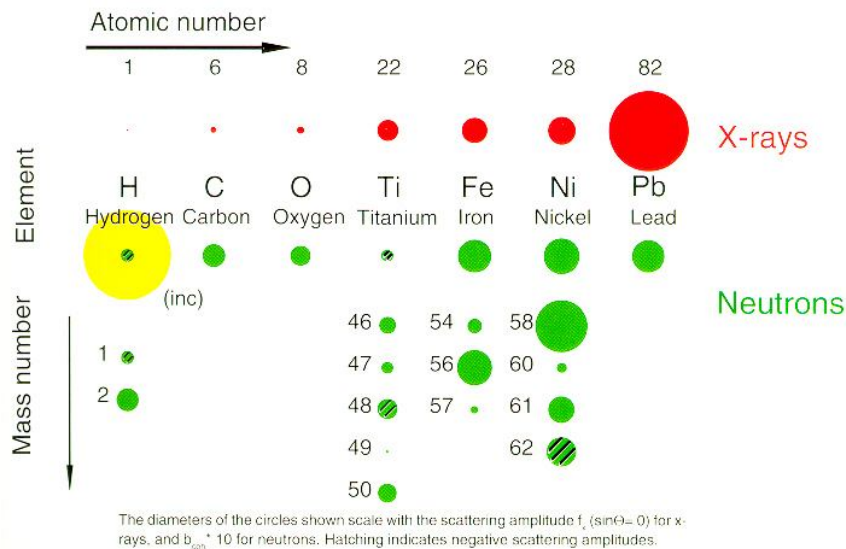


# Neutrons for condensed matter research

Property	Applicability
No charge, small cross sections	<ul style="list-style-type: none"><li>• can investigate bulk material</li><li>• can treat scattering in first Born approximation</li><li>• complex sample environment</li><li>• no damage to biological samples</li></ul>
Wavelength of thermal neutrons in the range of interatomic distances	<ul style="list-style-type: none"><li>• can determine crystal structures and atomic positions</li></ul>
Magnetic moment	<ul style="list-style-type: none"><li>• can examine magnetic properties on microscopic scale</li></ul>
Kinetic energy in the range of elementary excitations	<ul style="list-style-type: none"><li>• can investigate dynamical properties and excitation energies</li></ul>
Scattering by nuclei	<ul style="list-style-type: none"><li>• can “see” hydrogen, can distinguish isotopes → contrast variation</li></ul>
Coherent and incoherent scattering	<ul style="list-style-type: none"><li>• collective phenomena as well as single atom effects</li></ul>



# Neutrons for condensed matter



The diameters of the circles shown scale with the scattering amplitude  $f_x$  ( $\sin\theta=0$ ) for X-rays, and  $b_{\text{coh}} \times 10$  for neutrons. Hatching indicates negative scattering amplitudes

Penetration depth of thermal neutrons, low energy electrons and 8 keV X-rays into different elements

For neutrons: no regular wavelength dependence of scattering length (which is just a number, not the function of the scattering angle as in the case of X-rays!) and absorption coefficient from atomic number; enormous difference in scattering lengths and absorption coefficients for H and D; huge absorption for Cd, B, Sm, Gd

## Disadvantages

Relatively low intensity of neutron sources  $\Rightarrow$  weak signal, large sample volumes required etc.  
 Strong absorption of some elements, but isotope substitution can cure the problem.  
 Kinematical restrictions limit the achievable energy-momentum range..

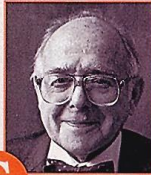


# Neutrons for condensed matter research

## The Nobel Prize in Physics 1994



Clifford G. Shull, MIT, Cambridge, Massachusetts, USA, receives one half of the 1994 Nobel Prize in Physics for development of the neutron diffraction technique.



**S** Shull made use of **elastic scattering** i.e. of neutrons which change direction without losing energy when they collide with atoms.

Because of the wave nature of neutrons, a diffraction pattern can be recorded which indicates where in the sample the atoms are situated. Even the placing of light elements such as hydrogen in metallic hydrides, or hydrogen, carbon and oxygen in organic substances can be determined.

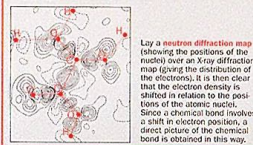
The pattern also shows how atomic dipoles are oriented in magnetic materials, since neutrons are affected by magnetic forces. Shull also made use of this phenomenon in his neutron diffraction technique.



An early (1950) neutron diffractometer with flexible wavelength control here, used by E.O. Wollan and C.G. Shull (standing) at Oak Ridge National Laboratory.

### Neutrons see more than X-rays

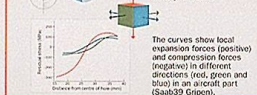
X-rays are scattered by electrons; neutrons by atomic nuclei. With X-rays it is easier to see atoms that have many electrons. Hydrogen, for example, which has only one electron, is not so easy to see. With neutrons, all kinds of atoms are visible.



Layer a neutron diffraction map following the positions of the nuclei over an X-ray diffraction map (showing the distribution of the electrons), it is then clear that the electron density is shifted in relation to the positions of the atomic nuclei. Since a chemical bond involves a shift in electron position, a direct picture of the chemical bond is obtained in this way.

### Neutrons reveal inner stresses

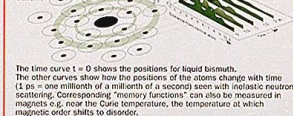
A hole has been punched in an important metal aircraft part. Does the part match up? Neutron diffraction can show how much the distance between the atoms has changed and hence the internal forces remaining round the hole after it has been punched.



The curves show local expansion forces (positive) and compression forces (negative) in different directions (red, green and blue) in an aircraft part (Saab-39 Gripen).

### Neutrons show what atoms remember

of their earlier positions when they move randomly in relation to each other in liquids and melts. Even here there is in fact some local order. The atoms cannot move infinitely close to each other. Some distances are more common than others.

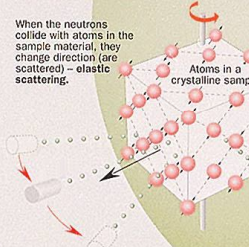


The time curve  $t = 0$  shows the positions for liquid bismuth. The other curves show how the positions of the atoms change with time (1 ps = one millionth of a millimetre of a second) seen with inelastic neutron scattering. Corresponding "memory functions" can also be measured in magnets e.g. near the Curie temperature, the temperature at which magnetic order shifts to disorder.

Neutrons behave as particles and as waves

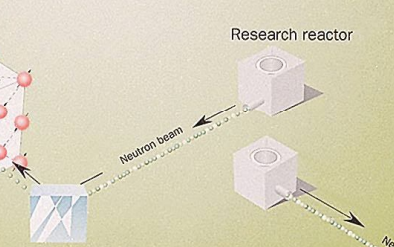
## Neutrons reveal structure and dynamics

Neutrons show where atoms are



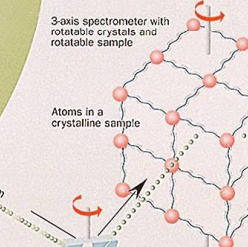
When the neutrons collide with atoms in the sample material, they change direction (are scattered) – elastic scattering.

Neutrons bounce against atomic nuclei. They also react to the magnetism of the atoms.



Research reactor  
Neutron beam  
Crystal that sorts and forwards neutrons of a certain wavelength (energy) – monochromatized neutrons

Neutrons show what atoms do



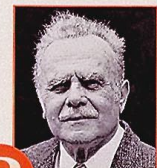
3-axis spectrometer with rotatable crystals and rotatable sample  
Atoms in a crystalline sample  
When the neutrons penetrate the sample they start or cancel oscillations in the atoms. If the neutrons create phonons or magnons they themselves lose the energy (are absorbed) – inelastic scattering

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – monochromatized neutrons

Changes in the energy of the neutrons are first analysed in an analyser crystal...  
...and the neutrons then counted in a detector.

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.

Bertram N. Brockhouse, McMaster University, Hamilton, Ontario, Canada, receives one half of the 1994 Nobel Prize in Physics for the development of neutron spectroscopy.



**B** Brockhouse made use of **inelastic scattering** i.e. of neutrons, which change both direction and energy when they collide with atoms. They then start or cancel atomic oscillations in crystals and record movements in liquids and melts. Neutrons can also interact with spin waves in magnets.

With his 3-axis spectrometer Brockhouse measured energies of phonons (atomic vibrations) and magnons (magnetic waves). He also studied how atomic structures in liquids change with time.

**How it started**  
Brockhouse and Shull made their pioneering contributions at the first nuclear reactors in the USA and Canada back in the 1940s and 1950s. It was then that the resources of the reactors became available for peacetime research.

**... how it continues**  
Thousands of researchers are now working at the many neutron research centers throughout the world. New and very advanced neutron scattering installations have been built and more are planned in Europe, the USA and Asia. At these super-installations the researchers are studying the structure of new ceramic superconductors, molecular movements on surfaces of interest for catalytic exhaust cleaning, virus structures and the connection between the structure and the elastic properties of polymers.

KUNGLIGA VETENSKAPSAKADEMIEN  
THE ROYAL SWEDISH ACADEMY OF SCIENCES

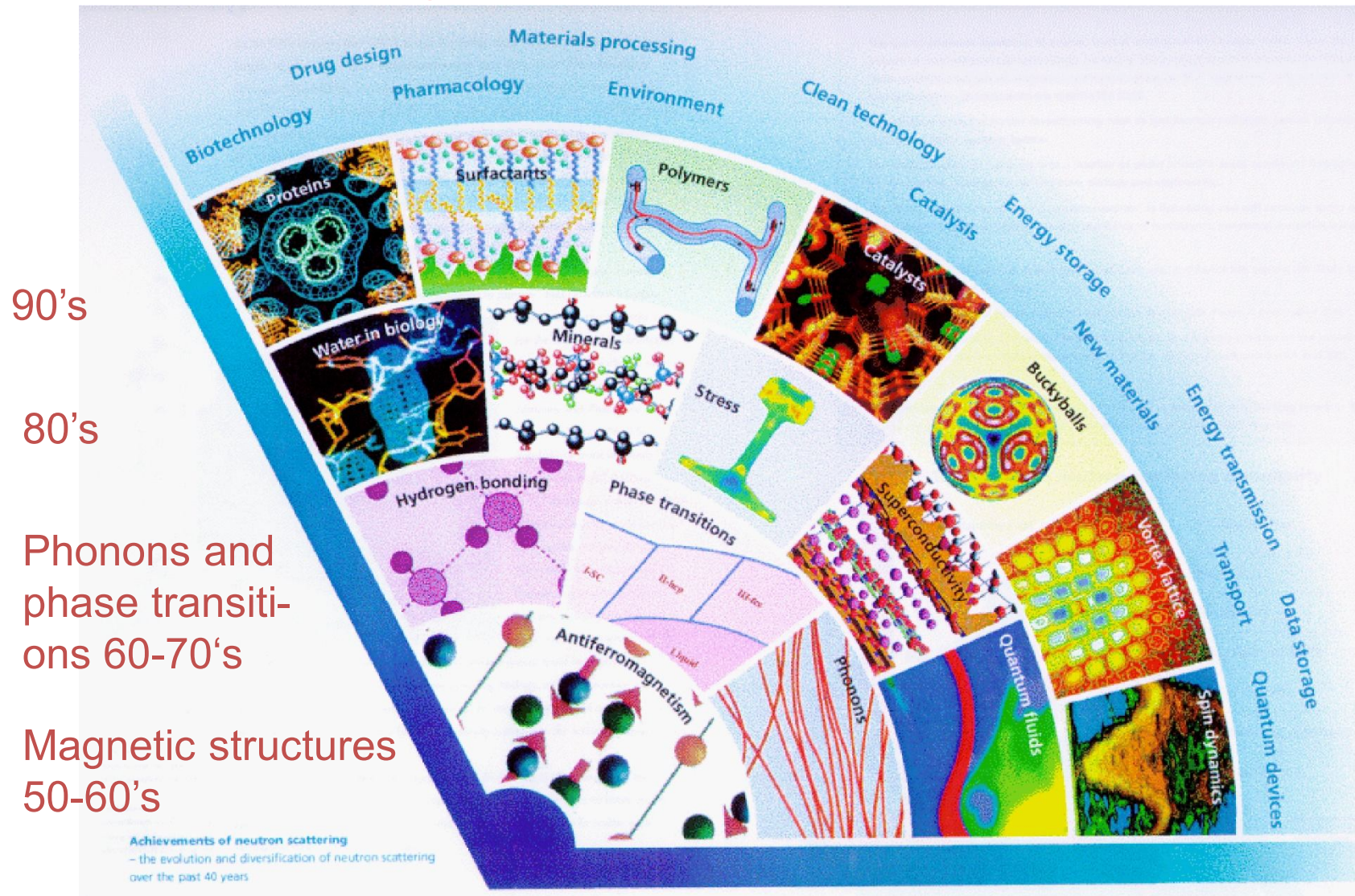
Information Department, Box 50005, S-104 05 Stockholm, Sweden. Tel +46-8 673 95 00, fax +46-8 15 55 70. Editors: Solgard Björn-Rasmussen, Margareta Wiberg Holmström, The Royal Swedish Academy of Sciences. Authors: Professor Erik Bäckström and Professor Carl Westberg, Department of Physics, Uppsala University, Members of The Nobel Committee for Physics. Layout and Illustrations: Kjell Lundin, Explicare AB. Printed by: Tryckindustri, 1994.

- Further reading:
- D.J. Hughes *The Neutron Reactor as a Research Instrument*, SCIENTIFIC AMERICAN, VOL. 159, AUGUST 1953, P. 21.
  - H. Lenzlinger and J.L. Finney *The European Spallation Source*, EUROPHYSICS NEWS, VOL. 25, P. 37, 1994.
  - Information about the Nobel Prize in Physics 1994 (press release), THE ROYAL SWEDISH ACADEMY OF SCIENCES.

