

PAUL SCHERRER INSTITUT



# Neutron Imaging

At the spallation source SINQ

Information for potential users and customers



## PSI in brief

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PSI concentrates on basic and applied research, particularly in those fields which are the leading edge of scientific knowledge, but also contribute to the training of the next generation and pave the way to sustainable development of society and economy. The Institute is actively involved in the transfer of new discoveries into industry, and offers, as an international centre of competence, its services to external organisations.

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Picture: Luftwaffe Schweiz

### Contact

#### NIAG-Team:

Dr. Eberhard H. Lehmann  
Tel. +41 (0)56 310 29 63  
E-mail: eberhard.lehmann@psi.ch

#### NEUTRA

Peter Vontobel  
Tel. +41 (0)56 310 36 87  
E-mail: peter.vontobel@psi.ch

#### ICON

Dr. Anders Kästner  
Tel. +41 (0)56 310 42 86  
E-mail: anders.kaestner@psi.ch

#### Industrial Applications:

Dr. Christian Grünzweig  
Tel. +41 (0)56 310 46 62  
E-mail: christian.gruenzweig@psi.ch

#### Communications Officer:

Dagmar Baroke  
Tel. +41 (0)56 310 29 16  
Fax +41 (0)56 310 27 17  
E-mail: dagmar.baroke@psi.ch

PAUL SCHERRER INSTITUT



Paul Scherrer Institut, 5232 Villigen PSI, Switzerland  
Tel. +41 (0)56 310 21 11, Fax +41 (0)56 310 21 99  
www.psi.ch, http://niag.web.psi.ch



**Battery research: distribution of the electrolyte inside the battery, visualized with neutrons.**

**Cover photo:**  
Placing a sample for radiographic inspection at the cold neutron imaging facility ICON.

## Imprint

**Concept/Editor**  
Neutron Imaging & Activation Group (NIAG)

**Photography**  
NIAG, H.R. Bramaz

**Layout**  
Irma Herzog, PSI

**Print**  
Druck und Fototechnik, PSI

Source details and specimen copy requested for reprints.

**Order from**  
Paul Scherrer Institut  
Kommunikationsdienste  
5232 Villigen PSI, Switzerland  
Telephone +41 (0)56 310 42 61

Villigen PSI, June 2011

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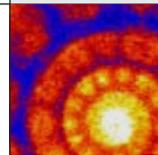
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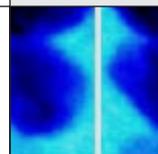


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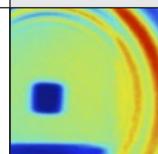


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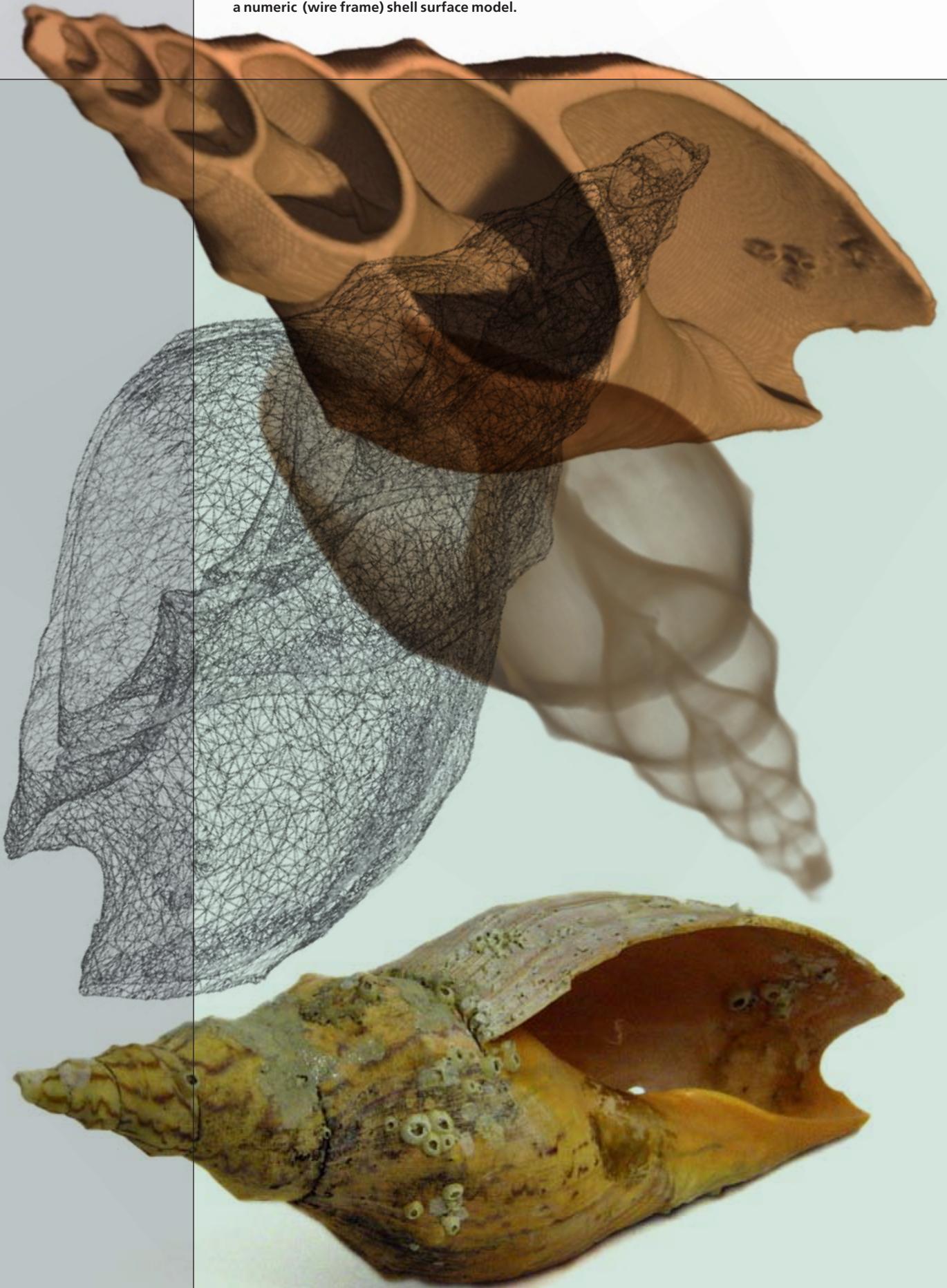


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The tomograph of a seashell describes exactly the 3 dimensional shell structure, allowing to extract a numeric (wire frame) shell surface model.



# Neutron Imaging

## Introduction

**This booklet presents information about “neutron imaging”, or as it is usually referred to, neutron radiography. Neutron radiography is in use at Paul Scherrer institute since 1997 and is still in further development, particularly with regard to new measurement methods and applications.**

**The following pages present information generally understandable by a broad audience, but targeted to potential users too. Fundamentals about neutron sources, area neutron detectors and the different measurement methods are explained. Selected results demonstrate the usefulness of neutron imaging for a wide range of applications.**

Neutrons are – as their partners the protons – the building blocks of the atoms, of which matter is made. Free neutrons are produced solely by nuclear reactions. Besides their use for energy production in nuclear reactors, they are essential probes for materials research on atomic and molecular length scales. However they also can be used, like ordinary medical

X-rays, for radiography purposes on macroscopic samples. In this booklet we concentrate on these latter, macroscopic, neutron imaging applications.

For neutron imaging, strong neutron sources are required in order to guarantee high quality radiography image. Paul Scherrer Institute operated for many years the research nuclear reactor SAPHIR (commissioned 1957), which was replaced by the spallation neutron source SINQ in 1997.

Because high intensity neutron sources are not transportable, all neutron imaging investigations have to be performed on the site of the neutron source. The PSI spallation neutron source is driven by the large PSI proton accelerator facility. Complementary to the neutron source, a large infrastructure allows investigating selected samples, monitoring transport processes, or detecting structural material changes.



Photograph (right) and transparent neutron tomograph (left) of an old camera. With neutron tomography the inner structure of the camera is unveiled.

## Nondestructive testing

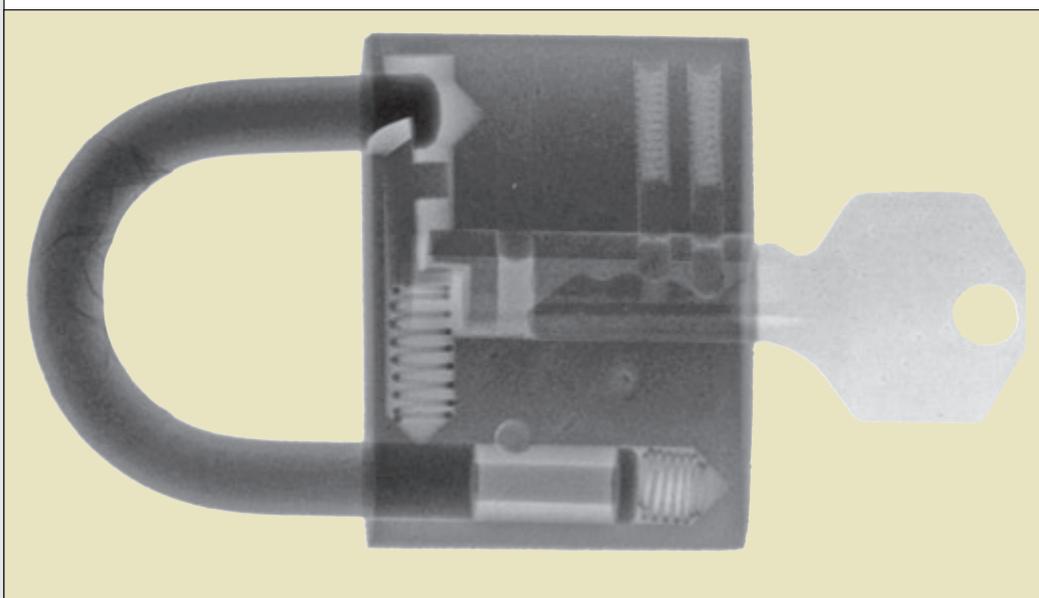
**Rendering an object transparent in order to directly detect cracks, hidden inner flaws or structural material changes is an engineer's dream. Visible light, because reflected from or absorbed by the surface of most materials (except e.g. glass, water...), leaves us only with an opaque view of the object's outer surface. Nondestructive radiography technologies are used to detect material faults inaccessible to direct observation.**

Nondestructive testing (NDT) methods are required if the functional capability has to be verified without object disassembly and/or if the sample integrity should not be affected by the investigation. Such methods are quite often mandatory, to guarantee the safe operation of a system or to check highly expensive or unique samples. NDT methods are therefore frequently applied in the aerospace and automobile industries or in investigations of cultural artefacts.

Partial or full object transparency can be provided by various physical modalities like X-ray, ultrasound, microwave, infrared radiation, etc. Since the discovery by Conrad Roentgen, X-ray is probably the best known radiation modality due to its widespread use in medicine and in industrial-scientific applications. The characteristics of the X-rays, i.e. wavelength and intensity, are chosen according to sample composition and the aim of the investigation.

Like X-rays, neutrons penetrate matter. The Figure below shows the neutron radiography of a lock. Material composition and thickness yield different image contrasts, illuminating the individual components of the lock and detecting component flaws or possible assembly errors. Neutron imaging provides a complement to conventional X-ray investigations. Specific differences between the modalities are discussed on page 9 of this brochure.

Neutron radiograph of a steel lock, showing individual metallic components.

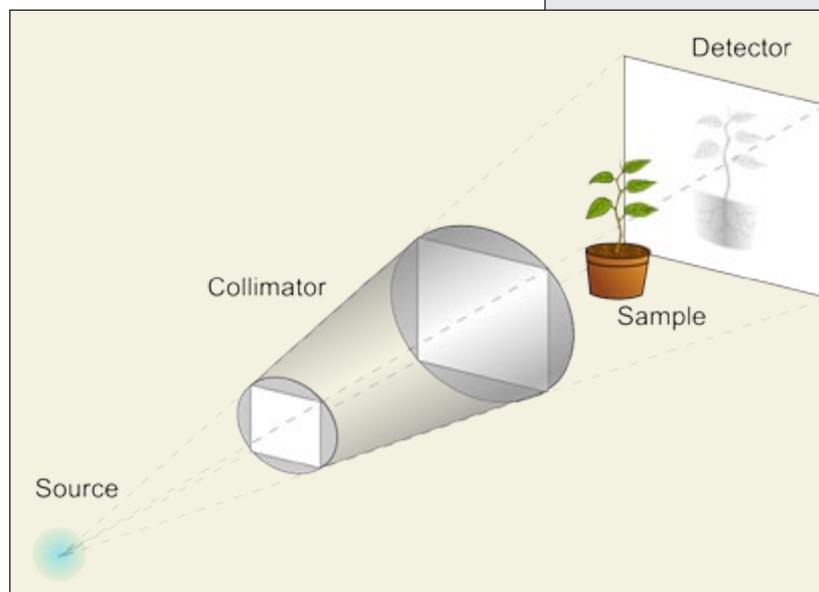


## Neutron transmission

Neutrons act as probes for nondestructive testing because they can penetrate thick-walled samples. Due to the interactions of neutrons with matter, they provide an image of transmitted radiation i.e. a neutron radiograph. Since X-rays interact differently with matter, the two radiation modalities highlight complementary properties of an object's internal structure. A powerful neutron imaging facility requires a strong neutron source. The neutron beam should be well collimated and, to insure radiation safety, strongly shielded. For imaging purposes, neutrons are detected nowadays mainly using special area detectors, which provide digital images of high sensitivity and spatial resolution. Previously, X-ray films were used for this. Paul Scherrer Institut offers two state-of-the-art neutron imaging facilities, NEUTRA and ICON for thermal and cold neutron radiography, respectively. Several experimental techniques are available for investigations in a wide range of scientific and industrial applications.

