Neutron Imaging at Spallation Neutron Sources

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Abstract. Neutron imaging is a powerful method for non-destructive investigations where the high penetration through metals and the high contrast for hydrogenous materials is exploited in particular. The complementary to X-ray studies is a clever alternative in many cases of scientific and industrial applications. Reactor based neutron sources are becoming less available, caused by the shutdown of aged facilities. Accelerator driven neutron sources, in particular spallation sources, can provide similar performance also for imaging now, when digital imaging systems are utilized. The article shows the properties of imaging beam lines at SINQ, the presently strongest stationary spallation source. They deliver thermal neutrons as well as cold ones. Several beam line properties as collimation, field-of-view, neutron energy and spatial resolution can be changed and adapted to the conditions of the various experiments. The imaging methods include simple transmission radiography, time-dependent studies, but also advanced methods like tomography and refraction enhancement. New aspects as quantitative tomography, phase contrast imaging and imaging with polarized neutrons are under consideration and implementation.
A new and challenging aspect will be the use of the pulse structure of newly available large spallation sources like SNS, JPARC or ISIS-TS2 for imaging purposes. Despite the high peak intensity, which can be used for the study of fast repetitive processes, a time-of-flight imaging approach will enable energy resolved investigations. This is of particular interest at the Bragg edges of structural materials, where textural changes (e.g. near welds) become directly visible. First data of such kind of investigations can underline the importance of the new methodical approach.

1. Introduction: motivation for neutron imaging

Neutron imaging as a non-destructive and non-invasive tool for applied research and industrial purpose is available today at few places word-wide on high-performance level [1]. It represents an inspection method similar to X-ray imaging, but delivers different contrast and transmission features. As shown in Fig. 1 (for the case of a gasoline dispenser), the resulting image quality in respect to spatial resolution, dynamic range, field-of-view can be the same for both imaging techniques.
Different contrast mechanisms are obtained for X-ray and neutron imaging, respectively, where neutrons are more sensitive for light elements while X-rays does nearly ignore e.g. hydrogen. Neutron imaging is a very attractive method when heavy metals (Pb, Bi, U, Cu, …) should be transmitted and small amounts of organic material have to be found inside such metallic structures.
The difference in the contrast/transmission is caused by the interaction of the two kinds of radiation with matter (the sample material). X-rays interact only with the electrons of the atomic shell, while neutrons make interactions with the atomic nuclei. Whereas the number of electrons increases the interaction probability for X-rays, there is no clear systematic rule in neutron interaction in dependency on the size of the atoms.
Neutron and X-ray imaging have to be considered as alternative and complementary methods. Due to the high dynamic in the detector development, most of the investigations have been performed in the last years with digital imaging methods [2]. Compared to the previously used film techniques, there are many advantages of the digital systems which are discussed elsewhere in detail [3]. They enable modern methodical approaches like tomography, time-dependent studies, phase-contrast imaging and quantitative analysis.
A short comparison between the neutron and X-ray approach is given in Table 1.

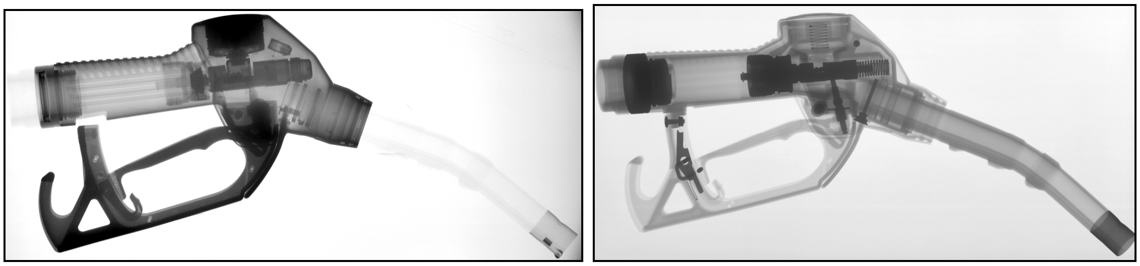

Fig. 1: Neutron (left) and X-ray (right) images of a gasoline dispenser obtained with digital imaging systems: while similarly at first glance, it is obvious that neutrons penetrate metallic parts better than X-rays but deliver higher contrast for hydrogenous materials (plastic cover, sealing, and fuel droplets)