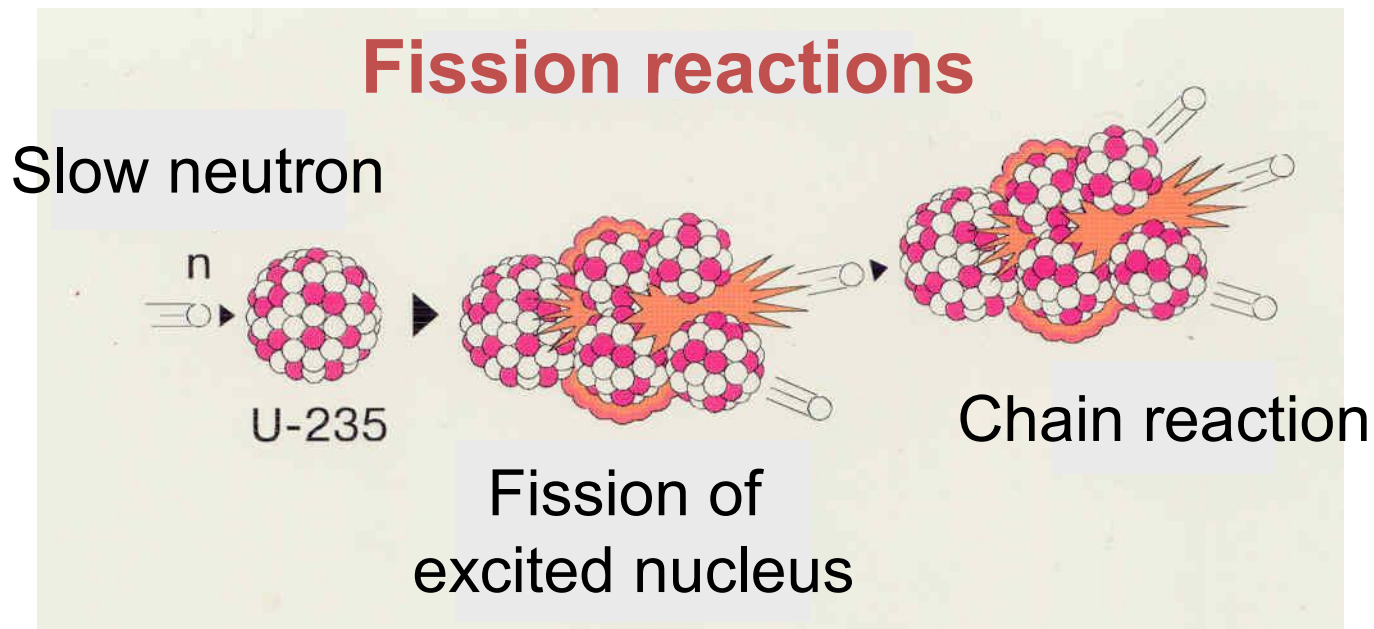


# Neutrons for condensed matter research

Interdisciplinary character of research with neutrons



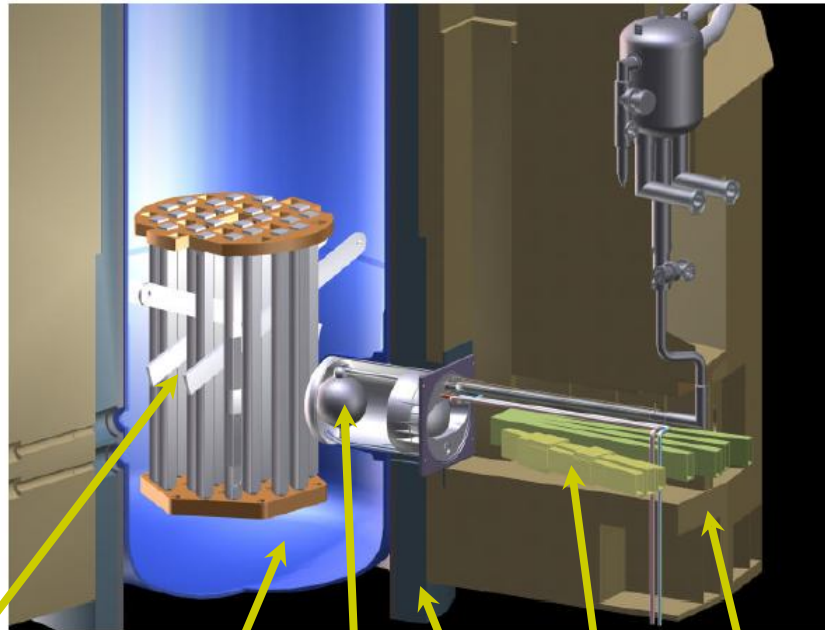
# Production of neutrons



Each fission act produces in average  $\sim 2.5$  neutrons with energy release about 200 MeV. In the case of chain (self sustained) reaction 1 neutron is necessary to ensure the next fission, 0.5 is lost because of absorption inside the neutron source and 1 neutron can be extracted for use in the experiment

# Production of neutrons

## Steady state nuclear reactor



reactor core with  
nuclear fuel and  
control elements

Neutron  
moderator

Neutron  
channels

reflector

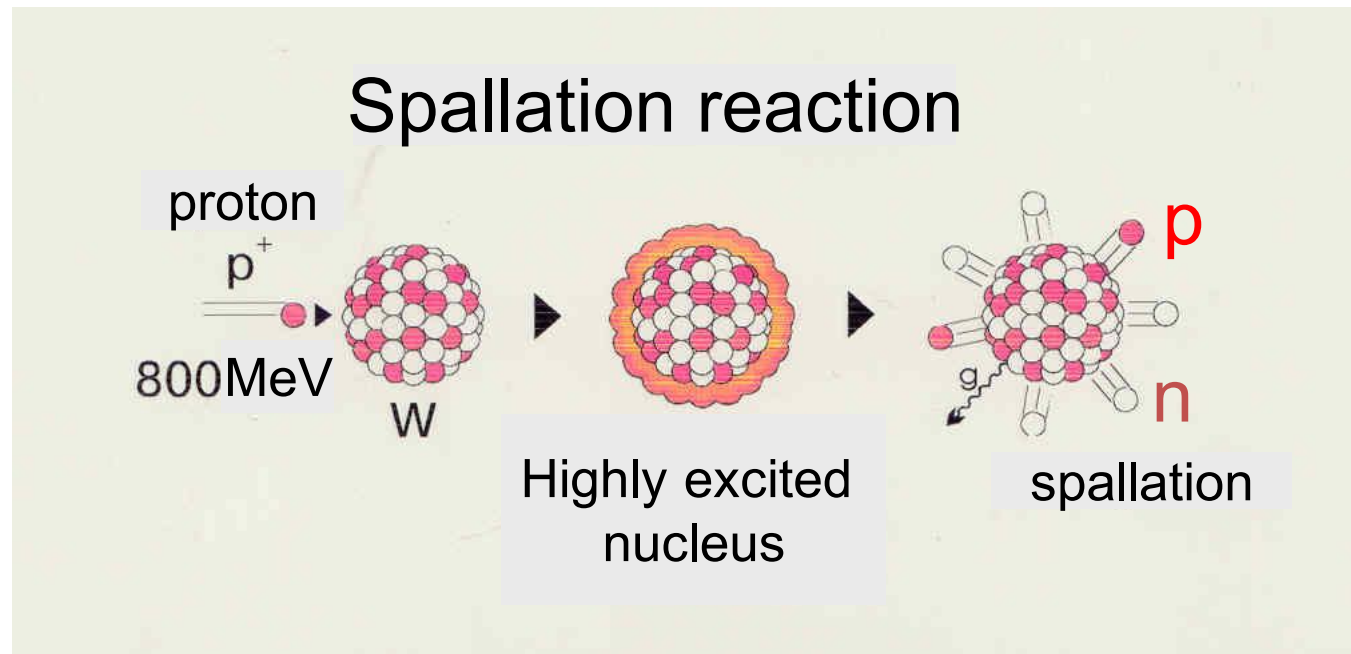
Cooling system

Biological shield



Research nuclear reactor.

# Production of neutrons

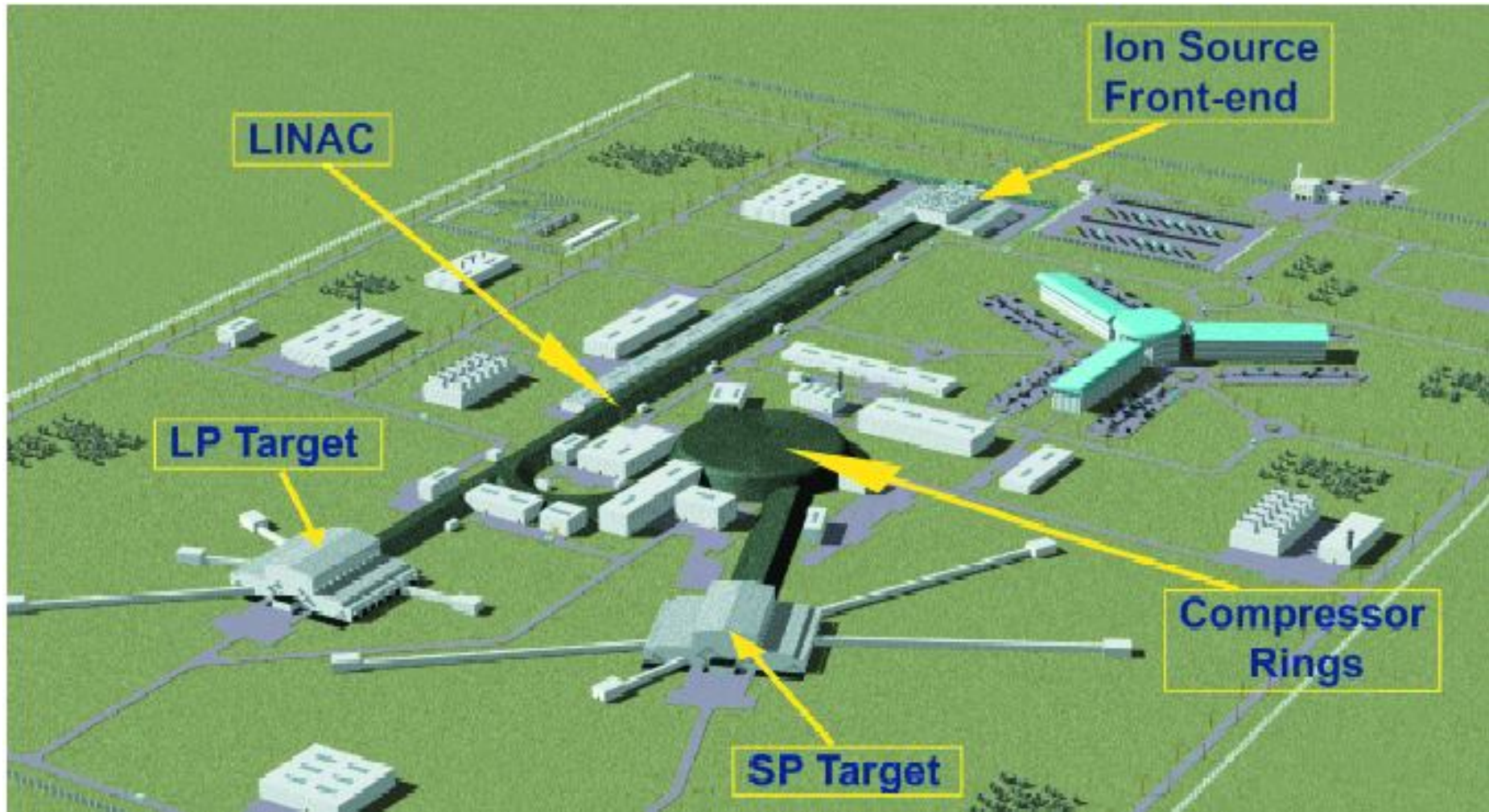


Spallation reaction gives up to 30 neutrons per 1 proton. There exists *empirical* expression for the estimation of neutron yield from the target when proton energy exceeds 120 MeV

$$N_n(E,A) = \begin{cases} 0.1 \times E_{\text{GeV}} \times (A+20) & \text{for non-fissile target} \\ 50 \times E_{\text{GeV}} & \text{for uranium-238} \end{cases}$$

# Production of neutrons

## Principal scheme of spallation neutron source



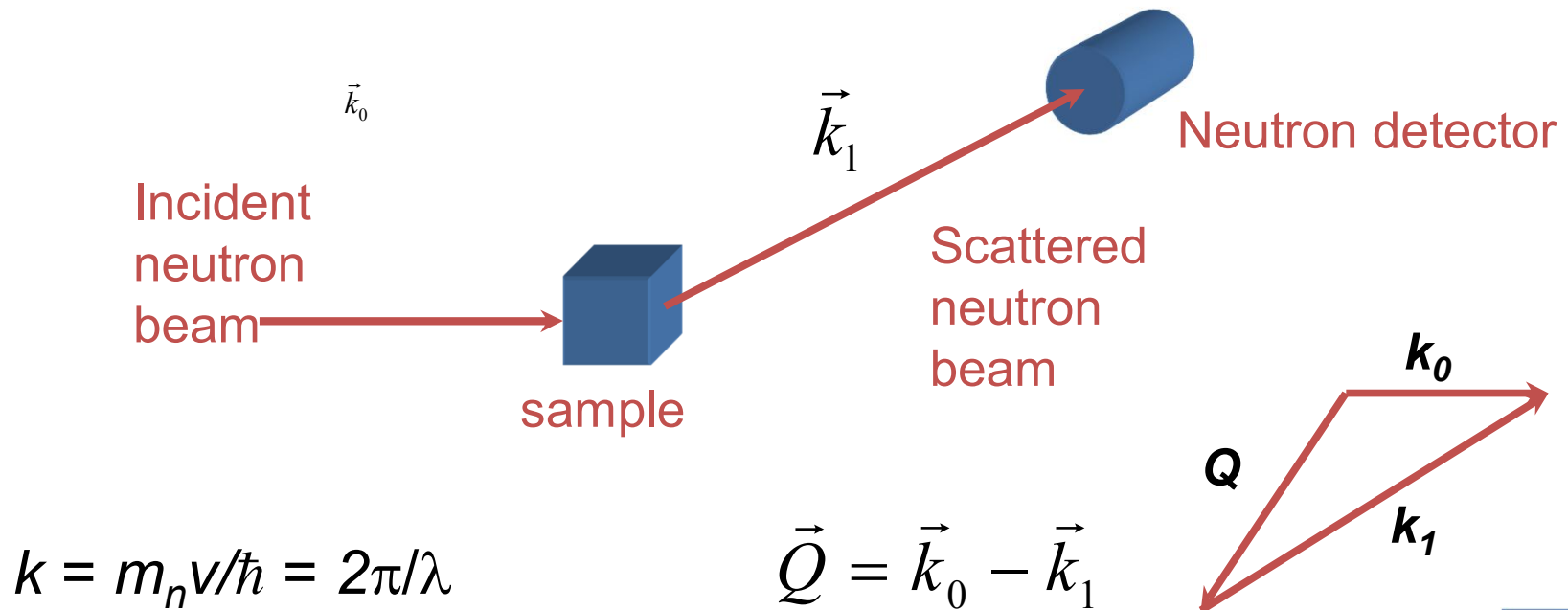


# Components of neutron scattering instruments

What do we need to perform good neutron experiment?