### Neutron radiography

A radiograph is an image produced by radiation which passes through an object. Radiography is commonly known as the technique, providing radiographs on films or digital detectors, which relies on radiation transmission measurements. Medical X-ray is the application familiar to most people, due to its frequent use by physicians or dentists. In the hospital, X-ray computer tomography (CT), the three dimensional variant known for several decades, provides volumetric information about inner organs, bone fractures, cancer, ... More and more, X-ray applications spread into other scientific and technical fields, where they are tuned to special requirements, e.g. sub micrometer resolution in synchrotron micro-tomography. Similarly, the use of ultrasound or nuclear magnetic resonance



techniques in science and industry is spreading. Neutron radiography however, although known a long time, is not yet widely used for nondestructive testing, because it is available only at a few places. Its complementarity to X-ray makes it an essential tool for NDT evaluations in cases for which ordinary X-ray fails e.g. transmission through heavy metal samples or detection of small amounts of hydrogen within a metallic base material. The principles of neutron and X-ray radiography measurements are the same, except for the different sources and interactions with matter of the radiation (see page 9).

The principle of a radiograph facility is shown in figure above. Neutrons are guided from the radiation source through an evacuated flight tube, the collimator, to the object. The neutron detector behind the sample first converts the transmitted radiation into another physical quantity, e.g. light, which is then measured and recorded digitally. Each area detector element records the intensity of the neutron transmission in a pixel, an element of the image plane. The spatially varying neutron transmission through the object is thereby mapped into

The principle of a neutron radiographic facility. The collimator selects a straight neutron beam. A neutron area detector behind the object measures the transmitted beam.

a plane radiography i.e. projection image. For tomographic neutron imaging, the sample has to be rotated in small angular steps around  $180^\circ$ . Images of plane sections, perpendicular to the objects rotation axis, can then be mathematically reconstructed from all projections and merged as a stack of slice images. Thus a volumetric, tomographic representation of its neutron attenuation characteristics is generated (see page 22).

In reality a neutron imaging facility is more complex than sketched in figure on page 7. As mentioned above, a strong neutron source is an important prerequisite for high quality neutron imaging. For every radiation source, there are legal requirements regarding the safe operation and radiation protection of the personnel. A neutron imaging facility is therefore located within a measuring room, constructed of thick concrete shielding walls, and accessible only through a labyrinth secured by a safety door (see pages 12 and 14).

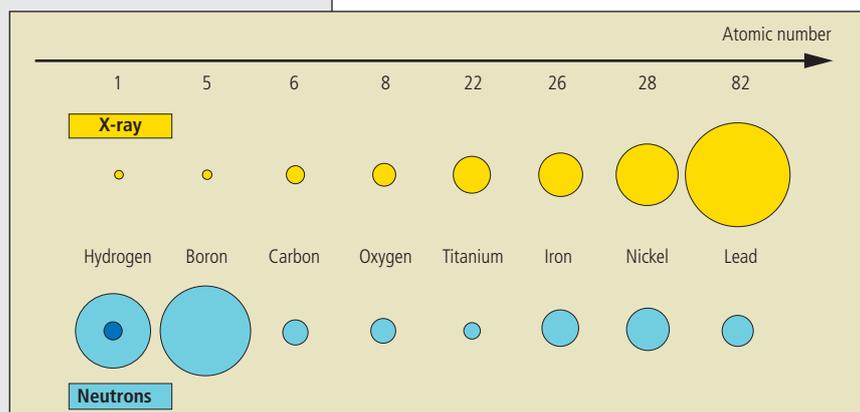
#### Properties of the neutron...

- Neutrons are neutral particles (i.e. particles without electric charge). Together with the positively charged protons, they are the building blocks of the atomic nucleus.
- The mass of the neutron is  $1.675 \cdot 10^{-27}$  kg or  $939.57$  MeV/ $c^2$ . ( $c$  representing the speed of

light, MeV is a physical energy unit. The two values relate to each other by Einstein's famous formula  $E = mc^2$ ).

- A free neutron is not stable, it is a radioactive particle. It decays after a mean lifetime of about 15 minutes into a proton, simultaneously emitting an electron and an anti-neutrino.
- The interaction of a free neutron with atoms is not influenced by their electron cloud. Therefore it can penetrate deeply into matter. The neutron reacts with the atomic nucleus in a manner which varies greatly with isotopic composition and neutron energy. Some atomic nuclei, e.g. boron, lithium, cadmium, gadolinium, capture neutrons incident at low speed. This interaction process is termed neutron absorption. Materials containing such elements are well suited as shielding materials or for neutron detection. Other atomic nuclei, e.g. aluminium or lead, interact only weakly with neutrons; they are almost transparent for neutrons. Some nuclei induce rather a deviation of the neutron from a straight trajectory, producing neutron scattering reactions. Occurring in most isotopes, they are especially strong in hydrogenous materials.
- Like other elementary particles, neutrons act not only like massive particles but also like waves. The wave propagation formalism using the same laws of optics as applied to light (see phase contrast on page 25 and 26), i.e. an index of refraction showing the effects of diffraction or interference, accurately describes some neutron interactions with matter.
- After their creation by fission or spallation reactions, free neutrons propagate at high speed. Their slowing down, termed neutron moderation, is determined by inelastic scattering processes with light elements e.g.

Comparison of X-ray and thermal neutron interaction probabilities for selected elements.



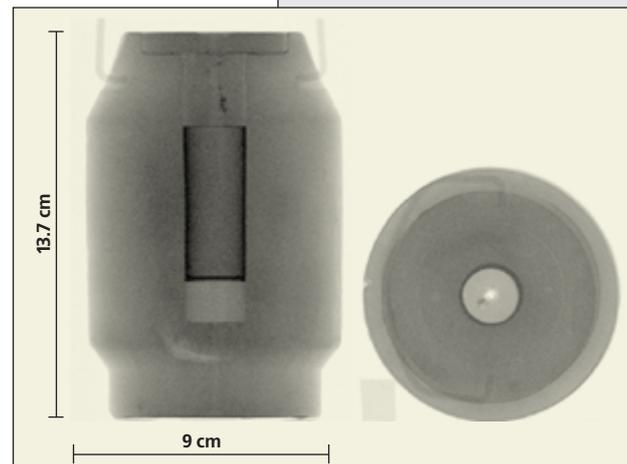
hydrogen or deuterium in the moderator tank. For materials research, thermal or cold neutrons are of special relevance because their energy or wavelength is appropriate to elucidate the structure and dynamics of solid-state or soft matter. The dependence of the interaction probability of neutrons with matter on energy or wavelength can be used to produce variable image contrast in neutron radiography applications. Neutron detection reactions yield high probabilities at low neutron energies, a prerequisite for sufficient sensitivity and spatial resolution in neutron imaging.

### ... and differences with X-ray

Differing essentially from neutron radiation as described above, X-ray radiation is electromagnetic radiation which interacts with the electrons in the atomic shell of a nucleus. The atomic interaction probability correlates strongly with the number of electrons of an element, i.e. the atomic number  $Z$ . Heavy materials induce strong X-ray attenuation, whereas light materials, like e.g. tissue, water, plastics ... attenuate weakly. No such  $Z$  dependence exists for thermal or cold neutron matter interaction. X-ray absorption (photoelectric effect) is the dominant reaction at low photon energies, whereas X-ray scattering (Rayleigh-scattering and Compton-effect) prevails at higher energies. Figure on page 8 depicts the differing interaction probabilities of radiation with matter for X-ray (yellow) and thermal neutrons (blue) for a range of materials from low  $Z$  (hydrogen) to high  $Z$  (lead). The size of the circles indicates increasing interaction probability. The figure suggests that lead is an efficient shielding material for X-ray radiation, but not for neutrons, for which lead is almost transparent. An example is shown in the figure above: the neutron radiograph of a quite massive lead

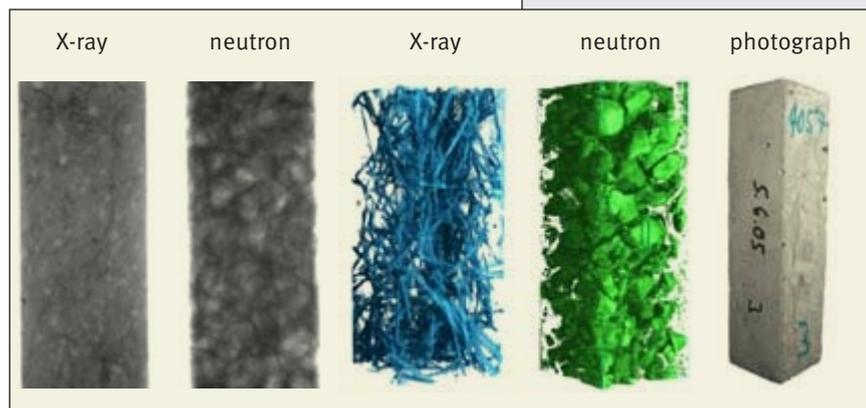
container of unknown provenance. An empty plastic at its centre was easily identified by neutron radiography, since the hydrogen content of plastic material leads to strong neutron attenuation and thereby to a sufficient image contrast. Thus, after neutron radiography, the lead container could be

opened without risk to the personnel. Figure below presents complementary images derived from X-ray and neutron radiography of a concrete sample embedded with steel fibres. The rendering of the neutron tomography volume in green shows clearly all components containing hydrogen e.g. cement, sand, but the embedded steel fibres are invisible. Displayed in blue, the X-ray CT of the same sample shows the embedded steel fibres. On the left in figure below, the X-ray and neutron radiograph of the concrete sample are shown in grey, illustrating that not as much detail about the sample composition can be derived from the ordinary radiographs as from three dimensional tomography.



**Lead shielding container made transparent by thermal neutron radiography: side view (left) and top view (right). Inside, a thin walled plastic can becomes visible.**

**Transmission radiographs (left) and tomographic views (middle) made from a concrete sample embedded with steel fibres with X-ray and neutrons.**



Bird's eye view of the spallation neutron source SINQ. The vertical proton beam impinges from below on the heavily shielded target block in the middle. Neutron beams are extracted horizontally to several instruments. The green area in the middle cover the NEUTRA imaging facility.



# Facilities

## SINQ

**To be used for neutron scattering or imaging, neutrons must be set free from the atomic nucleus. This can be achieved by nuclear reactions inducing fission or other types of nuclear transformation. The nucleus, or its fragments, reach thereby excited states, which de-excite by emission of secondary particles e.g. neutrons and photons.**

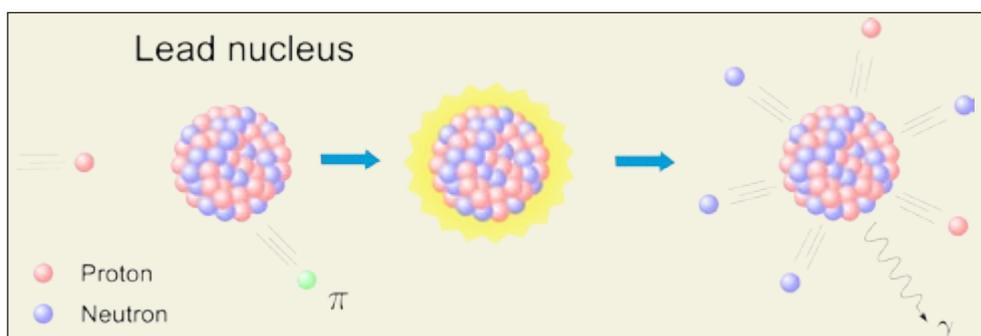
Nuclear fission and spallation are the two most important nuclear processes producing free neutrons. Nuclear fission is induced by the collision of thermal or fast neutrons with a neutron-rich, fissionable, heavy nucleus like uranium-235. There result, two radioactive, fission-product nuclei and 2–3 free neutrons. Under favourable conditions, one of the emitted free neutrons induces another fission reaction and sustains a chain reaction. This process drives nuclear reactors used for energy production or provides a neutron source for materials research. Most neutrons used for research purposes worldwide are generated by nuclear fission.

Nuclear spallation is induced by directing highly energetic charged particles, e.g. protons, onto metallic target nuclei. The charged particles, produced by a particle accelerator at energies of several hundred MeV, collide with individual nucleons (i.e. neutrons or protons) of the target nucleus, which then are ejected or experience further collisions (intra nuclear cascade). This process yields a highly excited

residual nucleus, which de-excites by releasing further neutrons or protons (see figure below). Below energies of 15 MeV, no further nucleons are ejected and the residual is called a “spallation product” nucleus. This whole process, known as spallation reaction, may release 10–15 neutrons per incoming charged particle.