TABLE 1: COMPARISON OF NEUTRON AND X-RAY IMAGING ASPECTS

X-ray imaging	**Neutron imaging**
X-rays interact with the electrons in the atomic shell	(thermal, cold) neutrons interact with the atomic nuclei
Light elements (organics materials) have low contrast only	Hydrogenous materials deliver high contrast
Heavy elements (e.g. metals) are difficult to transmit	Many metals can easily be transmitted
Method available in many labs	***Method available in only few dedicated labs***

With the implementation of X-ray imaging capabilities at synchrotron sources (e.g. [4]) the intensity of the beams has increased by orders of magnitude and the coherence and collimation was improved dramatically too. This development has particular importance for the improvement of spatial and temporal resolution. There is a challenge for advanced neutron sources to compete into this direction.

Many unique applications of neutron imaging (fuel cell research, nuclear fuel inspection, studies for cultural heritage objects, moisture distribution in various structures, …) have been reported in the literature [5, 6, 7], indicating the high demand and performance in this promising method.

2. New neutron sources: accelerator driven

Most of the neutron sources hosting a beam line for neutron imaging purposes are reactor based. Already a reactor power of about 250 kW enables neutron imaging nowadays with sensitive digital systems when the exposure is over several minutes. The strongest reactor with imaging capability is presently HFIR (Oak Ridge, USA, 80 MW now, 100 MW planned). However, the number of research reactors is decreasing due to decommissioning of aged ones and missing projects for new ones.
A competitive alternative in neutron generation is spallation, where an intense beam of high energy charged particles (predominantly protons, energies in the order of GeV) is send onto a target with heavy atoms. Typical target materials are Pb, Hg or W, when U is avoided for safety, proliferation and other reasons. There are some important advantages of such accelerator driven systems compared to reactors: less heat production (only about 15%), no

real target burn up longer operation cycles, less activated material, only short-time activation, no trans-actinides, no proliferation risk with fuel.
The number of spallation sources is still limited and the amount of investment is considerable. Most of the existing spallation sources and the facilities planed for future ones are pulsed with frequencies in the order of 50 Hz. This pulse structure of the initial proton beam is causing a pulsed neutron beam structure which can preferentially be used to separate different neutron energies with time-of-flight (TOF) techniques.
SINQ at PSI is still world strongest spallation source, comparable to a research reactor of about 15 MW and operating in a continuous beam mode. It is successfully in operation since 1997 and has permanently increased the neutron output by different target options (solid state Zr, solid state Pb, liquid Pb-Bi) and the increase of the proton current (about 1.5 mA on the target with proton energies of 570 MeV). The D_2O moderator delivers beams of thermal neutrons whereas the cold source (liquid D_2 at 25 K) feeds the beam lines for cold neutrons.

3. Facilities for neutron imaging at PSI

Neutron imaging is established at SINQ since the first days of its operation, when the thermal facility NEUTRA was set into utilization in 1997. Its performance characteristics are described in [8]. In 2006, the second beam line ICON with a cold spectrum was ready for use [9]. A comparison of the properties of the two facilities is given in Table 2.