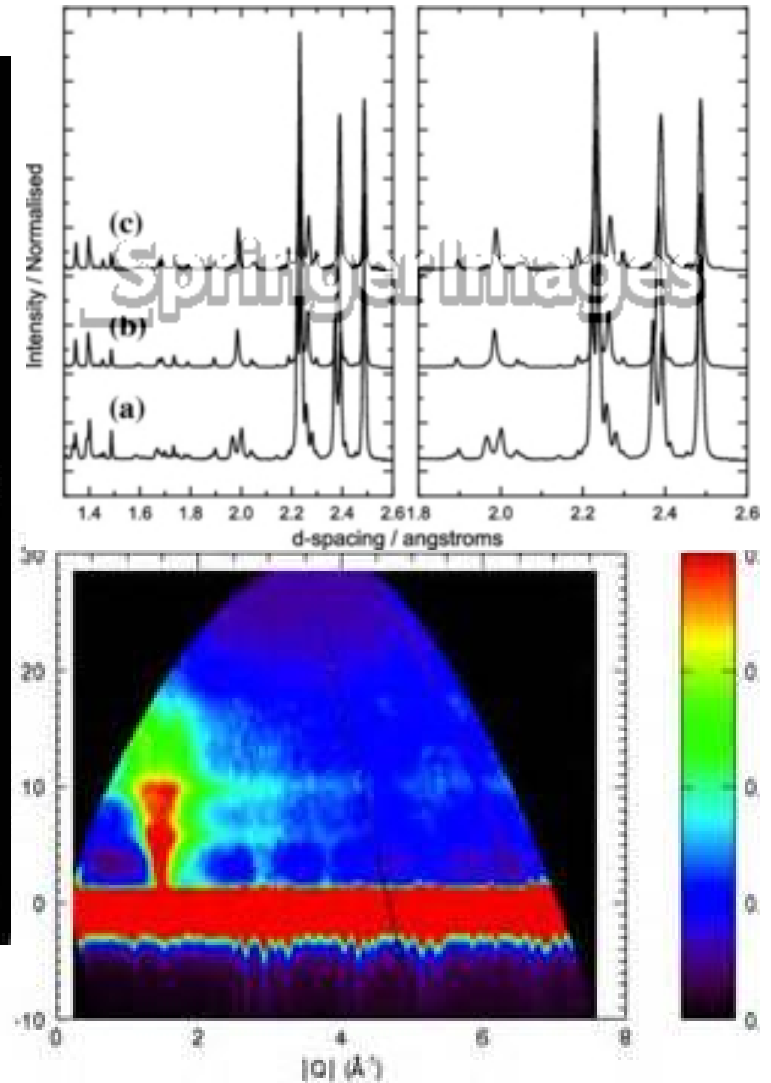
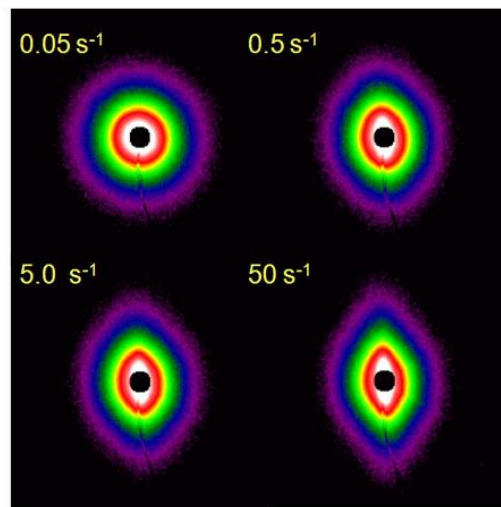
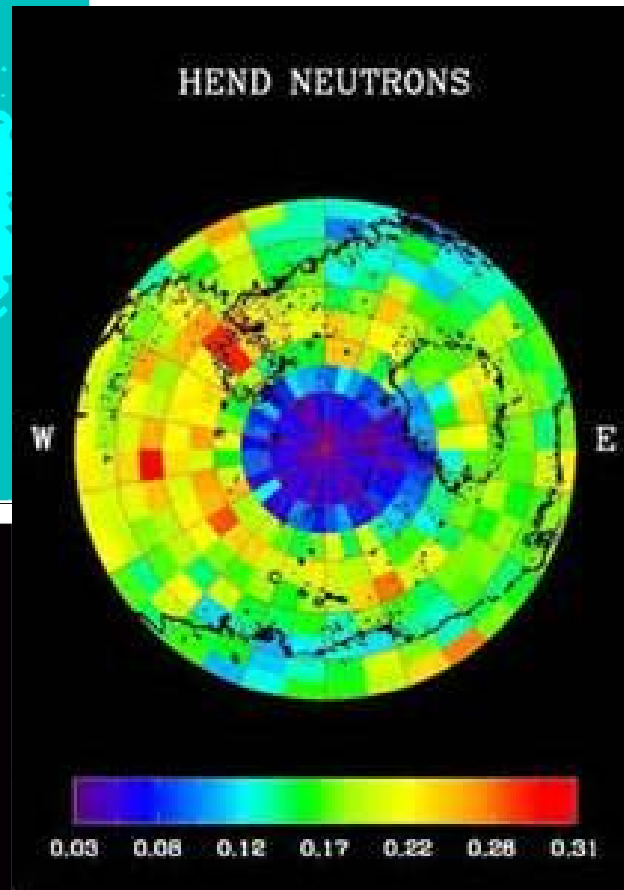
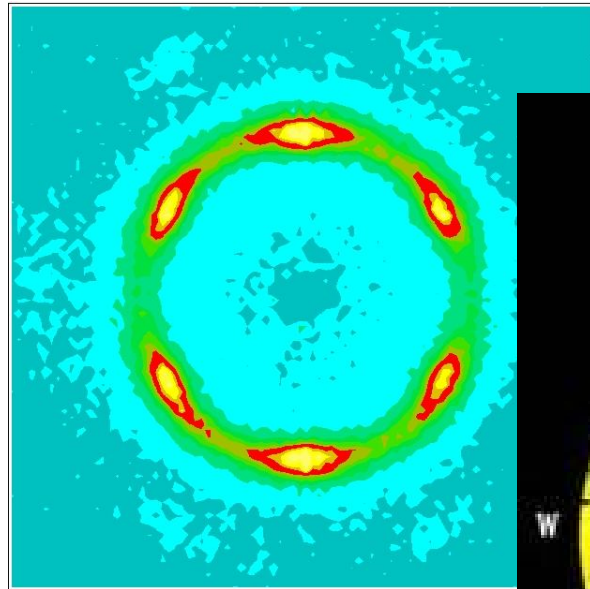
- ❖ Intense neutron source with efficient moderator
- ❖ neutron shaping, guiding and velocity selection system
- ❖ interesting sample for the study
- ❖ system to analyse parameters of scattered neutron beam
- ❖ advanced neutron detector

Typical scheme of neutron scattering experiment



## Examples of registered patterns on a detector

From the analysis of the signal on a detector, using advanced mathematical models one can extract information about characteristics of a sample under investigation



# Cross-sections definitions

Let the sample is irradiated by flux  $\Phi_{in}$  of neutrons per unit area per unit time. We define  $I_s$  and  $I_a$  as a number of neutrons scattered and absorbed by the sample per unit time, respectively. Then the **total cross sections** of scattering and absorption of neutrons by the sample are defined as:

$$I_s = \Phi_{in} \sigma_s$$

$$I_a = \Phi_{in} \sigma_a$$

Dimensionality of the total cross sections is [barn]:

$$1\text{barn} = 10^{-24}\text{cm}^2.$$

By definition the flux  $\Phi_{in} = 1/S \cdot t = v_0/N$ , where  $S$  – is the area irradiated by neutrons,  $t$  – time of irradiation,  $v_0$  – velocity of neutrons,  $V$  – volume of the irradiated sample.



# Nuclear neutron scattering

The interaction of neutron with nuclei is described by Fermi pseudopotential:

$$H = \frac{2\pi\hbar^2}{m_n} b\delta(\vec{r} - \vec{R})$$

Where  $m_n$  – neutron mass,  $b$  – scattering length,  $\vec{R}$  – vector defining the position of a nucleus in space.

Let us first consider the scattering of a neutron on isolated nucleus under the following assumptions:

- neutron wavelength is much larger than the scattering length which is the radius of action of nuclear force (this is the limitation of applicability of Fermi pseudopotential)
- the scattering is purely elastic, e.g. the energy of neutron is conserved before and after the scattering
- the absorption of neutrons by the nucleus can be neglected



# Nuclear neutron scattering

The nucleus is irradiated  
by plane wave

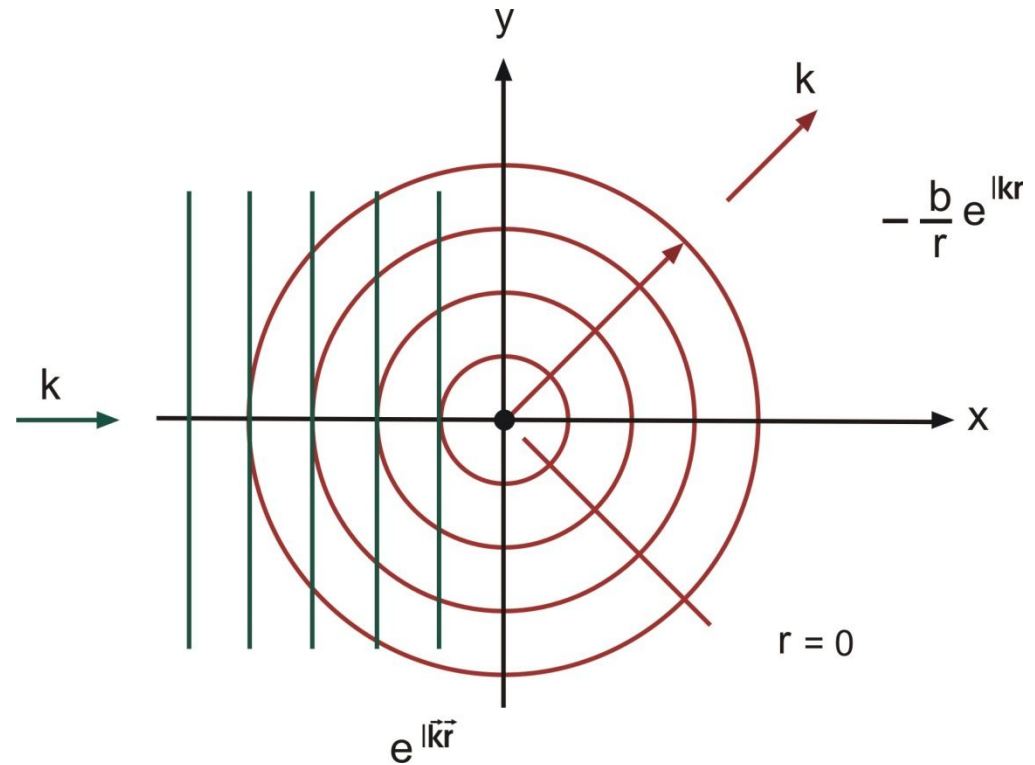
$$\Psi_{\text{in}} = \frac{1}{\sqrt{V}} e^{i\vec{k}_0 \vec{r}}$$

After the scattering  
we have a spherical wave

$$\Psi_{\text{out}} = \frac{1}{\sqrt{V}} \left( -\frac{b}{r} e^{ik_0 r} \right)$$

Then the flux of scattered neutrons is

$$\Phi_{\text{out}} = v_0 \Psi_{\text{out}}^* \Psi_{\text{out}} = |b|^2 \frac{1}{r^2} \frac{v_0}{V}$$



Place the nucleus at  
coordinate origin

# Nuclear neutron scattering

The number of neutrons passing through the element of spherical surface  $S = r^2 d\Omega$  is equal

$$dI_{\text{out}} = \Phi_{\text{out}}(\vec{r}) r^2 d\Omega = |b|^2 \frac{v_0}{V} d\Omega$$

And **differential scattering cross section** (i.e. the probability that neutron is scattered in a direction defined by a vector  $\underline{r}$  into an element of solid angle  $d\Omega$ ) is equal

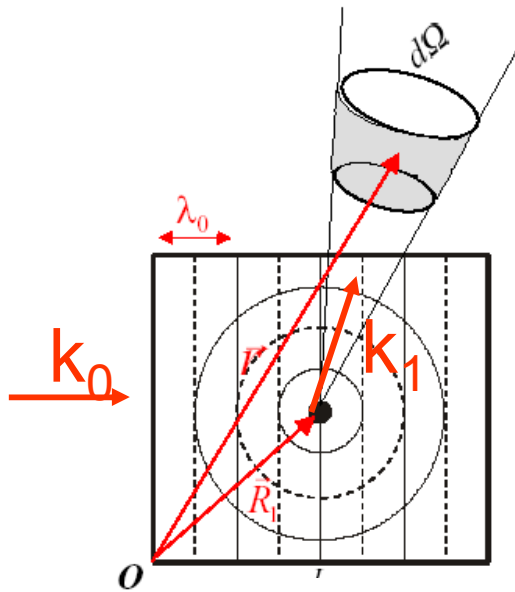
$$\frac{d\sigma}{d\Omega} = \frac{dI_{\text{out}}}{\Phi_{\text{in}} d\Omega} = |b|^2$$

And the total scattering cross section will be

$$\sigma = \int (d\sigma/d\Omega) d\Omega = 4\pi |b|^2 \quad \text{ISOTROPIC!!!}$$



# Nuclear neutron scattering



Let us now consider the scattering by a nucleus which position is defined by a vector  $\vec{R}_i$ . The wave function of incident neutrons will again be a plane wave:

$$\Psi_{\text{in}} = \frac{1}{\sqrt{V}} e^{i\vec{k}_0 \vec{r}}$$

And for the scattered neutrons

$$\Psi_{\text{out}} = \frac{1}{\sqrt{V}} e^{i\vec{k}_0 \vec{R}_i} \left[ \frac{-b_i}{|\vec{r} - \vec{R}_i|} e^{ik_0 |\vec{r} - \vec{R}_i|} \right]$$

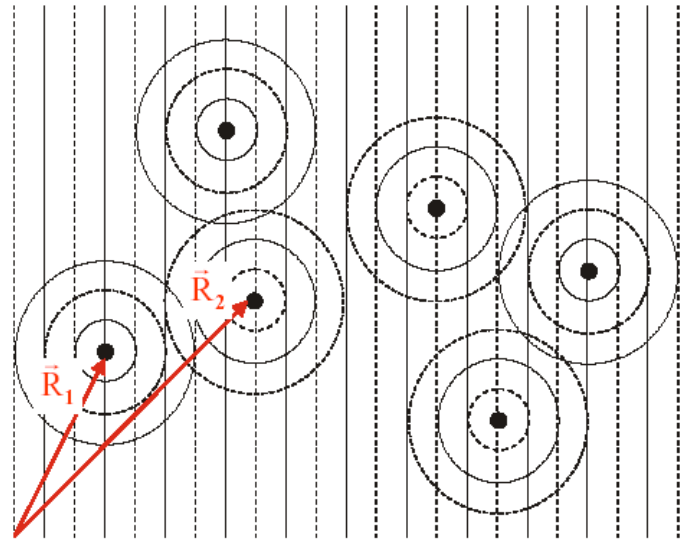
For  $r \rightarrow \infty$  we have:

$$|\vec{r} - \vec{R}_i| = r - \frac{\vec{r}}{r} \cdot \vec{R}_i + O\left(\frac{1}{r}\right)$$

$$e^{ik_0 |\vec{r} - \vec{R}_i|} = e^{ik_0 r} e^{-ik_0 \frac{\vec{r}}{r} \cdot \vec{R}_i} = e^{ik_0 r} e^{-i\vec{k}_1 \cdot \vec{R}_i}$$

$$\Psi_{\text{out}} = \frac{1}{\sqrt{V}} e^{-i\vec{k}_1 \cdot \vec{R}_i} \left( \frac{-b_i}{r} e^{ik_0 r} \right)$$

# Nuclear neutron scattering



The resulting neutron flux after scattering on the nuclei  $\underline{\mathbf{R}}_i$  and  $\underline{\mathbf{R}}_j$  will be equal