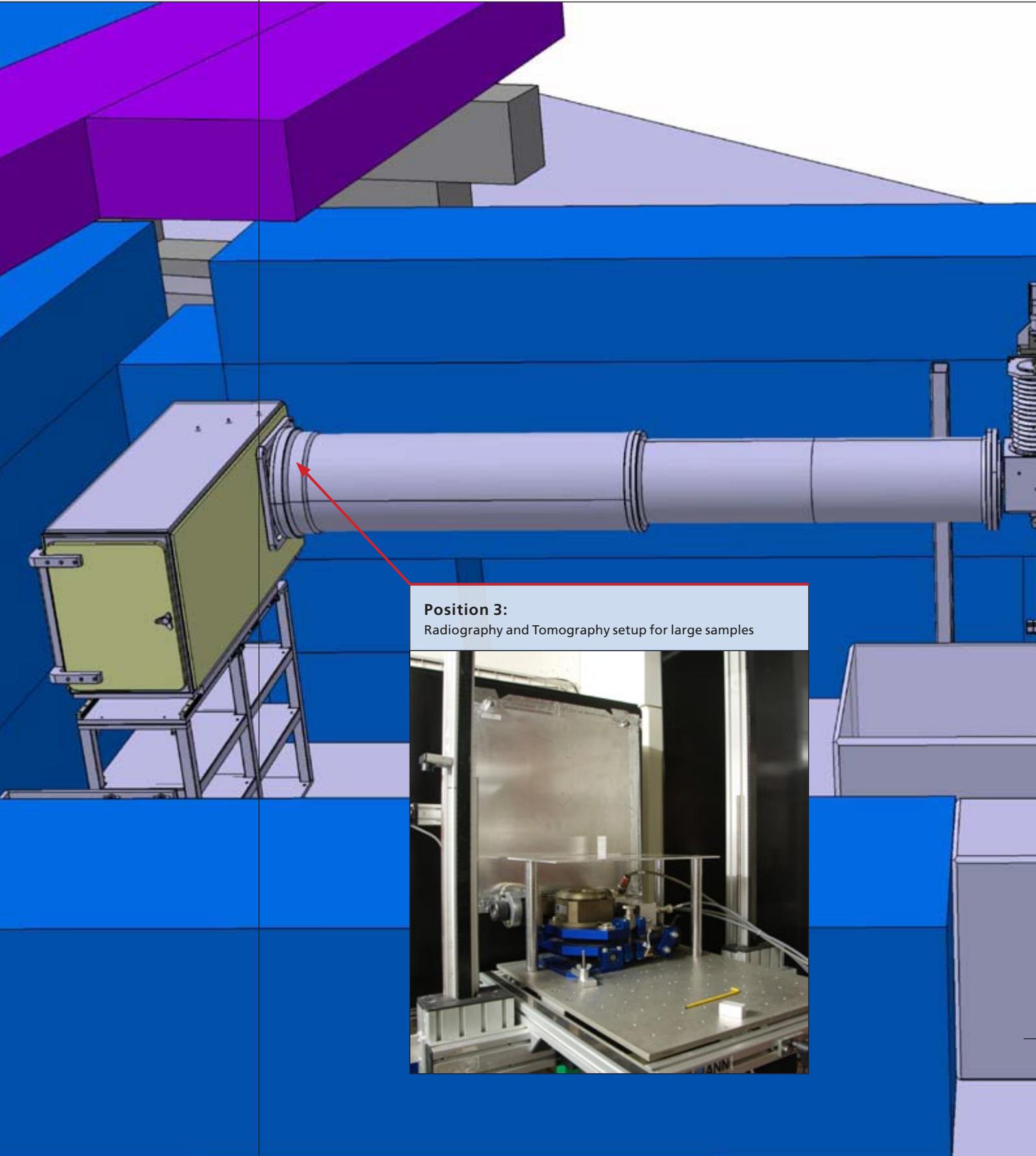
A spallation neutron source requires a powerful proton accelerator facility. The protons are confined and guided by magnets within evacuated tubes to the heavily shielded spallation neutron source (shown on page 10). The advantages of using a spallation source rather than a nuclear fission reactor are the much fewer nuclear safety concerns: no fissile material is needed, no chain reaction needs to be controlled, and less radioactive waste results. Neutrons generated either in a fission reactor or a spallation source are too energetic to be useful and must be slowed down by scattering processes to thermal energies ( $\sim 2200$  m/s) in a moderating medium, e.g. a heavy water tank. Cold neutrons are produced by scattering thermal neutrons on cold molecules e.g. liquid heavy hydrogen at  $-250$  °C.

The spallation neutron source SINQ of Paul Scherrer Institute has been in operation since 1996 (see figure page 10). This brochure gives an overview of the two neutron imaging facilities NEUTRA (thermal neutrons) and ICON (cold neutrons), explaining available experimental methods and presenting selected neutron imaging applications.

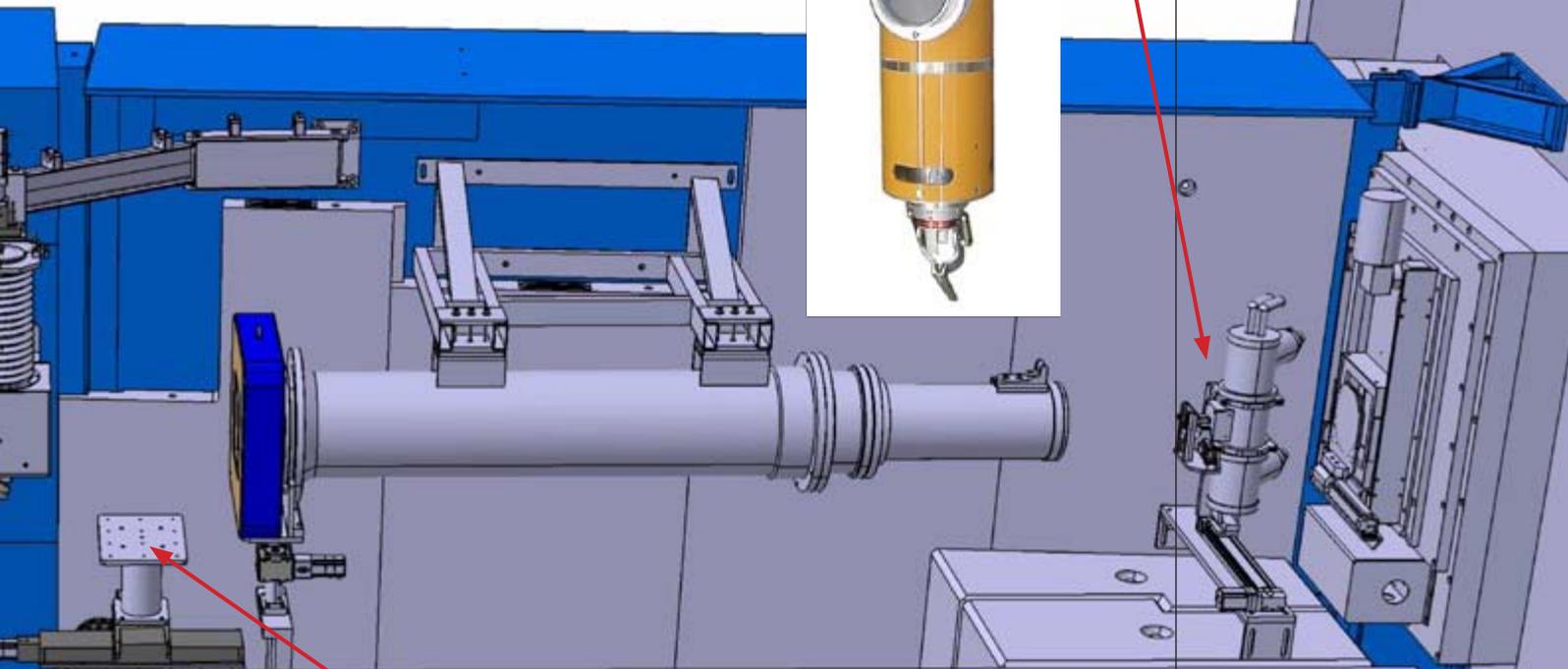


**Neutrons produced by spallation: high energy protons hit a heavy atomic nucleus (e.g. lead). The protons eject nucleons from the target nucleus, leaving a highly excited residual, which yields further nucleons.**

## NEUTRA



Optional use of a  
320 kV X-ray tube



**Position 2:**

Combined neutron- and X-ray tomography investigations of small objects.

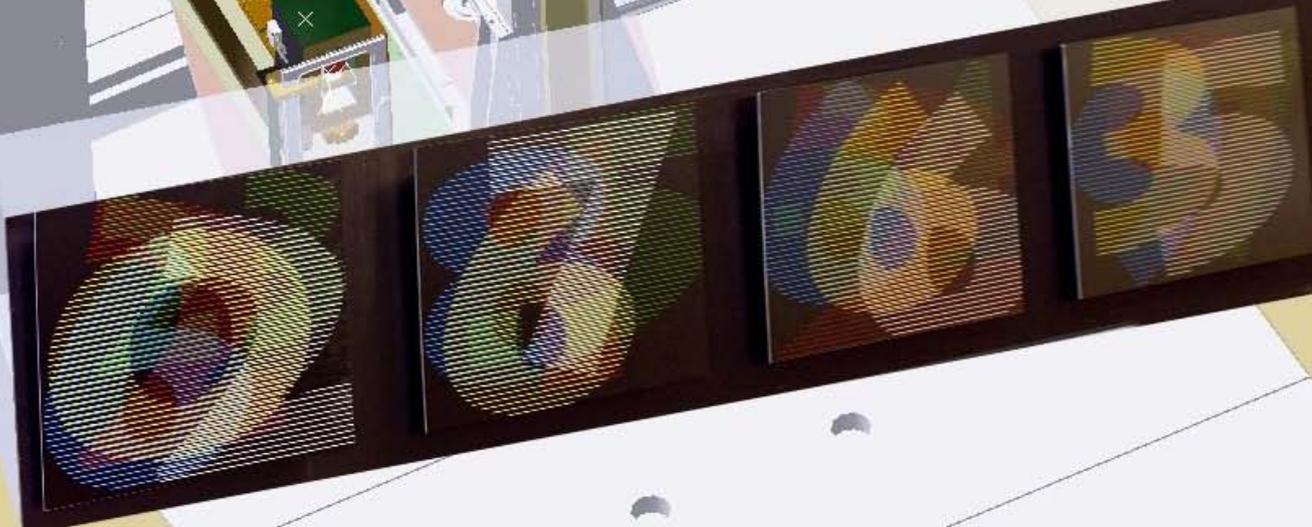
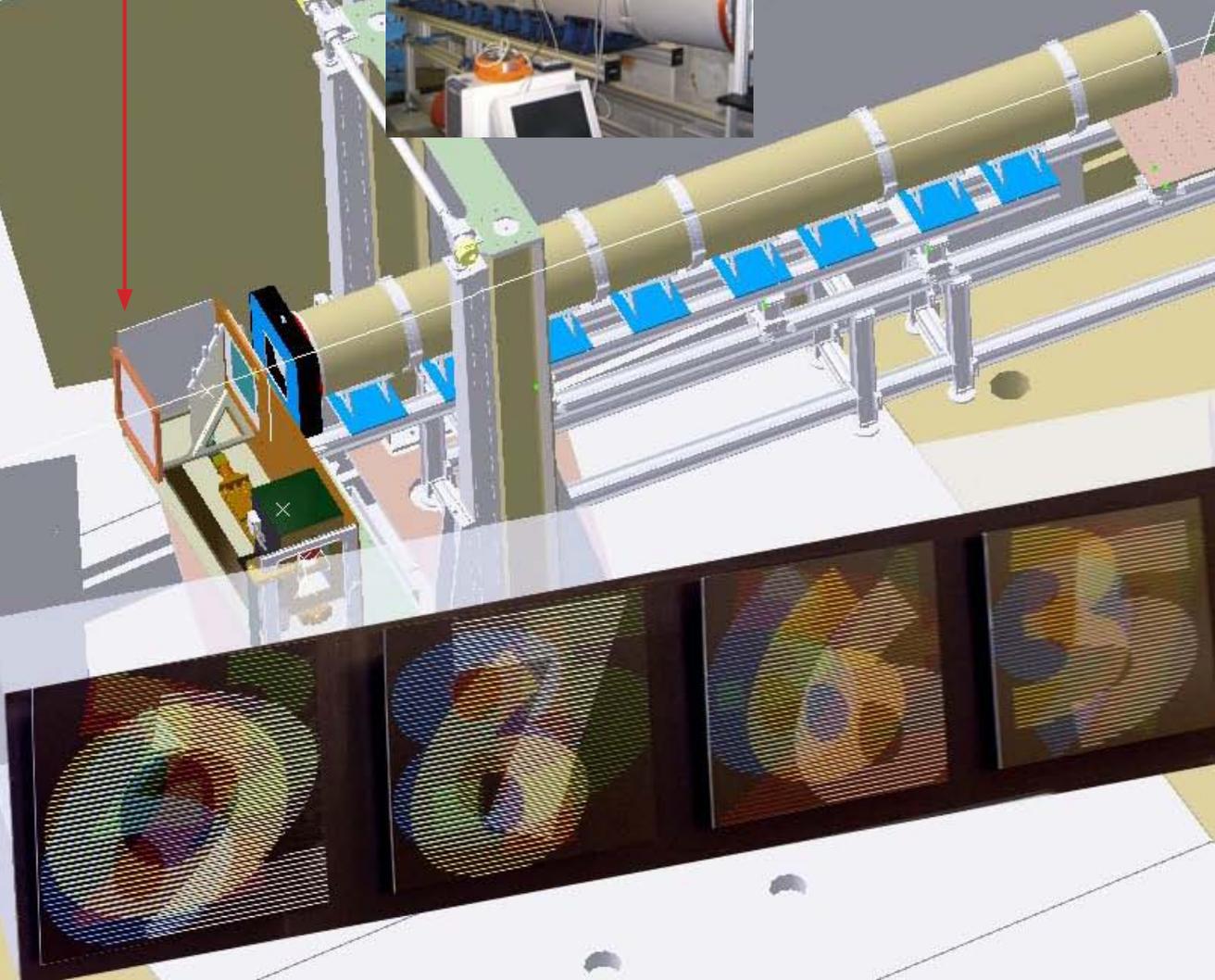


# ICON

**Position 3:**

Large and heavy objects, scanning.  
Macro-Tomography.