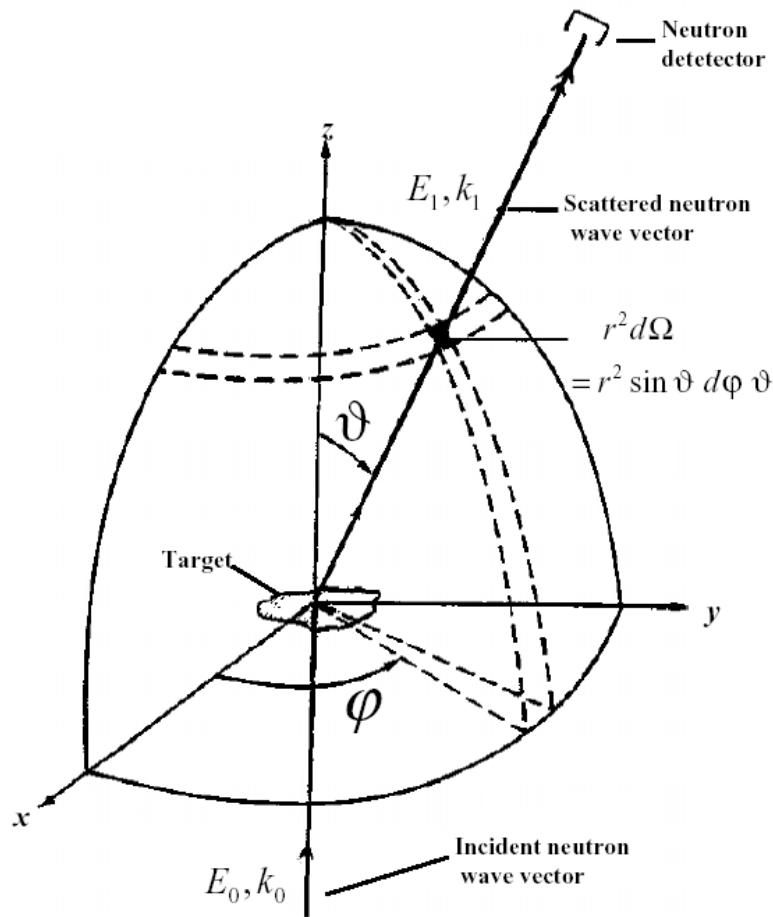
$$\Phi_{\text{out}}^{i,j} = \frac{v_0}{V} \Psi_{\text{out}}^i * \Psi_{\text{out}}^j = \frac{v_0}{V} b_i b_j e^{i\vec{k}_1 \vec{R}_i} e^{-i\vec{k}_1 \vec{R}_j}$$

Therefore, differential cross section for N nuclei:

$$\frac{d\sigma}{d\Omega} = \sum_{i,j}^N b_i b_j e^{i\vec{Q}(\vec{R}_i - \vec{R}_j)}, \quad \text{where } \vec{Q} = \vec{k}_1 - \vec{k}_0$$



# Nuclear neutron scattering



Now, consider more common case, when the velocity of neutron is changing during the scattering process due the fact that atoms perform thermal vibrations and their coordinates in space become time dependent. This means that  $v_1 \neq v_0$  and  $\mathbf{R}_i = \mathbf{R}_i(t)$ . Then the above formula can be written in a more common form giving the **double differential cross section**. This cross section defines the probability of neutron being scattered in a direction  $\underline{r}$  into an element of solid angle  $d\Omega$  with the neutron energy change  $E = E_1 - E_0$  in an interval  $dE$ .

# Nuclear neutron scattering

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{k_1}{k_0} \sum_i \sum_j \int_{-\infty}^{+\infty} \left\langle \mathbf{b}_i \mathbf{b}_j e^{i\vec{Q}\vec{R}_i(t)} e^{-i\vec{Q}\vec{R}_j(0)} \right\rangle e^{-i\omega t} dt$$

Angular brackets mean averaging over all values of nuclei coordinates in a space  $\mathbf{R}_i(t)$ , isotope content and all possible spin states of nuclei. It is known, that the scattering length depends on a relative orientation of nucleus and neutron spins. For parallel spins denote the scattering length as  $b^+$ , and for anti parallel as  $b^-$ . Scattering length is also different for different isotopes of the chosen chemical element. Then one obtains:

$$\langle \mathbf{b}_i \mathbf{b}_j \rangle = \begin{cases} \langle \mathbf{b}_i \rangle \langle \mathbf{b}_j \rangle & \text{for } i \neq j \\ \langle |\mathbf{b}_i|^2 \rangle & \text{for } i = j \end{cases}$$



# Nuclear neutron scattering

Then  $\langle \mathbf{b}_i \mathbf{b}_j \rangle = \overbrace{\langle \mathbf{b}_i \rangle \langle \mathbf{b}_j \rangle}^{\text{coherent term}} + \underbrace{\delta_{ij} \left( \langle |\mathbf{b}_i|^2 \rangle - |\langle \mathbf{b}_i \rangle|^2 \right)}_{\text{incoherent term}}$

$$b_{\text{coh}}^2 = \langle \mathbf{b}_i \rangle^2 \qquad b_{\text{inc}}^2 = \langle |\mathbf{b}_i|^2 \rangle - |\langle \mathbf{b}_i \rangle|^2$$

Consequently, neutron cross sections will consist of two terms – coherent and incoherent:

$$\sigma = \sigma_{\text{coh}} + \sigma_{\text{inc}}; \qquad \sigma_{\text{coh}} = 4\pi b_{\text{coh}}^2; \qquad \sigma_{\text{inc}} = 4\pi b_{\text{inc}}^2$$

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{coh}} + \left( \frac{d\sigma}{d\Omega} \right)_{\text{inc}} = \underbrace{\left| \sum_i^N \langle \mathbf{b}_i \rangle e^{i\vec{Q}\vec{R}_i} \right|^2}_{\text{coh}} + \underbrace{\left( \langle |\mathbf{b}_i|^2 \rangle - |\langle \mathbf{b}_i \rangle|^2 \right)}_{\text{inc}}$$



# Nuclear neutron scattering

$$\frac{d^2\sigma}{d\Omega d\omega} = \left( \frac{d^2\sigma}{d\Omega d\omega} \right)_{\text{coh}} + \left( \frac{d^2\sigma}{d\Omega d\omega} \right)_{\text{inc}}$$

$$\left( \frac{d^2\sigma}{d\Omega d\omega} \right)_{\text{coh}} = \frac{k_1}{k_0} \sum_i \sum_j b_i^{\text{coh}} b_j^{\text{coh}} S(\vec{Q}, \omega), \text{ где}$$

$$S(\vec{Q}, \omega) = \frac{1}{2\pi} \iint d\vec{r} dt e^{i(\vec{Q}\vec{r} - \omega t)} G_n(\vec{r}, t)$$

$$G_n(\vec{r}, t) = \sum_i \sum_j \int \langle \delta[\vec{r} - \vec{r}' + \vec{R}_j(0)] \cdot \delta[\vec{r}' - \vec{R}_i(t)] \rangle d\vec{r}'$$

$S(\vec{Q}, \omega)$  - Is called the SCATTERING LAW

$G_n(\vec{r}, t)$  - Is called PAIR CORRELATION FUNCTION,

Which is the probability, that if the arbitrarily chosen nucleus  $j$  at a time  $t=0$  had a coordinate  $\underline{\mathbf{R}}_j(0)$ , then at a moment  $t \neq 0$  another atom  $i$  will have a coordinate  $\underline{\mathbf{R}}_i(t)$ .



# Nuclear neutron scattering

$$\left( \frac{d^2\sigma}{d\Omega d\omega} \right)_{\text{inc}} = \frac{k_1}{k_0} \sum_i (b_i^{\text{inc}})^2 S^{\text{inc}}(\vec{Q}, \omega)$$

$$S^{\text{inc}}(\vec{Q}, \omega) = \frac{1}{2\pi} \iint d\vec{r} dt e^{i(\vec{Q}\vec{r} - \omega t)} G_a(\vec{r}, t)$$

$$G_a(\vec{r}, t) = \sum_i \int \langle \delta[\vec{r} - \vec{r}' + \vec{R}_i(0)] \delta[\vec{r}' - \vec{R}_i(t)] \rangle$$

$G_a(\vec{r}, t)$  - Is called an AUTOCORRELATION FUNCTION,

Which is the probability, that if at a time  $t=0$  the arbitrary chosen atom  $i$  had a coordinate  $\underline{\mathbf{R}}_i(0)$ , then at a time  $t \neq 0$  its coordinate will be  $\underline{\mathbf{R}}_i(t)$ .



# Nuclear neutron scattering

Possible types of neutron scattering experiments and corresponding scientific applications

Type of scattering	$\vec{Q}$	$\omega$	$\vec{r}$	$t$	Scattering law	Scientific applications
elastic	$\vec{Q}$	$0$	$\vec{r}$	$\int dt$	$S(\vec{Q}, 0)$	Atomic and magnetic structures
	$\vec{Q} \rightarrow 0$	$0$	$\vec{r} \rightarrow \infty$	$\int dt$	$S(\vec{Q}, 0)$	Submolecular structures
total	$\vec{Q}$	$\int d\omega$	$\vec{r}$	$0$	$S(\vec{Q})$	Disordered structures
inelastic	$\vec{Q}$	$\omega$	$\vec{r}$	$t$	$S(\vec{Q}, \omega)$	Collective excitation
	$ \vec{Q} $	$\omega$	$\vec{r}$	$t$	$S( \vec{Q} , \omega)$	Atomic and molecular spectroscopy
	$\int \vec{Q}$	$\omega$	$r = 0$	$t$	$S(\omega)$	Density of vibrational states
quasi-elastic	$\vec{Q}$	$\omega$ $\downarrow$ $0$	$\vec{r}$	$t$ $\downarrow$ $\infty$	$S(\vec{Q}, \omega)$	Diffusion of atoms and molecules

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# Magnetic neutron scattering

The detailed evaluation of the expressions for cross sections of elastic and inelastic neutron scattering on different magnetic structures is rather complicated. Therefore, let's see only the final result for several most common cases.

General expression for double differential cross section (unpolarised neutrons)

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{k_1}{k_0} (\gamma r_0)^2 \left| \frac{g}{2} F(\vec{Q}) \right|^2 e^{-2W(\vec{Q})} \sum_{\alpha\beta} \left( \delta_{\alpha\beta} - \frac{Q_\alpha Q_\beta}{Q^2} \right) \times \int dt e^{-i\omega t} \sum_{ij} e^{i\vec{Q}(\vec{R}_i - \vec{R}_j)} \langle S_{R_i}^\alpha(0) S_{R_j}^\beta(t) \rangle$$

Diagram labels and arrows:

- Debye-Waller factor** points to  $e^{-2W(\vec{Q})}$
- Magnetic form-factor** points to  $\left| \frac{g}{2} F(\vec{Q}) \right|^2$
- Polarisation factor** points to  $\left( \delta_{\alpha\beta} - \frac{Q_\alpha Q_\beta}{Q^2} \right)$
- Spin correlation function** points to  $\langle S_{R_i}^\alpha(0) S_{R_j}^\beta(t) \rangle$

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# Magnetic neutron scattering

Magnetic form factor  $F(\underline{Q})$  is the Fourier transform of the magnetisation density in a crystal. It is important to note, that neutron magnetic form factor is defined by distribution of electrons with uncompensated spins only.

$r_0 = e^2/m_e c^2$  – electromagnetic radius of the electron

$\gamma = -1.913$  – neutron magnetic moment in Bohr magnetons

$$\delta_{ij} = \begin{cases} 0, & \text{if } i \neq j \\ 1, & \text{if } i = j \end{cases} \text{ – Kroneker symbol}$$

Polarisation factor  $(\delta_{\alpha\beta} - \frac{Q_\alpha Q_\beta}{Q^2})$  indicates that neutrons interact only with the components of atomic spin which are perpendicular to the scattering vector  $\underline{Q}$ . This fact allows uniquely measure in an experiment the directions of atomic spins and polarisation of spin waves.  $r_0$  value indicates that the magnetic neutron scattering cross section is of the order  $10^{-24} \text{ cm}^2$ , therefore comparable with nuclear scattering cross section.





# Uses of neutron scattering in magnetism

## Static properties (elastic scattering)

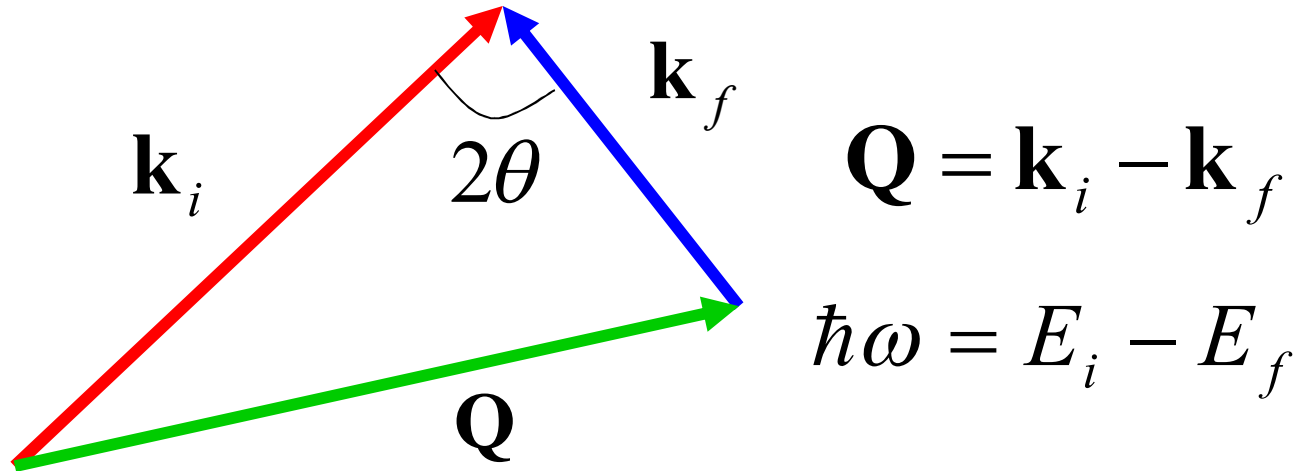
- Spin arrangements in ordered magnetic structures
- Static spin correlations in disordered or frustrated magnets
- Magnetisation density (magnetic form factor)
- Flux distributions in superconductors
- Magnetism of surfaces (reflectometry)
- etc*

## Dynamic properties (inelastic scattering)

- Crystal field excitations
- Inter-multiplet atomic excitations
- Spin waves in ordered magnetic structures
- Spin fluctuations in strongly correlated or frustrated magnets
- Magneto-phonon coupling
- etc*



## Basic idea of the method



Nuclear scattering

$$S(\mathbf{Q}, \omega) = \frac{1}{2\pi\hbar} \int dt e^{-i\omega t} \frac{1}{N} \langle \rho_{\mathbf{Q}}(0) \rho_{-\mathbf{Q}}(t) \rangle$$

Magnetic scattering

$$S^{\alpha\beta}(\mathbf{Q}, \omega) = \frac{1}{2\pi\hbar} \int dt e^{-i\omega t} \frac{1}{N} \sum_{\mathbf{R}\mathbf{R}'} e^{i\mathbf{Q}\cdot(\mathbf{R}-\mathbf{R}')} \langle S_{\mathbf{R}}^{\alpha}(0) S_{\mathbf{R}'}^{\beta}(t) \rangle$$

# Modern challenges - novel fields of neutron scattering application

“There are no such things as applied sciences, only applications of science.”

“A bottle of wine contains more philosophy than all the books in the world.”