Exit of flight tube, scintillation screen.

**Neutron flight-tube**

**Position 1:**

Fail safe and experiment neutron shutter.

Options:

Evacuated flight tube

Neutron velocity selector

Time of flight chopper

Beryllium filter

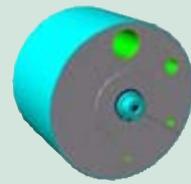
Source grating for neutron interferometry

**Position 2:**

Small objects

Micro tomography, scanning

**Rotating drum with  
neutron apertures.**



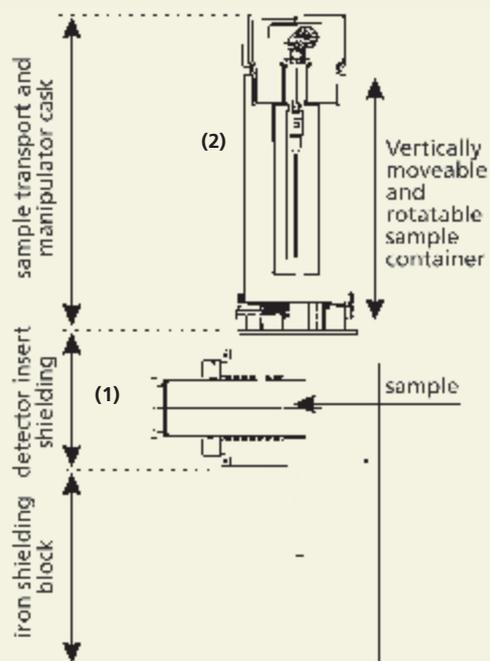
## NEUTRA

NEUTRA, the thermal neutron radiographic facility, contains a convergent inner collimator tube section, guiding neutrons to a fixed size aperture 2 cm in diameter. From there, a divergent collimator section opens to a useful area of 15 cm diameter at the beam exit (measuring position 1) – 29 cm at position 2, and 40 cm at position 3. This permits neutron imaging of samples with dimensions ranging from a few cm to a maximum of 30 cm. Both radiography or neutron tomography experiments can be set up at the two measuring positions. The investigation of highly radioactive samples is made possible by a special setup, **NEURAP**. In addition, an X-ray tube may be positioned in the neutron beam path at position 1, thereby providing almost identical imaging geometry for neutrons and X-rays, **XTRA**. Thus the complementarity of X-ray and neutron attenuation may be fully exploited.

Highly radioactive objects are strong  $\gamma$ -sources, making nondestructive imaging by X-ray transmission impossible. However neutrons can be used for this purpose, if a special detector, sensitive only to neutrons, is employed. Moreover, neutrons pass easily through the heavy metal components of nuclear power plants or neutron spallation sources. For radiation safety reasons, these samples must be transported and manipulated using shielding containers and remotely controlled equipment. The NEURAP setup, shown in figure below, permits positioning such samples in the neutron beam. Consisting of a heavily shielded steel cask with a built-in aluminium transport container which can be lowered into the radiography facility, it can be rotated about its vertical axis for tomography. Some results of investigation can be seen in the figure on page 30 (in the middle).



NEURAP setup with shielding block (1) and transport cask (2) containing the sample manipulator.



## ICON

The cold neutron imaging beamline, ICON, is a versatile beamline specialized on high resolution and small samples. It has two experiment positions which are equipped with digital camera systems. Each position is equipped with motorized sample tables for exact sample positioning and turn tables for tomography. The position closest to the source can use two different camera setups. They provide fields of view from 30 mm to 150 mm and pixel sizes from 13.5  $\mu\text{m}$  to 150  $\mu\text{m}$ . The other experimental position has a field of view of 300 mm and is more suited for large samples. The neutron aperture is variable in five steps from 1 mm to

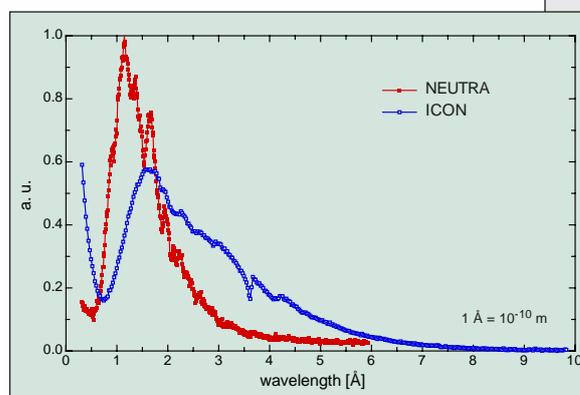
80 mm, this can be used to balance the collimation ratio versus the neutron intensity.

ICON provides equipment for advanced neutron imaging. An energy selector is mounted as a plug-in with short installation times. The selector can be used for material studies. Many materials have their major Bragg-edges in the cold spectrum. This material feature can be used to increase the image contrast of the sample. A setup for neutron grating interferometry is also available. This setup can be used for phase contrast and dark field imaging (see page 25–26).

### Comparison of NEUTRA and ICON

The flight tube of NEUTRA views the heavy water moderator tank at the position of maximal thermal neutron flux density. The end of the ICON flight tube inside the moderator tank is located near the cold source box, containing liquid heavy hydrogen at  $-250\text{ }^{\circ}\text{C}$ . Distinct neutron wavelength spectra for the two facilities result, as shown in figure right, which induce different image contrasts.

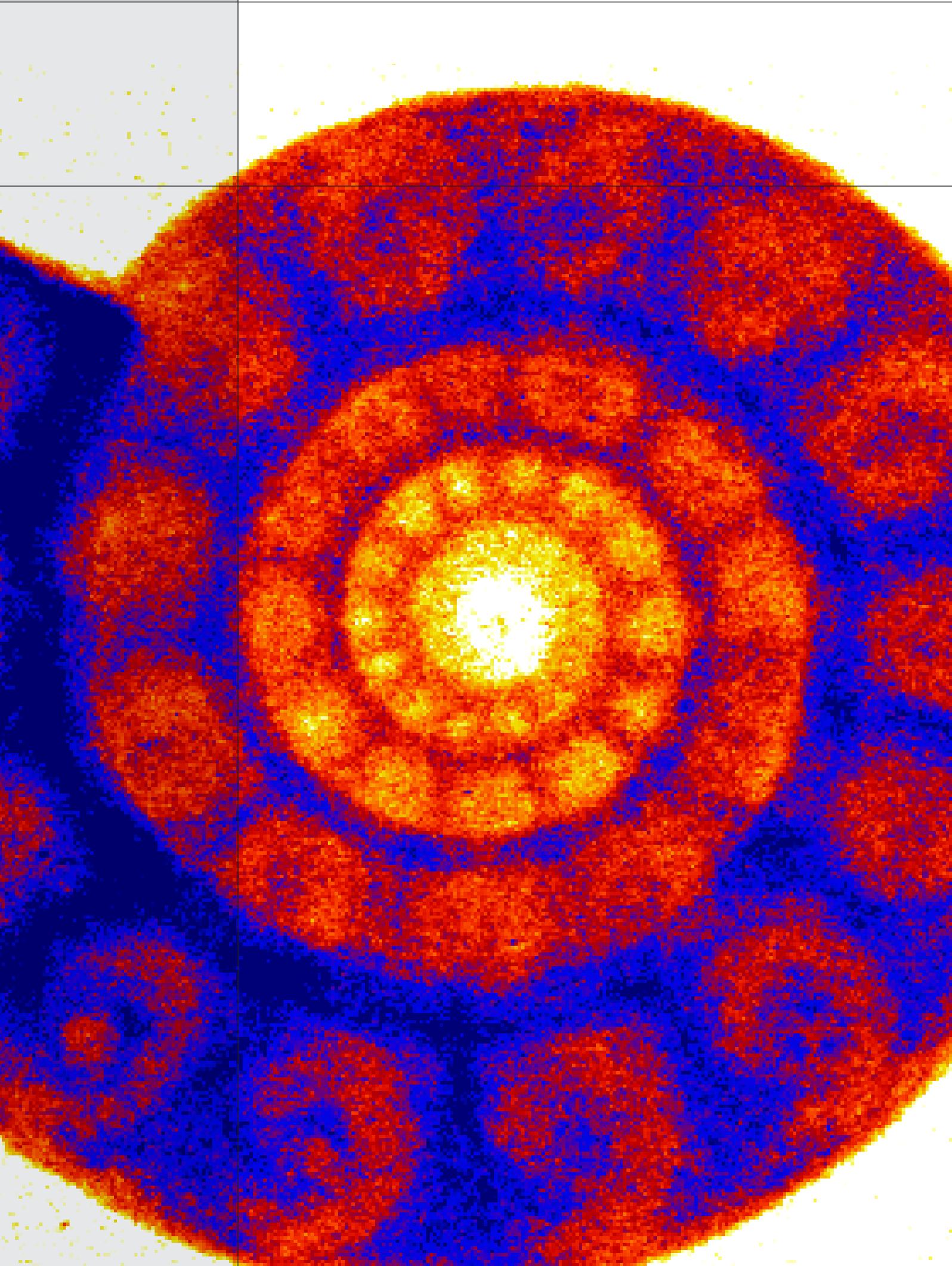
The scattering of cold neutrons by thin layers of hydrogenous material is markedly enhanced relative to thermal neutrons, leading to greater hydrogen detection sensitivity. At longer neutron wavelengths, some materials show sharp edges in neutron interaction strengths. These Bragg edges are due to scattering phenomena of cold neutrons with the material's lattice structure. Using neutron wavelength selectors, the Bragg edges may be used to enhance image contrast. More specific beamline characteristics are listed in table.



Neutron wavelength spectra of NEUTRA (red) and ICON (blue).

	NEUTRA	ICON
Neutron aperture D	fix: $\varnothing$ 20 mm	variable: $\varnothing$ 1 – 80 mm
Collimation ratio L/D	200, 350 and 550	many steps: 90 – 12'000
Neutron flux ( $\text{n}/\text{cm}^2/\text{s}/\text{mA}$ ) (L = 7.1 m, D = 2 cm)	$7.5 \cdot 10^6$	$5.8 \cdot 10^6$
$\gamma$ filter, and filter for fast neutrons	bismuth	no filter
Tomography setup	large samples	additional micro-tomography
Beryllium filter	none	optional
Neutron energy selector	none	optional
Combined X-ray investigation	XTRA	none
Highly radioactive samples	NEURAP	weakly radioactive samples

Comparison of NEUTRA with ICON.



# Detectors & Methods

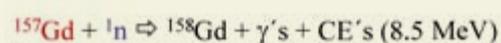
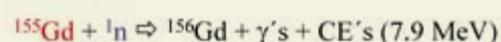
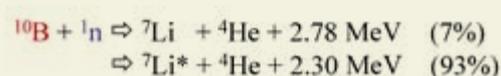
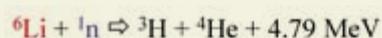
## Principle of measurements

**Neutron detection is based mainly on the creation of free electric charge carriers. Electrically neutral particles, i.e. neutrons produce such carriers by direct collisions with nuclei or neutron capture reactions that lead to the emission of charged particles (e.g.  $\alpha$ -,  $\beta$ -particles, protons, tritons, ...). The most important elements for thermal or cold neutron detection exhibit very high neutron capture probabilities.**

In a neutron imaging detector, the amount of electric charge produced by nuclear reactions is quite often not measured directly, but converted into another more observable physical entity such as light. In neutron scintillation screens, the charged particles stimulate light emission in zinc sulphide. The charged particles create electron-hole pairs which produce light when de-excited by laser stimulation via photostimulated luminescence in neutron imaging plates known as storage phosphors. In X-ray films, the electromagnetic radiation produced by charged particles creates a latent image in the photoemulsion, which results in selective film blackening during chemical film-development.

In the past, neutron imaging relied exclusively on X-ray films, used together with a screen converting neutrons to X-rays or light. During the last several years, digital neutron detectors have gradually replaced the analogue, film-based detection schemes. The main advantages of digital systems are: chemical development is unnecessary, the digital images can easily be stored or copied and transferred quickly over long distances, and they can be post-processed. Additional important reasons favouring the use of digital detectors in neutron imaging are: the much reduced activation risk and the possibility of quantitative evaluation. Neutron irradiation of an object induces a – usually short-lived – activation. The shorter the

neutron exposure is, the smaller the induced activity. Digital neutron detectors are more sensitive than X-ray films by orders of magnitude, permitting exposure times on the order of seconds rather than tens of minutes. In most cases the induced activity reaches safe levels within a few minutes. As described on pages 20 and 21, many digital neutron detection systems covering a broad range of spatial- and time-resolution are available. They show a linear response over a wide range of neutron exposures permitting additional quantitative information about the shape/dimension or the composition of a sample under investigation to be derived. The requirements and aim of the investigation determine which system should be used. By their nature, digital images allow numerical processing. Statistical or systematic image distortions can be eliminated by methods of digital image analysis e.g. noise filtering, contrast enhancement. Multiple images can easily be compared or transformed (e.g. divided) into new images. These methods are indispensable in analysing the images acquired with the elaborate techniques like tomography, time-resolved radiography or neutron phase imaging described in forthcoming sections.

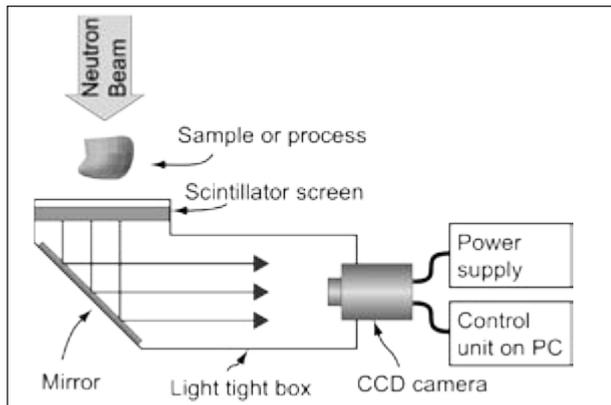


Selected thermal neutron detector materials and their reactions.

## Detectors

### Neutron scintillation screen and CCD camera

The cooled, light-sensitive CCD chip of the camera captures the light emitted from the neutron-sensitive scintillation screen. Optical lenses fitted to the camera head capture variably sized fields-of-view from 4 to 40 cm. This detector is especially useful for neutron tomography.

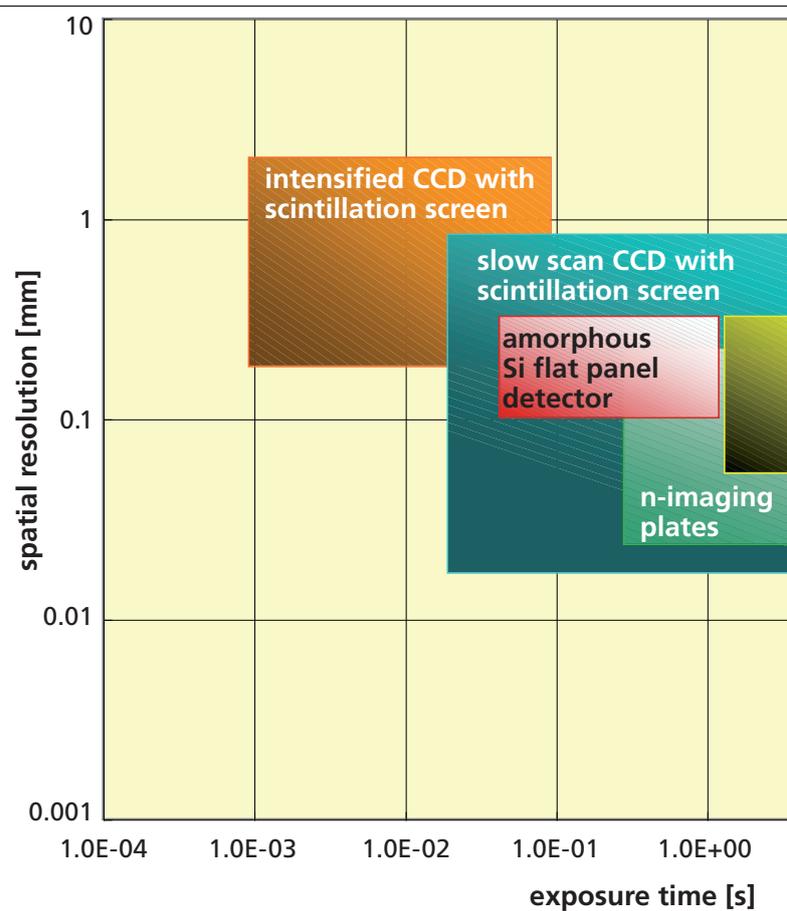


### CCD camera with light amplifier

The light intensity can be enhanced by an amplifier for very low light applications. The amplifier can be gated, i.e. triggered at exact time points, for short exposures, permitting in particular the analysis of fast, periodic movements.

### Film based methods

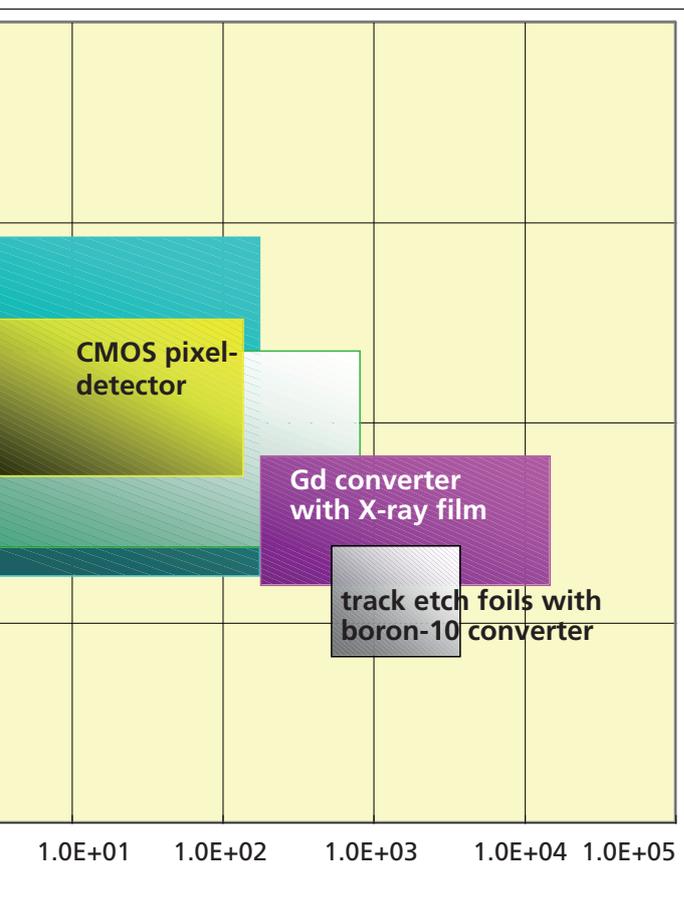
X-ray films and special "track-etch foils" provide analogue images of high spatial resolution, but require long neutron exposures and film-development times.



### Amorphous silicon flat panel detector

Light emitted from the neutron scintillation screen is captured by a narrow array of small photodiodes in direct contact with the screen. The diodes accumulate charges, which can be read out at high frequency, permitting "real-time" neutron imaging.





**Imaging Plates**

These large-area, thin, plastic-like foils capture neutrons in a matrix containing gadolinium isotopes mixed with a barium, fluorine, europium. Electron-hole pairs are generated, which, by laser irradiation, induce light emission. This photostimulated luminescence can be recorded with high spatial resolution using a laser scanning device.



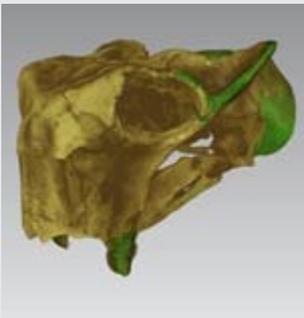
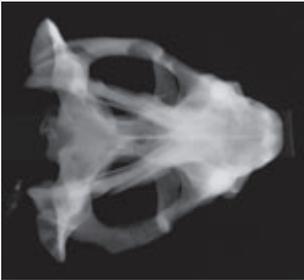
**CMOS pixel detector**

An array of pixels collects the charges generated by neutron capture. Each pixel has its own amplifier and digital converter, permitting low-noise acquisition of multiple neutron events and fast detector read-out.



Detector system	Field of view (typical)	Pixel size [mm]	Dynamic range [greylevels]	Typical exposure time [s]	Read-out time [s]	Read-out rate [1/s]	Special prop.
Film + converter	18 cm * 25 cm	0.02	100	approx. 1000	approx. 2000	not relevant	
Track-etch foil + B10	10 cm * 10 cm	0.02	100	approx. 2000	approx. 2000	not relevant	
CCD-camera + scintillator	25 cm * 25 cm	0.05–0.2	65536 (16 Bit)	1–90s	1–10s	0.1 – 0.5	
intensified CCD + scintillator	25 cm * 25 cm	0.05–0.3	4096 (12 Bit)	0.001 to 1	1 to 5	0.1 – 0.5	trigger
n-sensitive imaging plate	20 cm * 40 cm	0.05	65536 (16 Bit)	approx. 10	approx. 300	not relevant	multiple use
amorph-Si flat panel	20 cm * 25 cm	0.127	4096 (12 Bit)	0.03 to 2	continuous	1 to 30	
Pixel-detector	3 cm * 8 cm	0.25	unlimited	> 1	< 1		

## Tomography

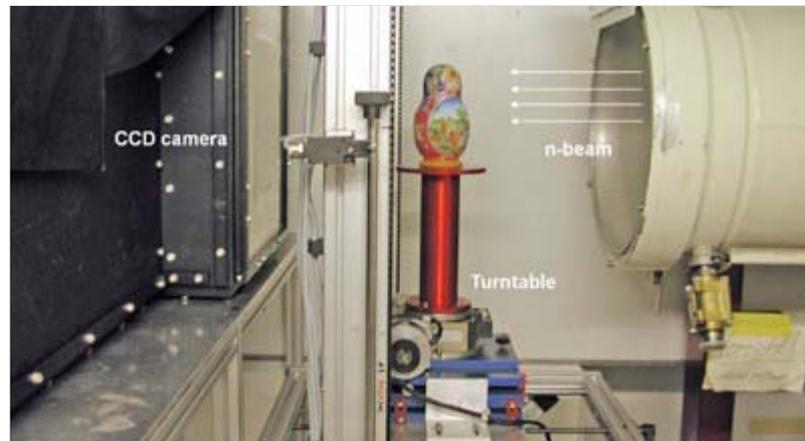


The 250 million year old skull of the mammal-like reptile *Lystrosaurus*. Top, a radiograph of the skull reveals that the structures provide sufficient contrast for a tomography. Bottom, a 3D rendering of the CT-image with segmented regions that show the restored parts of the skull. The sample was kindly provided by Dr. R. Schoch, Staatliches Museum für Naturkunde Stuttgart, Germany.

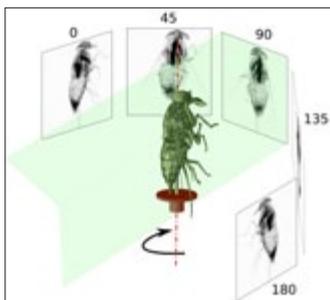
Computed tomography is a method to acquire three dimensional information about the structure inside a sample. The method applies to neutron as well as the more known X-ray imaging. It uses radiographic projection images from many views to reconstruct the distribution of materials in the sample. Mostly, the projections are acquired with equiangular steps over either  $180^\circ$  or  $360^\circ$  to cover the whole sample. Figure below shows an experiment setup used for neutron tomography. Here, the sample is rotated using a turntable in contrast to medical imaging where the beamline is rotated around the patient. The projection images are acquired using a combination of a scintillator to convert the neutrons to visible light and a CCD camera.

The transform of the projection data into a three dimensional image is a computationally intensive task handled by special reconstruction software. During the reconstruction process, slices perpendicular to the rotation axis are produced. When these slices are stacked in a sequence they form a three-dimensional volume image of the sample.

The reconstructed volume data can be visualized using three-dimensional rendering graphics software. Using such tools, regions can be segmented based on their attenuation coefficients and geometry. This can be used to reveal the inside of the sample in three-dimensions as seen by the neutrons.



Tomography setup at position 3 of the NEUTRA radiographic facility.