**Louis Pasteur**



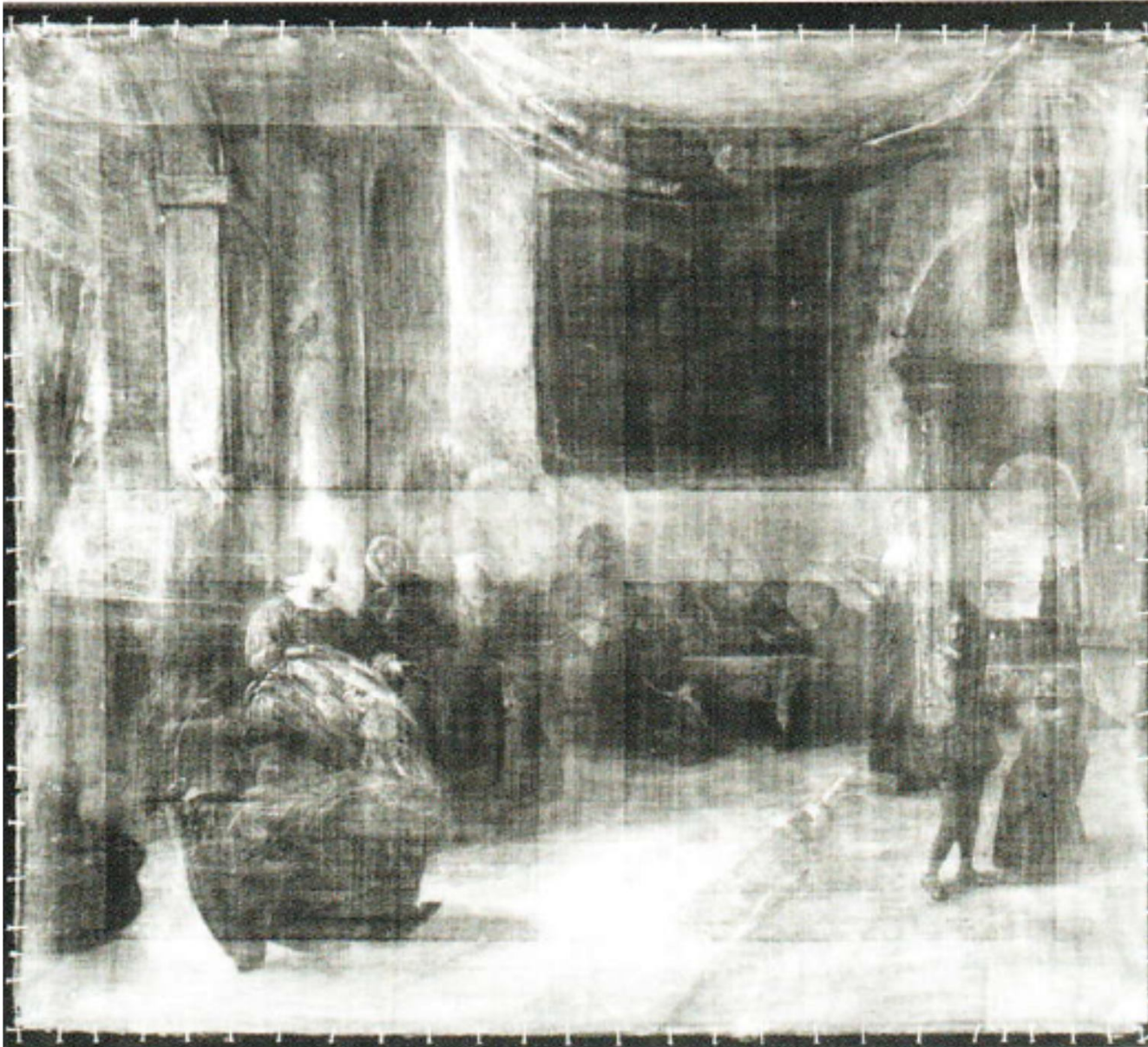


## What neutron autoradiography tells us about Old Masters: The genesis of Jan Steen's "Wie die Alten sungen, so zwitschern die Jungen"

By Dr. K.Kleinert (HZB, Berlin) and M.Reimelt (Gemaldegalerie, Berlin)



Jan Steen, "Wie die Alten sungen, so zwitschern die Jungen", 1665/66, canvas, 84.8x 100.4 cm, Gemaldegalerie Berlin



The X-ray image already shows that large areas of the painting, like the drapery on the upper part of the archway on the right have been changed during the painting process.

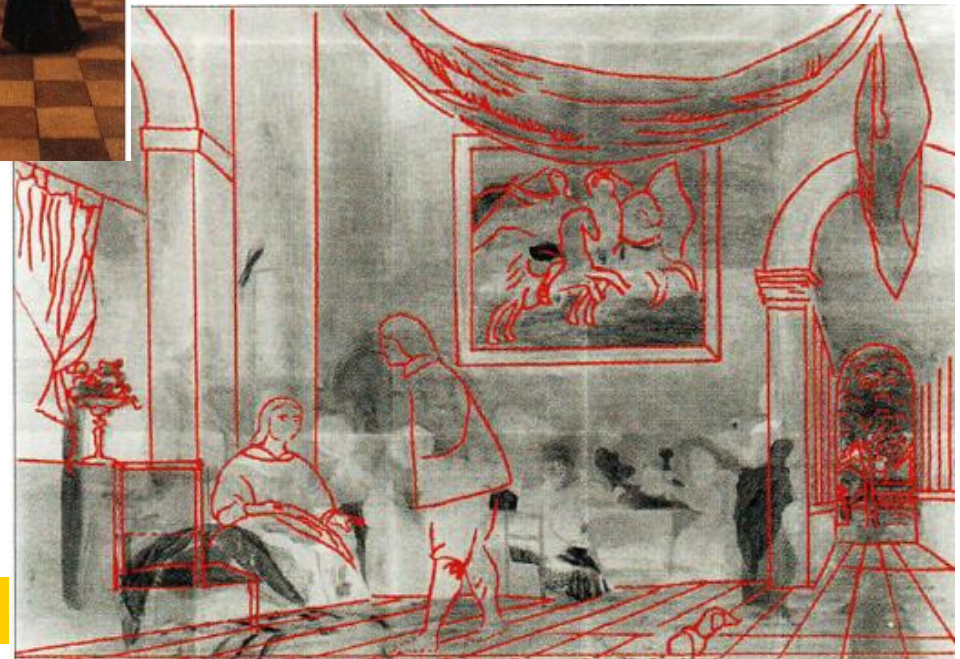


Neutrons allow the visualisation of structures and layers beneath the surface and, in addition, enable the detailed identification of the elements contained in the pigments. Neutrons immediately clearly reveal the drapery and the landscape in the archway.

Cultural heritage



Today's version of the painting



Contour drawing of the reconstructed original version

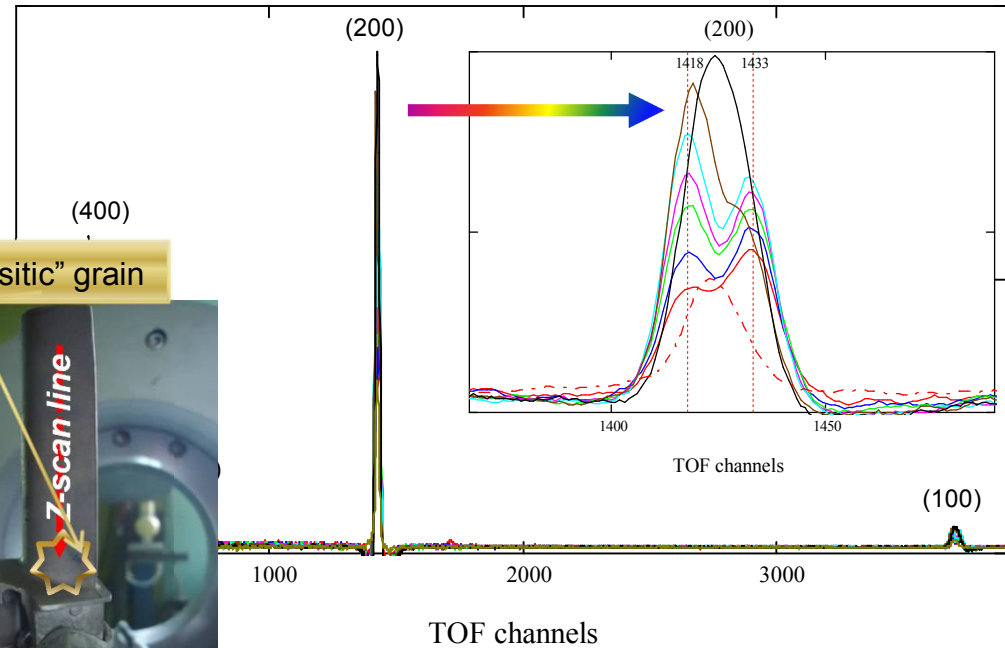
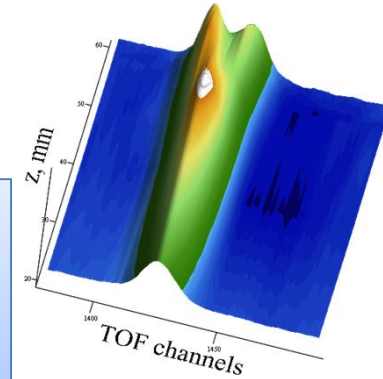


(IBR-2, FSD, October 2011)

Travel and Transport



Top: 3D plot and map of the neutron diffraction pattern near (200) reflection during scan along z coordinate in the “parasitic” grain region.  
Bottom: Total neutron diffraction pattern from single crystal turbine blade. The inset demonstrates (200) reflection shape evolution during z-scan.







**Date** 8 January 1989

**Summary** Engine fan blade fracture (design flaw), [Pilot error](#)

**Site** [Kegworth](#), [Leicestershire, England](#)

[52°49'55"N 1°17'57.5"W](#)Coordinates: [52°49'55"N 1°17'57.5"W](#)

**Passengers** 118 **Crew** 8

**Injuries (non-fatal)** 79 **Fatalities** 47 **Survivors** 79

**Aircraft type** [Boeing 737-4Y0](#)

**Operator** [British Midland](#)

**Flight origin** [London Heathrow Airport](#) **Destination** [Belfast International Airport](#)

# Neutron Reflectivity Reveals Suspected Air Layer under Water Drops on Lily Pads

Nanotechnology

- **Hydrophobic forces govern protein folding, lipid aggregation, and hence life itself**

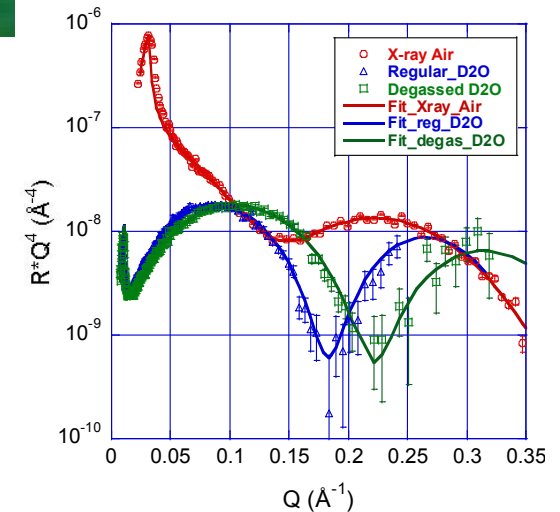
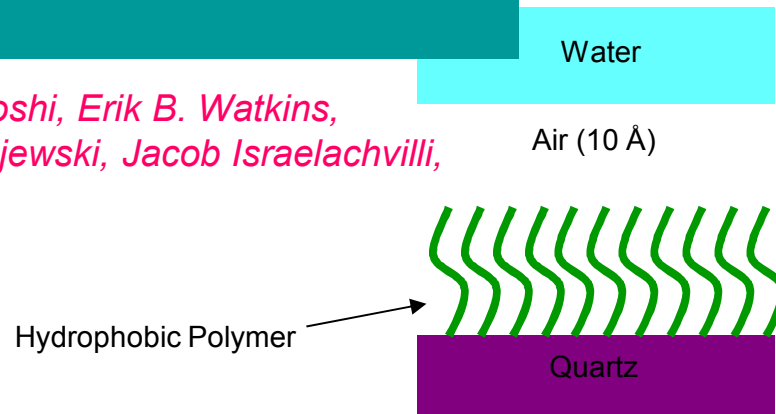
- Dew drops roll off lily pads because their surfaces are hydrophobic (“water fearing”)

**An air layer has been long-suspected under such a drop**



Removal of dissolved gases reduced the layer thickness; aeration increased it

*Dhaval A. Doshi, Erik B. Watkins,  
Jaroslaw Majewski, Jacob Israelachvili,  
PNAS*

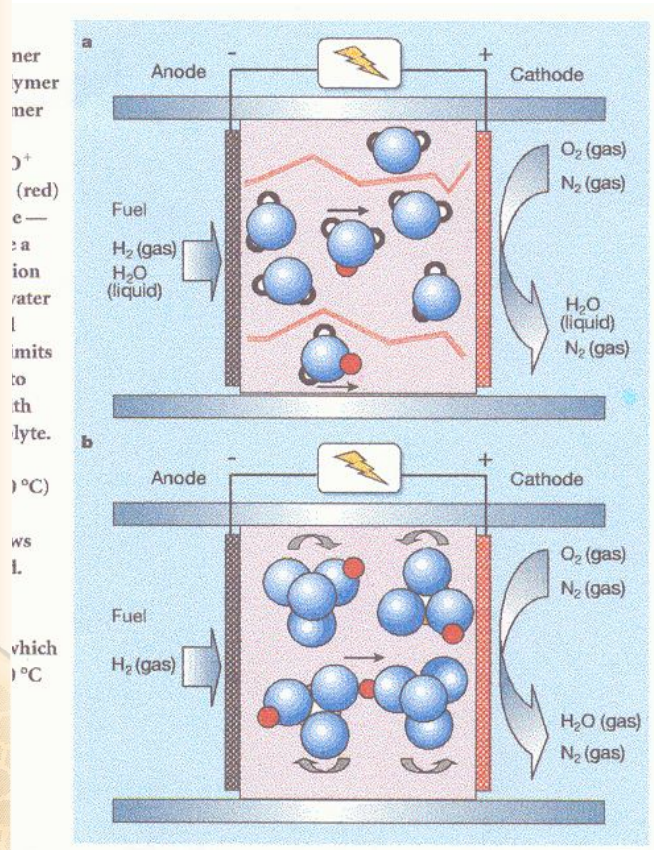




**Clean transport based on hydrogen technology requires synthesis of advanced proton conducting materials**

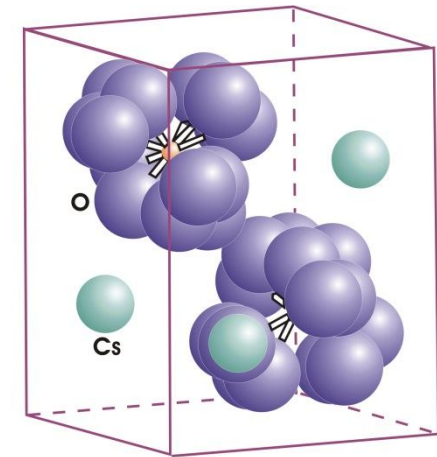
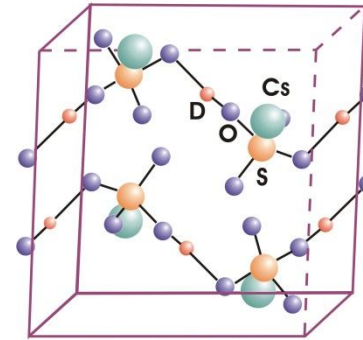
# Neutrons are unique to study light atoms positions in structurally disordered phases