**Data acquisition**  
300–1200 projections  
Scan time 1–24 h



**CT reconstruction**  
Processing time ~1 h



**Data evaluation**  
Image processing/analysis  
3D Visualization  
Processing time hours or days

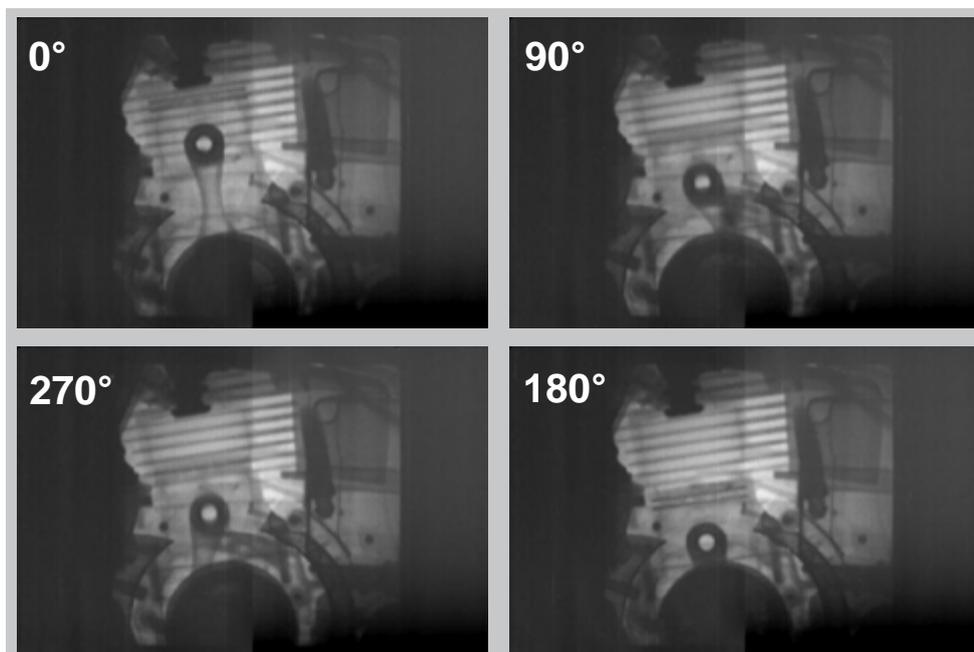
## Time dependent neutron radio- and tomography

### Dynamic neutron radiography: running engine

Rapid periodic processes which can be found as an example in a running engine can be investigated by exact chronologically triggered exposures and therefore with short exposure times. The exposures of the identical cycle positions are summed up and merged into one image. This is shown as an example for a running chain saw motor, running at idle speed with 3000 rpm. In total at 40 different crankshaft positions neutron images of the interior of the full rotation of 360 degree were acquired. The therewith obtained images can be put together to a movie. In this way the movie resembles a flip-book of the moving parts inside the motor. The current status of the measuring technology enables to take images with up 10000 rpm.



Setting up a real-time experiment (stroboscopic mode) with a combustion engine driving a chain saw (results below).



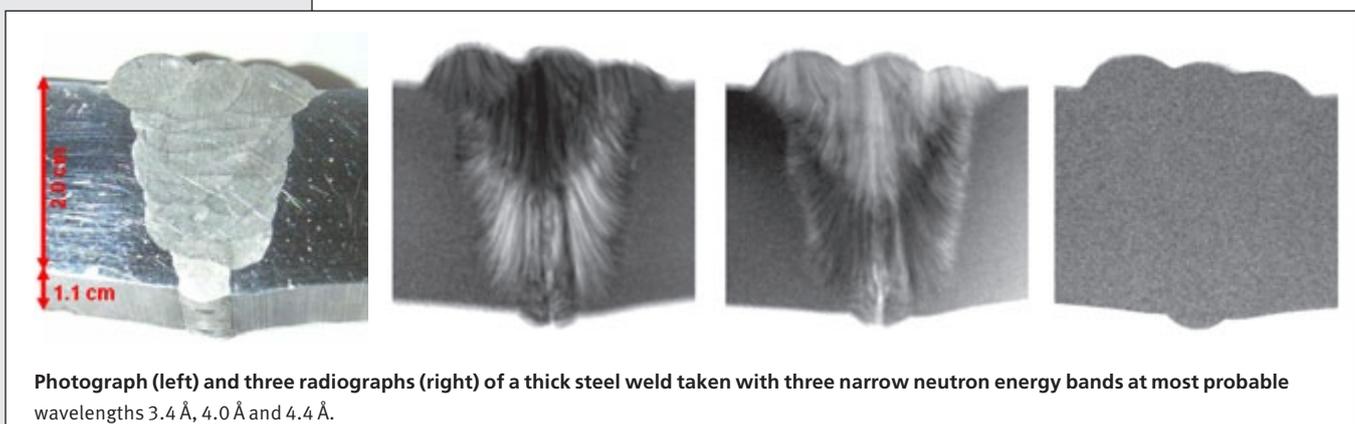
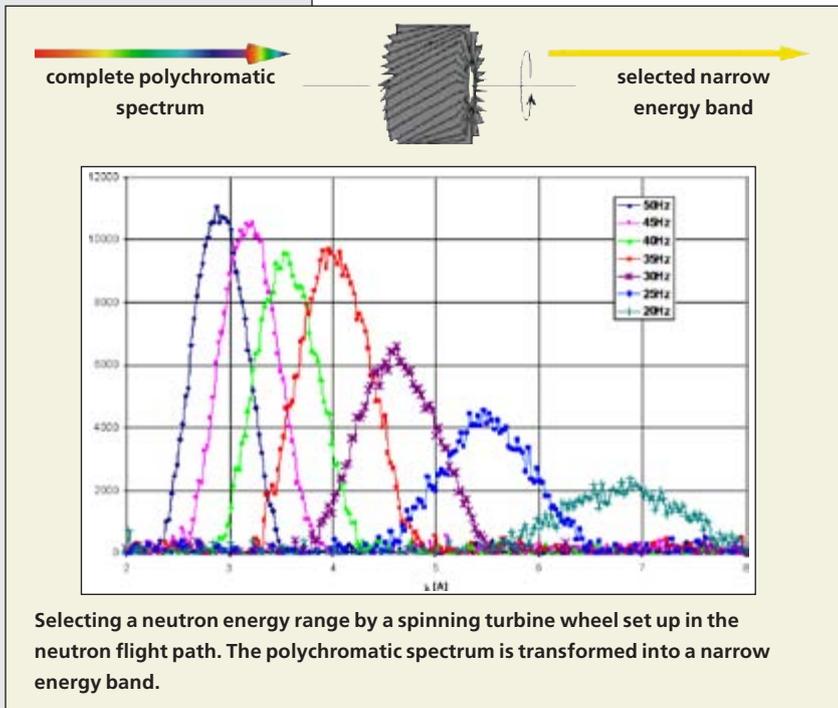
Dynamic neutron radiography images of a running two-stroke engine. The images originate during idle speed at 3000 rpm. Four different crank shaft positions out of 40 are shown. The exposure time for the triggered measurement is 500  $\mu$ s. The corresponding movie can be found: [http://neutra.web.psi.ch/annual\\_reports.html](http://neutra.web.psi.ch/annual_reports.html).

## Energy-selective imaging

Neutrons extracted from the NEUTRA or ICON flight tube have a wide range of velocities, or equivalently energy or wavelength. Images acquired with such polychromatic spectra are therefore energy averaged. Many polycrystalline materials, notably metals, show steep steps in their neutron interaction probabilities at low

neutron energies. By means of energy selective imaging measurements, these Bragg edges can be used to enhance contrast or to elucidate changes in material properties. Narrow bands of neutron energies are selected by a spinning turbine wheel featuring lamellas which strongly absorb neutrons (see left figure). Only neutrons within a given velocity range pass through the wheel rotating at a selected frequency; the others are absorbed by the lamellas. Resulting wavelength spectra are shown in figure left.

Figure below displays the photograph (left) and three neutron images (right) of a thick steel weld acquired with three narrow energy spectra of most probable wavelength 3.4 Å, 4.0 Å and 4.4 Å. The inhomogeneity in the weld, visible differentially at the three energies, is due to variations in the crystal lattice properties of the material in the weld zone. Only energy-selective neutron radiography can reveal such changes.



## Phase contrast and dark-field microscopy with neutrons

**Phase contrast and dark-field images with visible light are indispensable tools for the modern microscopy technology. PSI had succeeded to develop the corresponding imaging techniques for neutrons. Hereby quantum mechanical interaction of neutrons with matter can be made visible in two-dimensional and three-dimensional images.**

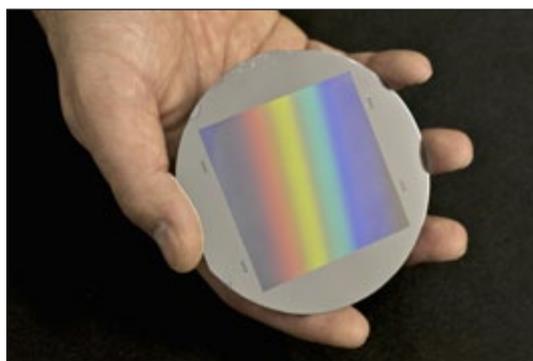
Particle physicists consider neutrons as small particles; though due to wave-particle dualism neutrons can also be described by matter waves with a certain wavelength. Contrary to the conventional absorption contrast, where the contrast differences arise from the different attenuation of the materials, the image information in the phase contrast and dark-field images originate from a change in wavelength within the material.

In the case of the phase contrast method, one uses the fact that the waves which transverse an object have a different velocity to those which do not, and therefore have a different wavelength. The resulting displacement of the wave maxima leads to a change of the propagation direction and therefore to an angular change. An example from classical geometrical optics clarifies how a phase sensitive image can be obtained. By considering a beam path through a collection lens, it follows from the law of refraction that initially parallel light rays are refracted towards the optical axis. In a wave-optical description this corresponds to a lens induced angular change of the light rays, and namely a spatially dependent phase shift of the wave front.

In order to obtain phase contrast imaging, we measure the local angular variation of the neutron beam caused by the object. The experimental difficulty is therefore to measure efficiently, for a variety of image points, such small diffraction angles, in the range of  $10^{-4}$  degrees.

Therefore one uses two grids (G1 and G2) which are composed of lines with lattice constants of a few micrometers. Such a grating is shown in Figure on this side above. The gratings together with a spatially resolving neutron detector then form the so-called neutron grating interferometer, as depicted in the Figure below. The local angular change can be determined by pixel wise analysis of the measured intensity.

Measurements of the phase shift of neutrons in interferometry experiments have been used so far to experimentally verify quantum mechanical predictions. The work at PSI aims to combine the available information about the phase shift with a space-resolved imaging technique, in order to image the quantum mechanical interaction of neutrons with matter and to offer new contrast possibilities.



One of the gratings with fine lines in the micrometer range manufactured at PSI as used in the neutrons grating interferometer. The wafer has a diameter of 100 mm. The grid area is  $64 \times 64 \text{ mm}^2$ . The rainbow is caused by the refraction of light at the fine structures of the grating.

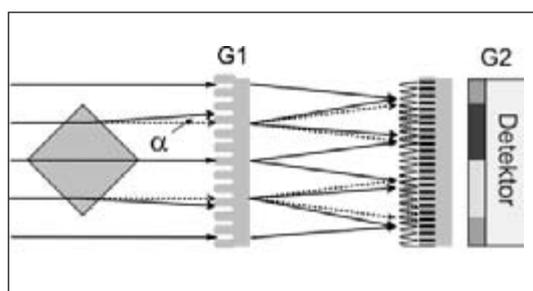


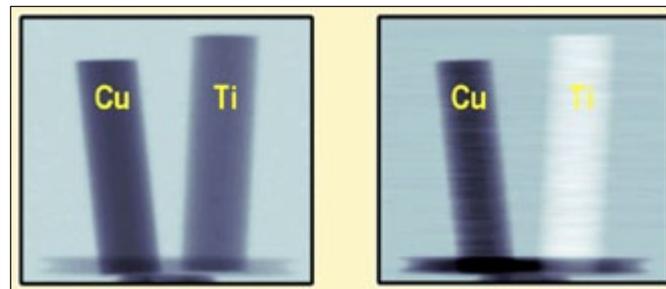
Illustration showing the setup of the neutron grating interferometer, consisting of a phase and an absorption grating and an imaging detector. With the help of this setup neutrons can be detected, which have been deflected or scattered at an angle of  $10^{-4}$  degrees.

Figure below shows the results obtained for test samples. The conventional neutron absorption image (left) shows no measurable difference in the attenuation behaviour of the two metals, Copper and Titanium. The image of the measured phase shift (right), however, clearly shows a difference. Particularly interesting is the opposite sign of the phase shift of Copper (black in the image against the gray background) and Titanium (white to gray); this is a consequence of the different signs of the refractive indices of the materials.

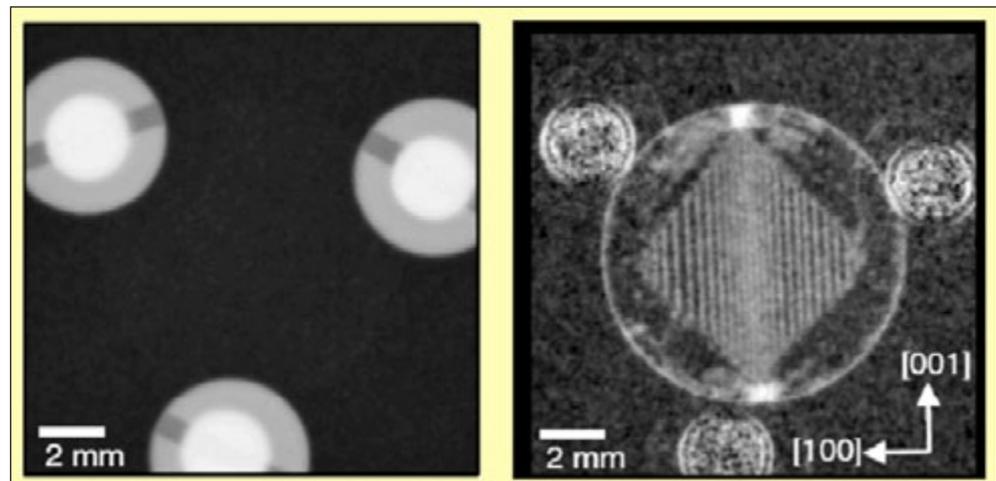
For the dark-field imaging method the scattering properties of the interior of the materials is considered, resulting in Neutrons being scat-

tered during their passage through the material; the passage through the material consists of interactions with materials of different refractive indices, resulting in a small angle change. This method can be used, for example, to visualize magnetic domains in ferromagnetic materials, as shown in Figure below. Neutrons are deflected due to the interaction of the neutron spin with the local magnetic fields, since magnetic domains with different orientations have different refractive indices. Therefore, neutrons are scattered in the transition from one domain to the next at the domain walls, seen in the dark-field image as white lines.