Functional materials

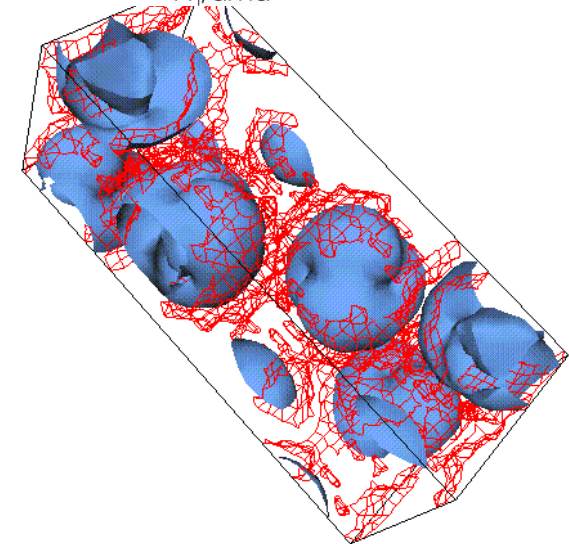


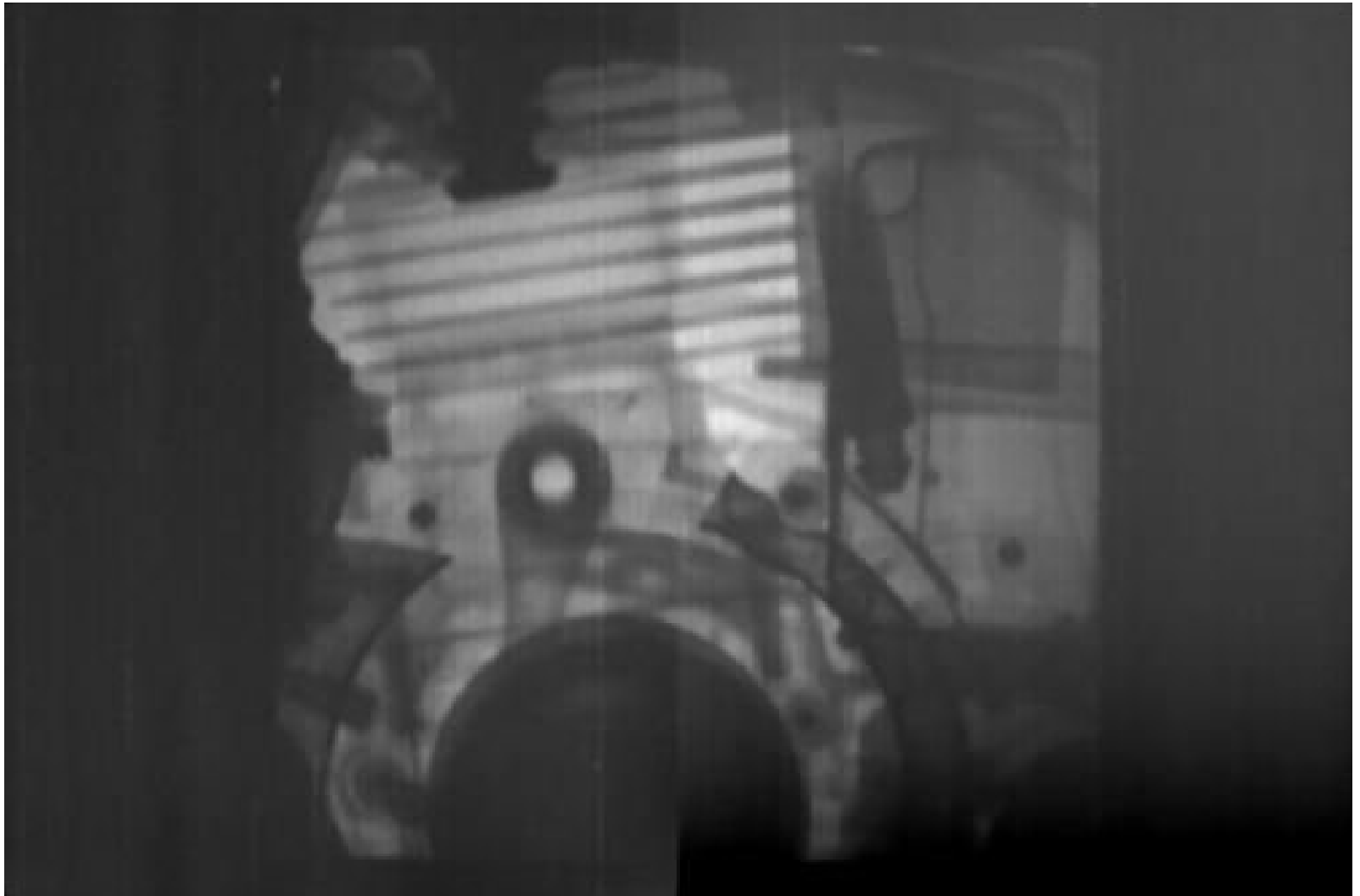
Fuel-cell on the basis of  $CsHSO_4$

$CsDSO_4$

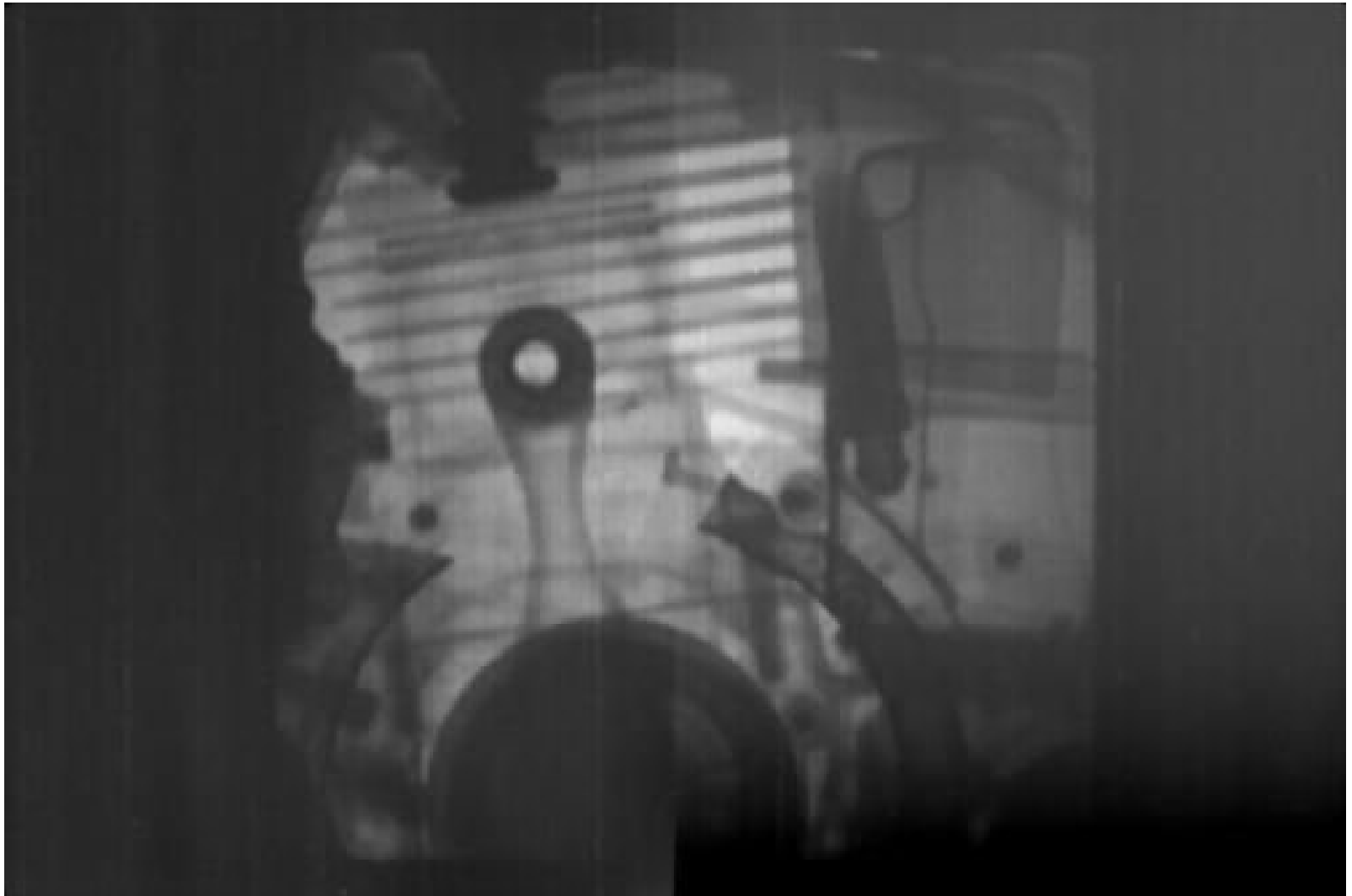


$\Phi a3a II$   $\xrightarrow{412K}$   $\Phi a3a I$   
 $P2_1/c$   $I4_1/amd$

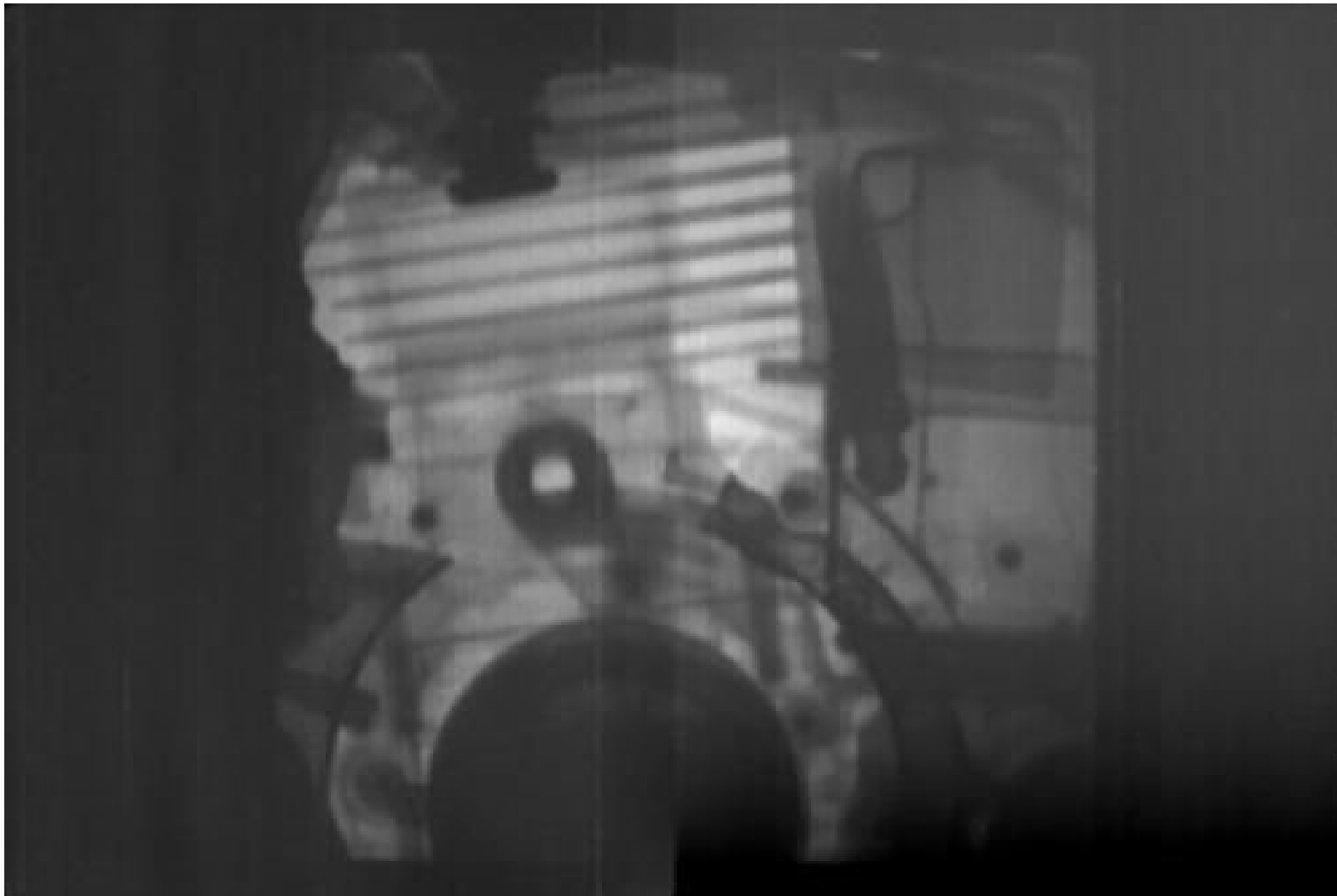




Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

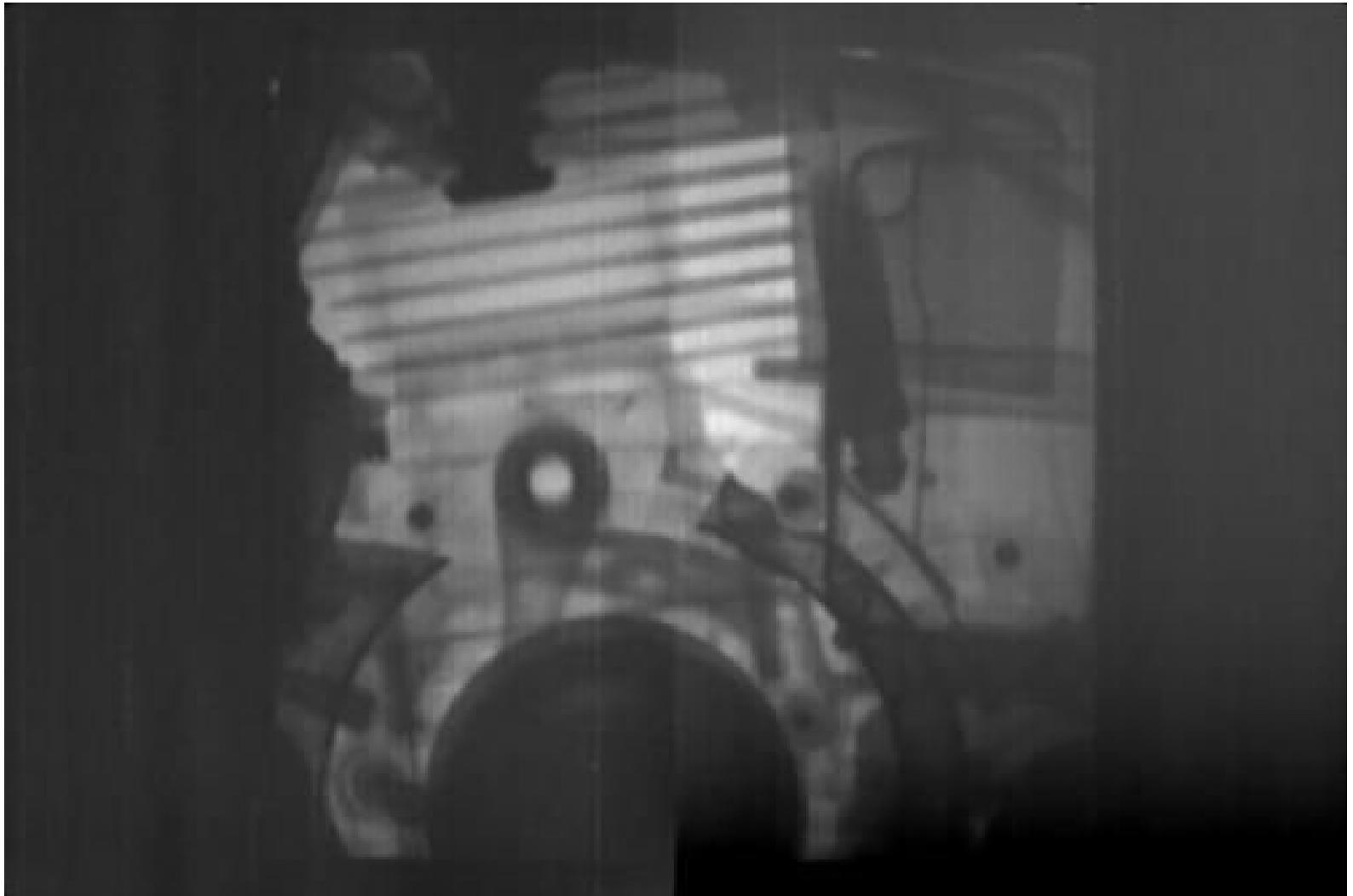


Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

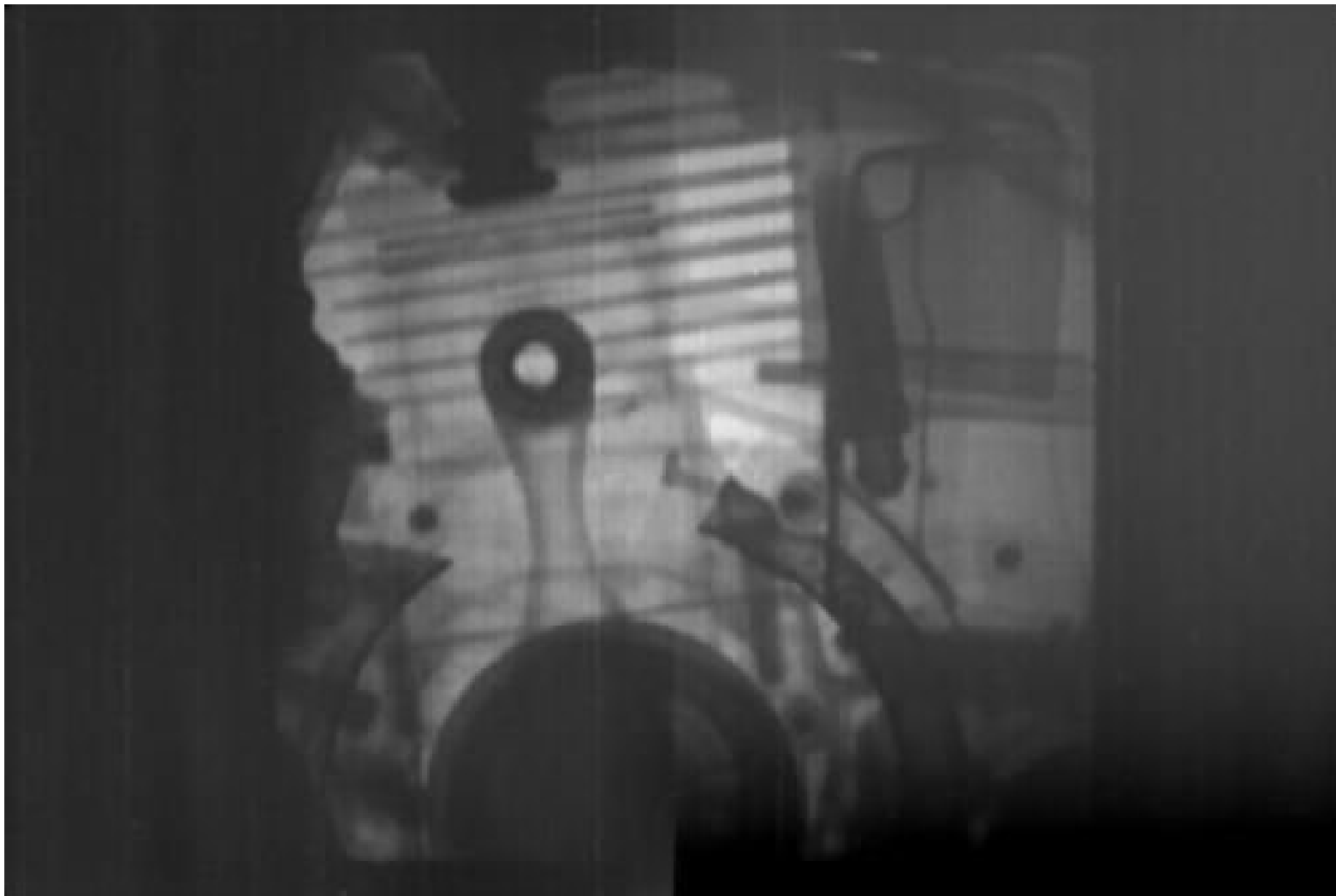


Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland

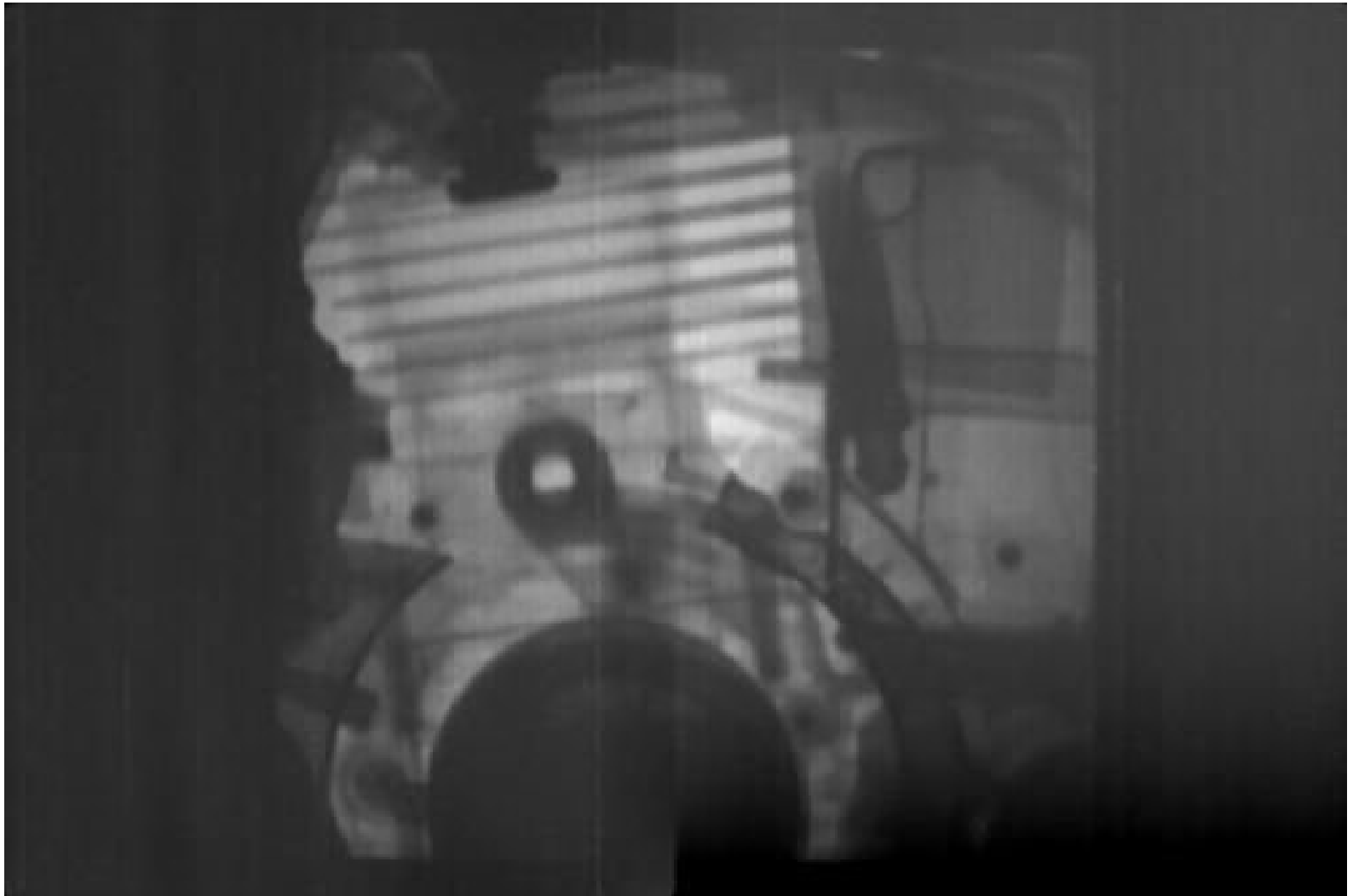




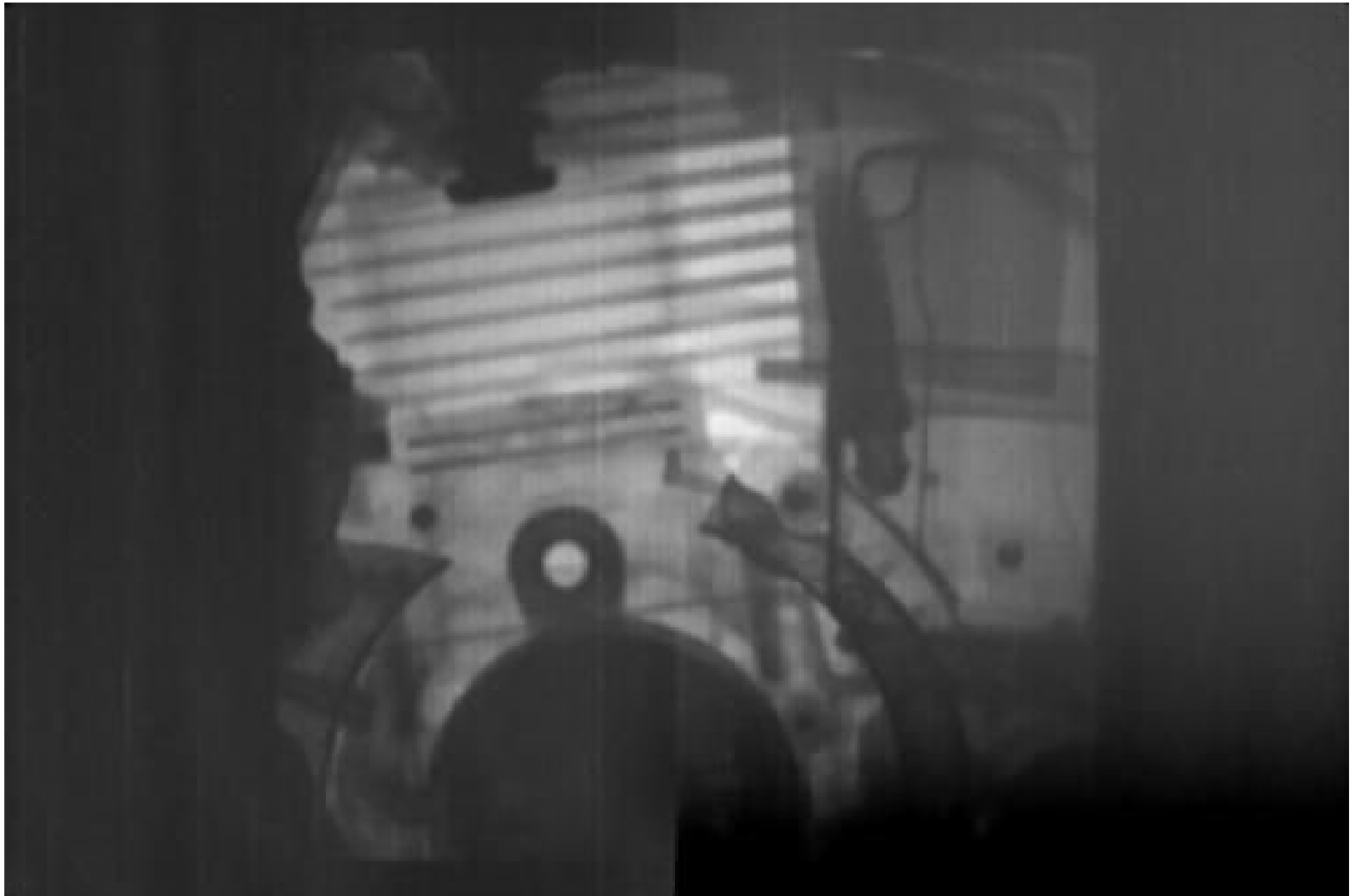
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



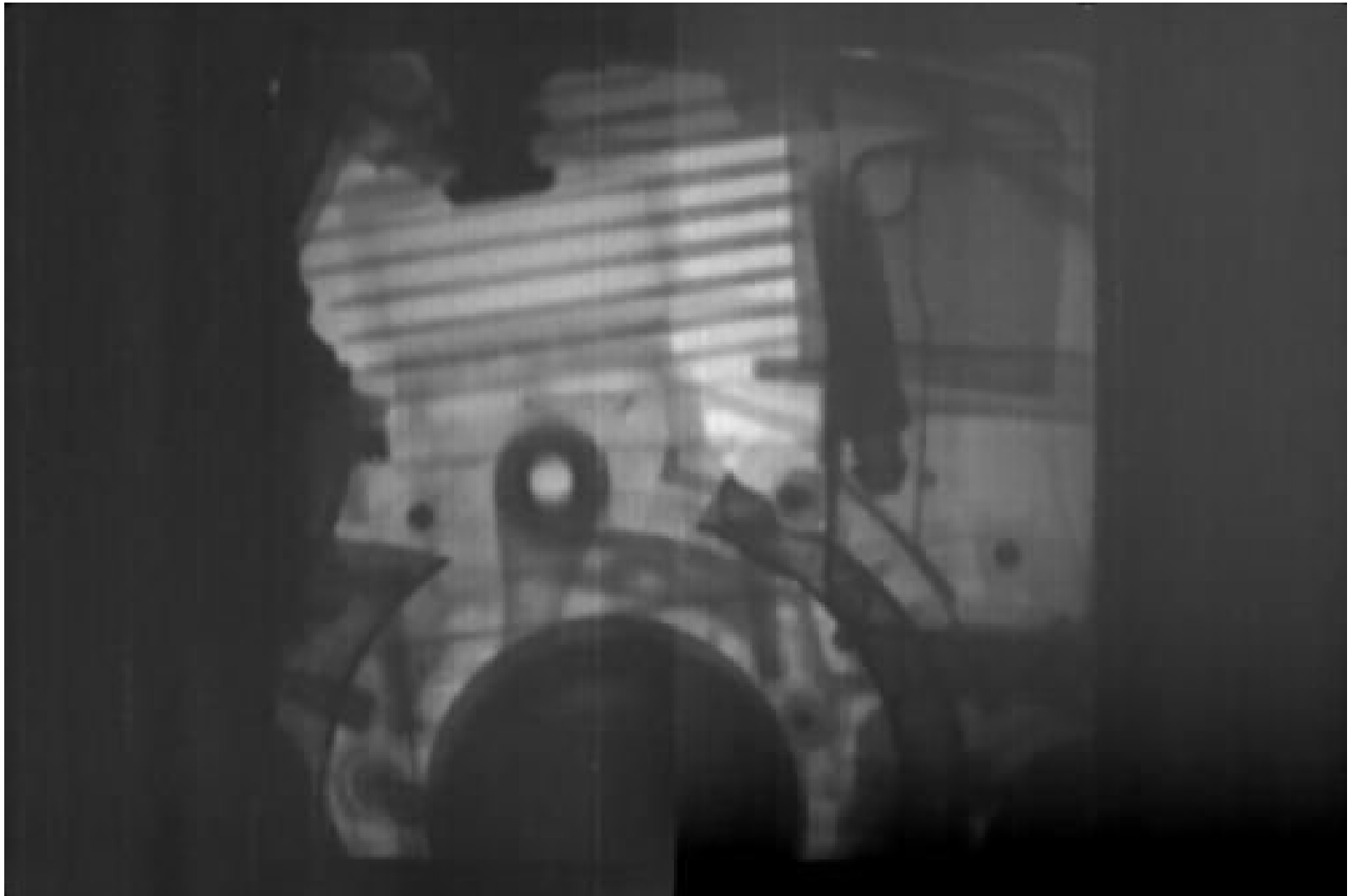
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