Measured neutron images of two metallic rods with a 6 mm diameter and made of Copper and Titanium. (Left) Conventional absorption image; (right) phase contrast image.



Measured neutron images of a magnetic sample (Silicon Iron) in the form of a disk with a thickness of 300 microns and a 10 mm diameter. Left: Conventional absorption image; Right: Dark-field image. The white lines which form a rhombus are magnetic domain walls.



# Scientific use



**Research into wood and soil:**  
e.g. precise analyses of moisture content in wood samples

**Hydrology and geology:**  
e.g. analyses of rock formation or geological transport processes

**Nuclear technology:**  
e.g. examination of fuel elements and quality control

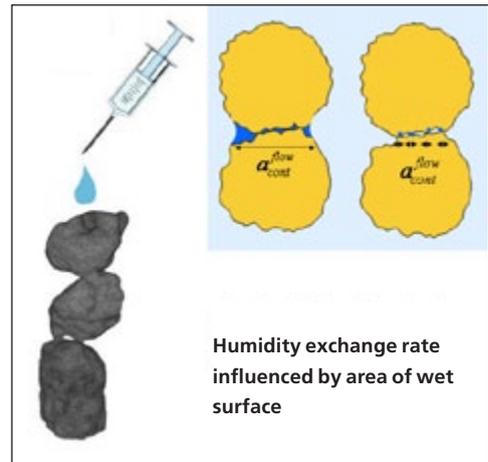
**Archaeology and museum research:** e.g. research into bronze and iron objects or paintings

**Palaeontology:**  
e.g. examination of fossils

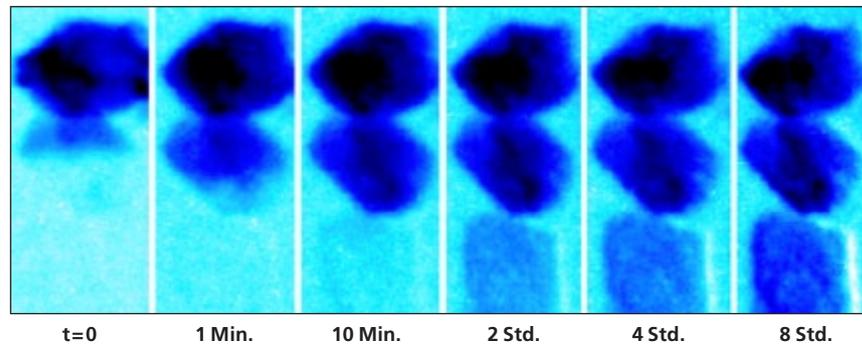
**Materials research:**  
e.g. investigations of alloys, welds, etc.

### Soil structure and humidity transport

Due to its high sensitivity to small amounts of hydrogenous compounds in a matrix, neutron radiography and tomography can be used to measure humidity transport in soil. The measurements are needed for the validation of simulation models used to analyze the mobility of nutrients, pesticides, contaminants ... in soil. Typically, radiographic time series of representative soil agglomerates, as shown in figure below, are used to quantify water transport. Volumetric tomography measurements can be acquired of quasi-stationary states.



Humidity transport in small soil agglomerates (diameter 5 mm) as recorded by radiographic snapshots taken over several hours. The moisture alone is revealed by dividing the radiograph of the wet state by the radiograph of the initial dry state.



### Renaissance bronzes

Renaissance bronzes from the Rijksmuseum Amsterdam were investigated by neutron tomography in order to study their casting. Old bronzes usually have a quite high lead content, which make them ideal candidates for nondestructive analysis by neutron tomography. From

the tomographic volume, virtual slices can be generated, revealing the inside of the bronze as figure below shows. The shape and size of bronze hollows or additional filling materials yield conclusions about the casting process. Resins or varnish used for the conservation of sculptures appear with high contrast.



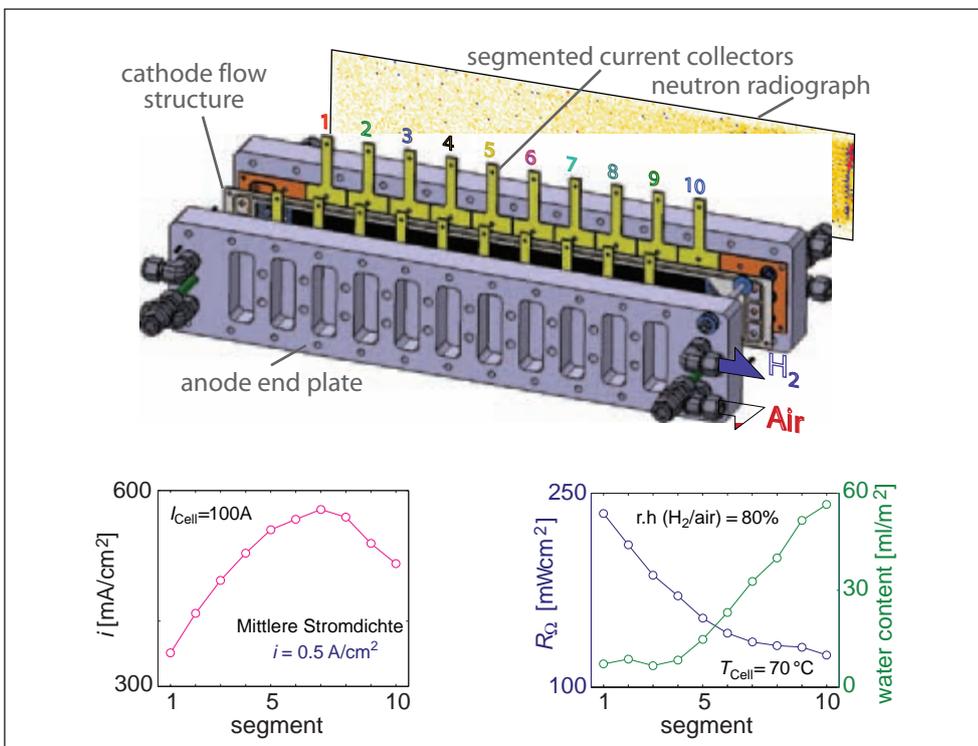
Tomographic views of a bronze sculpture: virtual slices and transparent views can be created without damaging this unique object.

Photo: Rijksmuseum Amsterdam

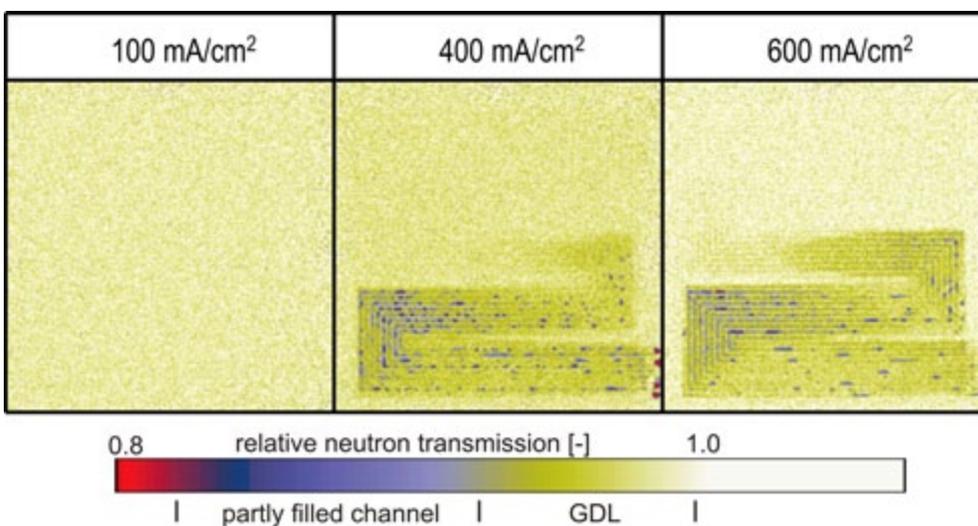
### Fuel cell investigations

In comparison to combustion engines, fuel cells are attractive, because they allow for a highly efficient conversion of chemical energy stored in a fuel into electricity. A major application of fuel cells is in the automotive industry, where they are considered as promising alternatives to the internal combustion engine. The characterisation and optimization of the physico-chemical processes taking place within the device are a main objective of fuel cell research and development, worldwide.

The electrochemical reaction of hydrogen with oxygen in a fuel cell produces water, an essential aspect of fuel cell operation. Neutrons can monitor water distribution within a working fuel cell non-invasively, because they penetrate the exterior holding plates easily and yield radiographs with sufficient spatial and time resolution. Used simultaneously with other advanced, spatially-resolved characterization methods of the cells' electrochemistry, neutron radiography provides important insight into fuel cell operation.



The changing water content of the fuel cell membrane affects fuel cell behavior. Performance characteristics, i.e. current density and cell resistance, of a PEM fuel cell are shown as a function of channel length.



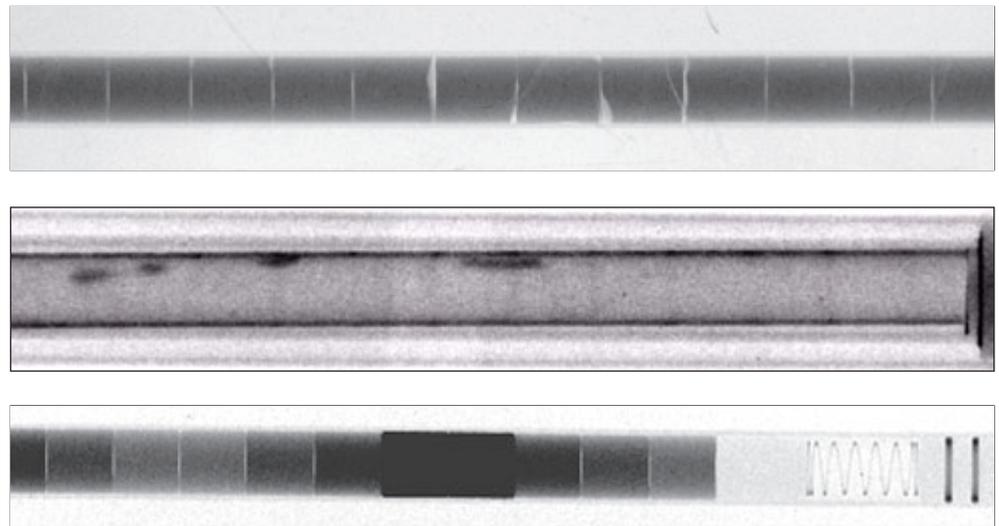
The increase of the moisture content inside the fuel cell at different the power densities is clearly visible and quantifiable by neutron imaging techniques.

### Neutron imaging of nuclear fuel

Traditional X-ray investigations of nuclear fuel elements are almost impossible, since irradiated nuclear fuel is a strong emitter of  $\gamma$ -rays. Contrary to X-rays, neutrons easily penetrate heavy metal samples like e.g.  $\text{UO}_2$ . Therefore, neutron radiography, using area detectors sensitive to neutrons only, permits the nondestructive evaluation of highly radioactive material. Fuel rod segments from nuclear power plants are investigated in collaboration with the PSI hot cell facility. They must be transported and

manipulated with in heavily shielded containers and equipment as provided by the NEURAP setup presented on page 16. The aim of nuclear fuel investigations is to check the integrity of fuel pellets after long term irradiation (figure below) or to evaluate the corrosion of zircaloy cladding material (figure below middle). The high sensitivity of thermal neutrons to the U-235 isotope can be used to check isotopic enrichment by neutron transmission measurements (figure below bottom).

Radiographic inspection of nuclear power plant fuel rod segments: single fuel pellets show fractures and chips (top), zirconium hydride lenses due to cladding corrosion (middle), or fresh fuel pellets with varying isotopic enrichment (lower).

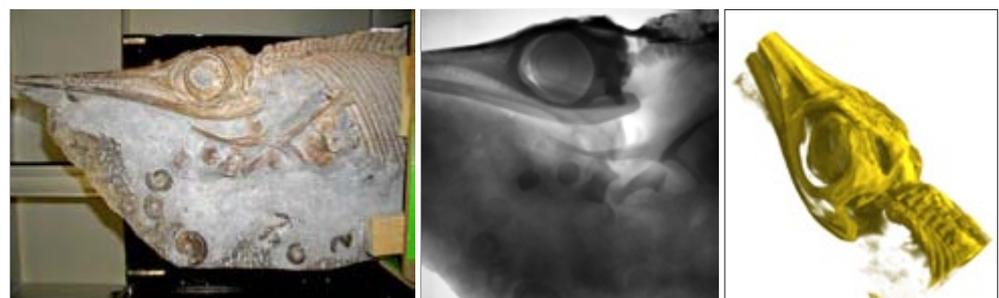


### Palaeontology

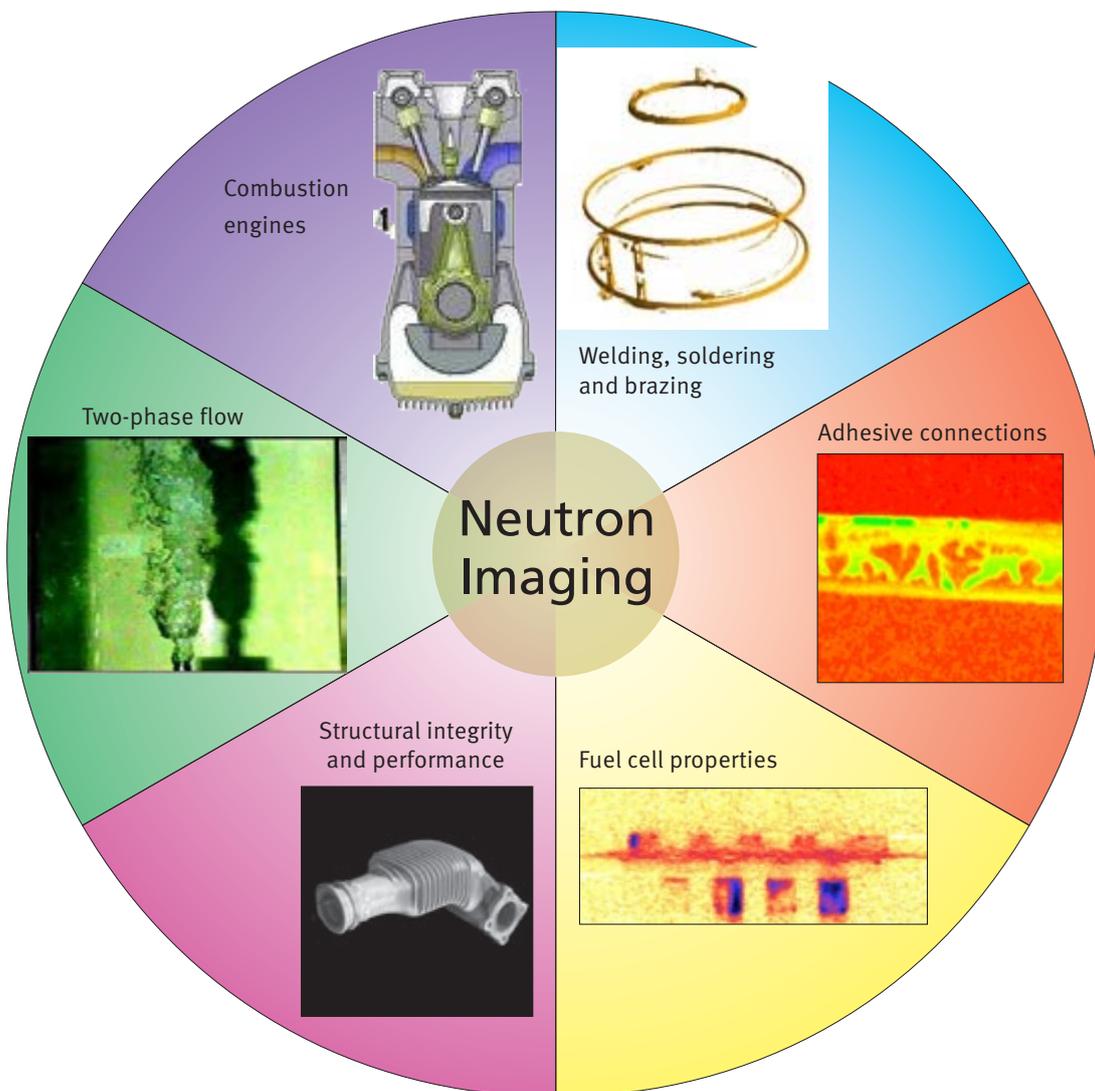
Neutron radiography permits nondestructive evaluation of large fossils. The Figure below shows the photograph and neutron radiograph of the partly dissected head and neck of an ichthyosaur. In the tomographic study of the

head section, the skeleton can be segmented from the surrounding sediment. If sufficiently precise details about skeleton can be retrieved, further restoration steps can be envisaged to yield additional insight into the development of ichthyosaurs.

Fossilised skeleton of an ichthyosaur partially dissected by U. Oberli, St Gallen. Photograph (left), radiograph (middle), and tomographic view of head section (right).



# Industrial applications



**Welding, soldering & brazing:** quality assurance and tightness, integrity

**Adhesive connections:** glue distribution, in particular behind thick metal layers

**Fuel cell performance:** water production rate and local distribution

**Structural integrity and performance:** observation for cracks, corrosion after operation

**Two-phase flow:** water detection in metal pipes, time dependent, e.g. refrigerator

**Combustion engines:** real time studies of running devices, Diesel particulate filter performance

### Industrial Applications

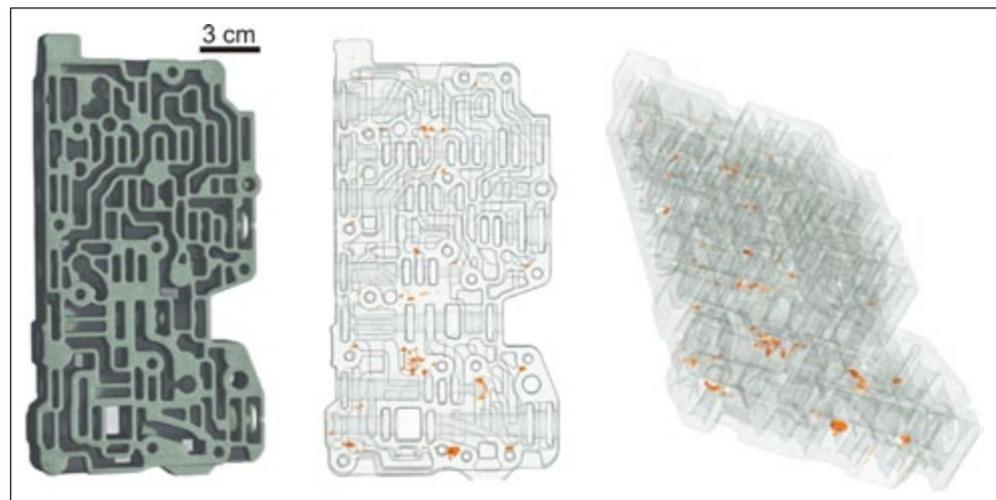
Neutron Imaging is in use as a tool for non-destructive and non-invasive inspection of industrial components. The higher standards in safety issues, the permanent improvement of material properties and more complex structures in industrial systems require more sophisticated techniques for diagnostics.

Here, neutron imaging fits in as a complementary option in respect to the well-known X-ray techniques which are also under progres-

sive improvement. The example in figure on the right of an actuator shows impressively the difference in the image results of the two methods – neutron and X-ray inspection. Whereas neutrons better identify plastics and sealing materials, the X-rays show metallic components while “ignoring” organic materials more or less.

Neutron imaging techniques can favorably be applied when larger metallic components have to be transmitted and small amounts of hydrogenous materials have to be visualized.

Study of a casted Al part from car industry where some shrinkage cavities filled with casting remains can be identified with the help of neutron tomography (left: the outer shape of the object; middle, right: semi-transparent metal with the holes in colour).



Adhesive connection of a metallic car component (photo left) where neutron tomography allows a separation of the glue (red colored) from the metallic structure; the inhomogeneous distribution becomes obvious and might limit the solidity of the structure.

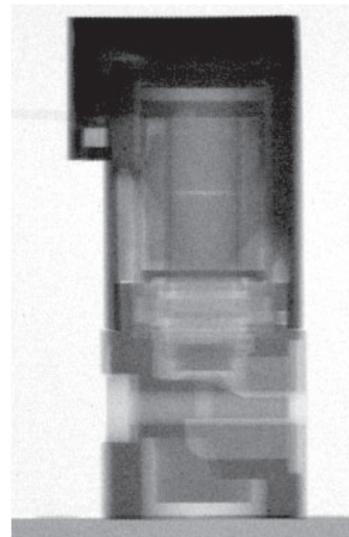


There are also some materials with a high absorption ability (B, Cd, Li, Gd, ...) for neutrons which can be observed in very high detail and sensitively inside structures.

Based on these main features of neutron imaging the following principle categories of industrial applications could be identified until now:

- Gluing connections between metals and other materials
- Solder and brazing connections of metals
- Casting failures and structural defects in metals
- Thin films of lubricants, water, corrosion and lacquer
- Periodic processes (running engines, pumps, injectors, ...)
- Deposits in filters and on sensors in small amounts
- Water deposition and distribution in running electric fuel cells

There is certainly the potential for further applications for industrial partners. First tests will be done on demand in order to define the performance for the particular study and find out the best possible boundary conditions.



X-ray (above) and neutron images (below) of an encapsulated initiator device showing complementary information about the inner structure and performance. While the X-rays show the metallic structures through the plastic cover in very detail, the organic materials (sealing rings, plastics, adhesives) becomes better visible with neutrons than the metal. In particular the fit and condition of the O-ring was highly relevant for the customer.



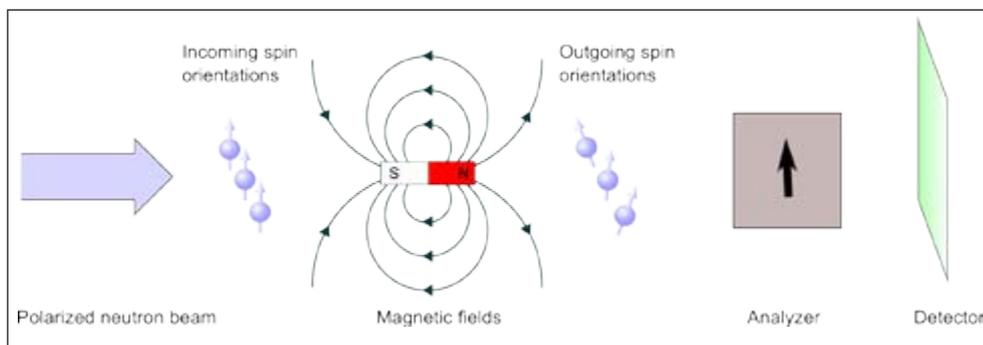
A non-invasive inspection tool for boron containing soldering connections is found in neutron imaging. A destructive inspection is not required when neutron tomography is applied to the object on the left. By suitable software tools the metal can be separated from the solder distribution shown on the right.

A petrol station filler nozzle is prepared for investigation at the ICON neutron radiography facility. The radiograph is shown on the right.



# Outlook

## Neutron Imaging with polarized neutrons



Principle setup of experiments with polarized neutrons for the study and visualization of magnetic phenomena

It is well known that neutrons as elementary particles obey a spin which occurs in two states (up/down). A neutron beam extracted from a source contains both states in the same amount,

Polarized neutrons with only one spin state can only be obtained if the other state is sorted out by means of different filter options which absorb and suppress 50 % of all neutrons.

Neutrons also carry a magnetic moment which follows the spin orientation. In this way, neutrons can be considered to be small microscopic magnets. They can be arranged in a magnetic field and precise around the direction of the field.

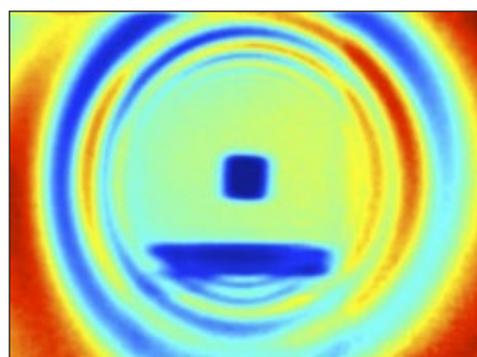
This property of the polarized neutrons enables to visualize directly magnetic structures, the distribution of magnetic fields and effects of magnetization in different materials.

For this purpose, a setup is needed as shown in Figure: after their polarization the neutrons hit the area with the magnetic relevant structure where a variation of the distribution of the polarized neutrons happens. This influence of the magnetic effects onto the distribution of the polarized neutrons can be measured by means of a neutron sensitive imaging detector arranged behind the analyzer of the polarized neutrons.

The principle of this kind of measurements has already been demonstrated [1]. At PSI we intend to establish and to improve the method by using the BOA beam line which already delivers a highly intense polarized beam in order to improve the spatial resolution and to reduce the acquisition time in the measurements. New magnetic materials and magnetic phenomena should be investigated and visualized on the macroscopic level.

### Reference:

- [1] N. Kardjilov et al., Nature Phys. 4 399-403 (2008)



Visualization of the distribution of the magnetic field around a magnet levitated above a superconducting sample of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>. This measurement was done at the CONRAD facility of the Helmholtz Centre Berlin [1].