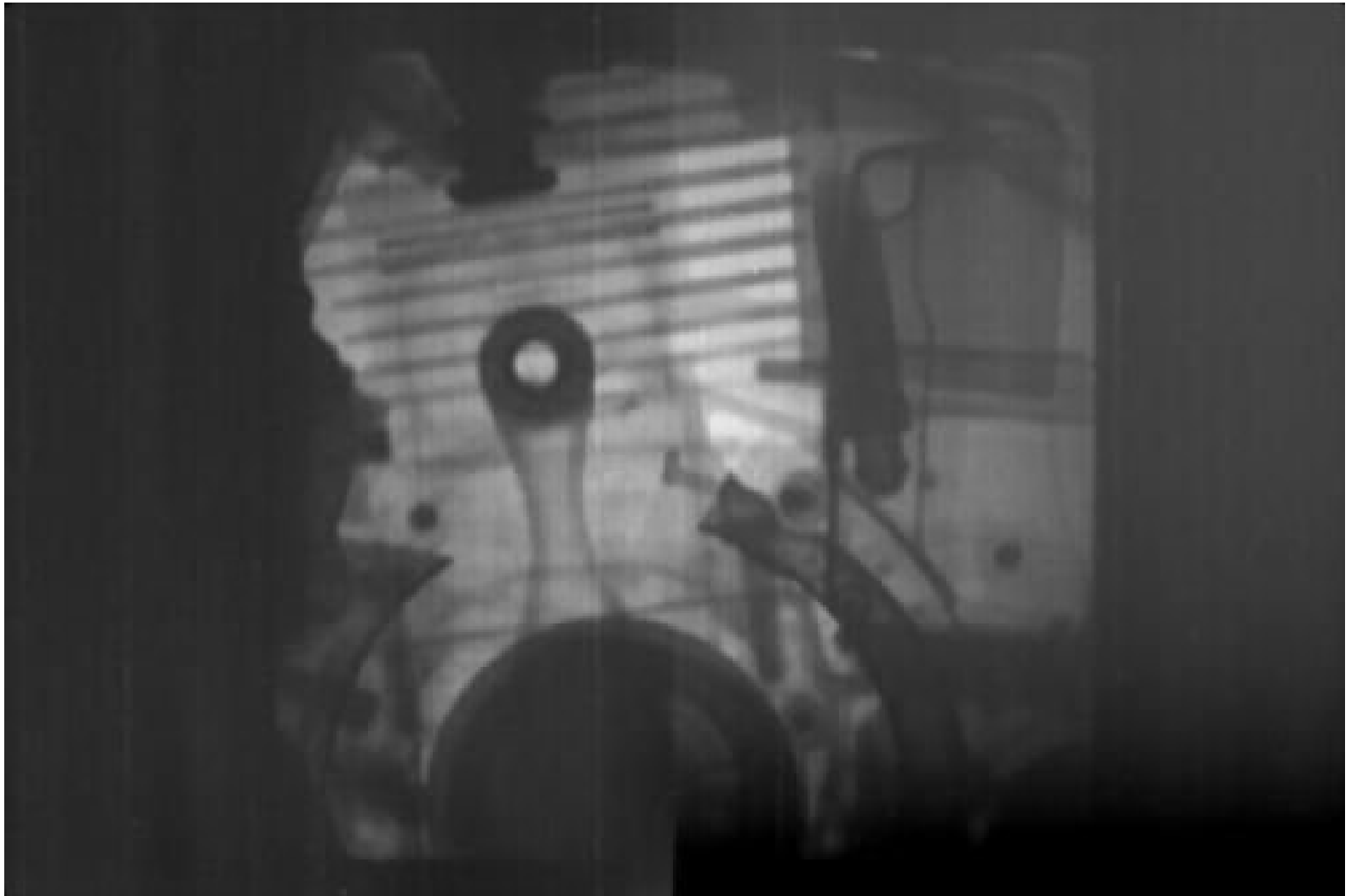
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



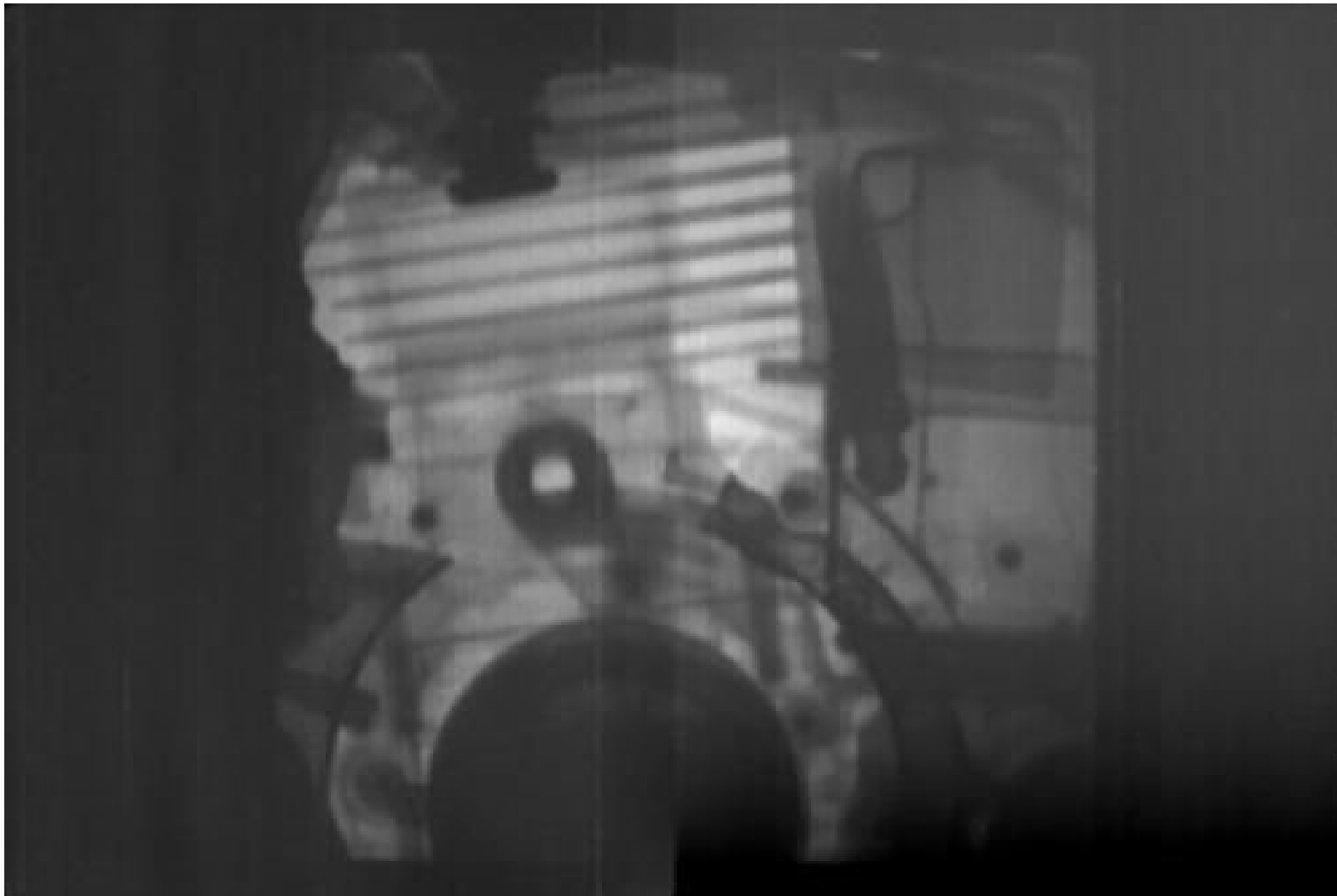
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



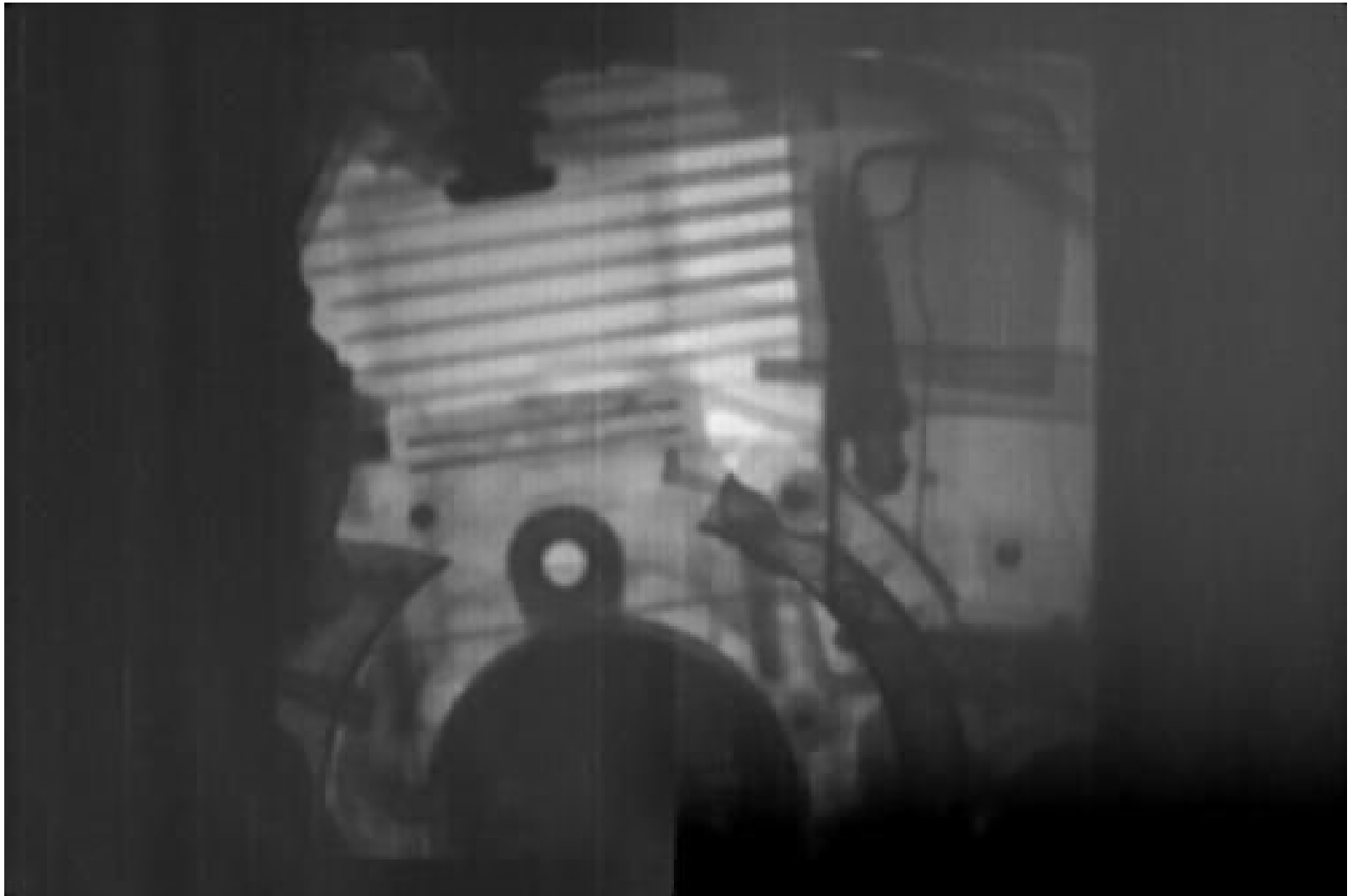
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



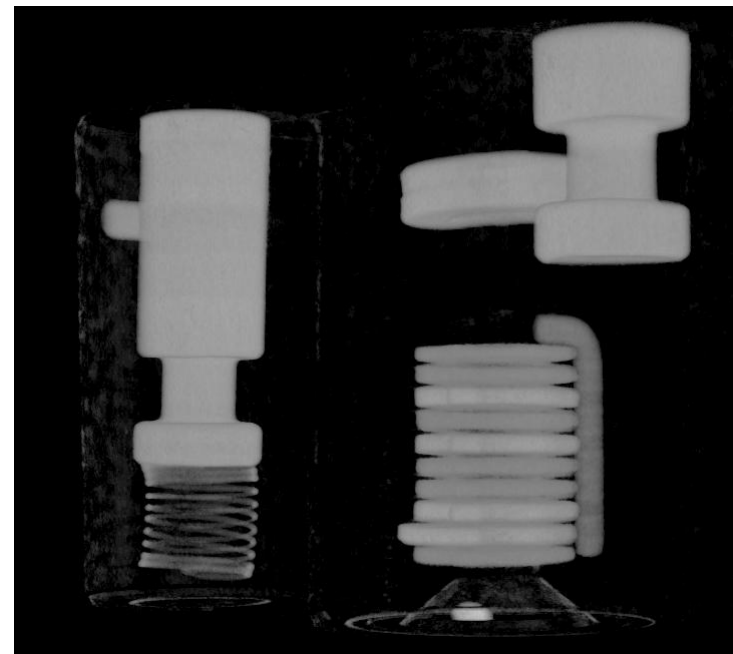
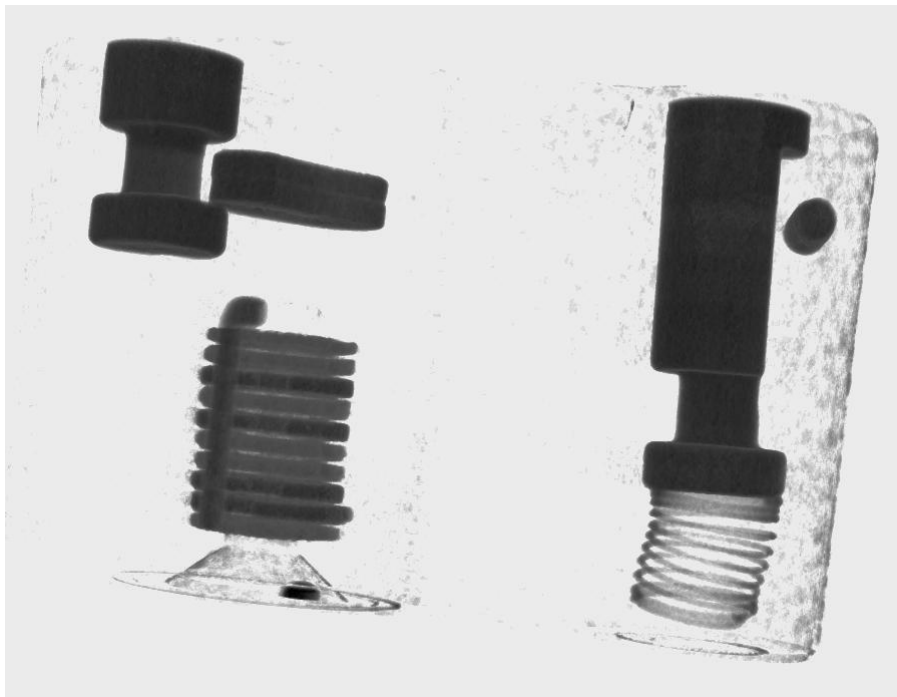
Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



Frames from a two-stroke engine running at 3000 rpm. Picture: ICON, PSI, Switzerland



# Tomography of padlock





**Thank you for your attention**

**Reactor IBR-2,  
FLNP, JINR**