TABLE 2: COMPARISON OF PROPERTIES OF NEUTRON IMAGING FACILITIES AT SINQ, PSI, CH

ICON	**NEUTRA**
Cold neutrons	Thermal neutrons
Higher contrast	Higher penetration
Variable aperture, Bi-filtre option	Homogeneous illumination for large objects
Two beam positions	Two beam positions
Micro-tomography setup	Two detector boxes
Tilted detector option	X-TRA option with a 320 kV tube
Turbine type energy selector	Infrastructure for highly activated samples
Fuel cell research infrastructure	Sample manipulator 80 kg
Sample manipulator 500 kg	

As shown in Fig. 2 with the example of the neutron imaging facility ICON, a well shielded area covers the whole installation, protected by a controlled access system. The beam is sent to the observation area through an evacuated tube system. Several positions along the flight path enable either higher beam intensity or higher spatial resolution (or larger fields-of-view).
The two facilities enable a high flexibility in the user program in respect to sample size, spatial resolution, image contrast, time-dependency or specific sample environment. About 100 different research and development tasks have been performed yearly at these imaging facilities.
For a stationary spallation source like SINQ, the principle layout outside the shielding block is not very different from a reactor based imaging facility. However, the shielding around the target region is more extended and water is not sufficient to protect against high energy particles. Therefore, about 6 meters iron and concrete are needed, which defines the minimal distance between source and imaging position too.

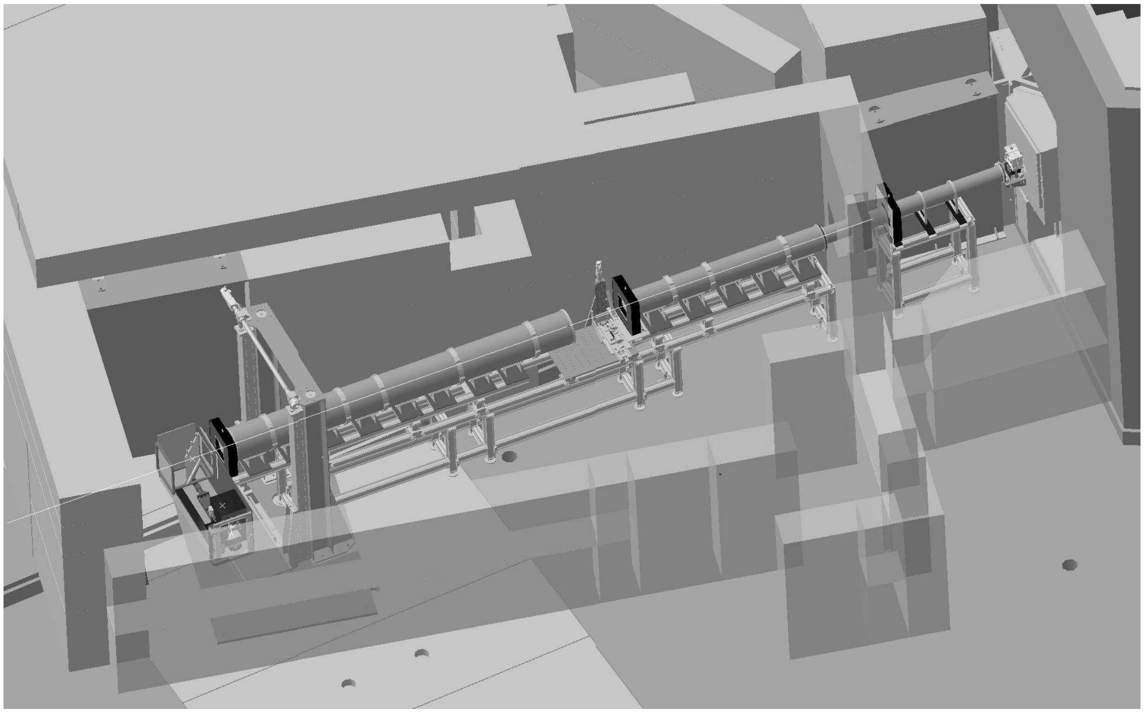

Fig. 2: The neutron imaging facility ICON at glance: the beam of cold neutrons is delivered from the cold source (from the right in the figure) through the inner aperture system and the evacuated flight to the observation places. In the middle, the position for micro-tomography is situated. At the left end position large samples with up to 500 kg can be manipulated and positioned remotely.

4. Challenges for neutron imaging at pulsed spallation sources

Contrary to SINQ, which is a source with a stationary beam output, the latest large projects for advanced neutron sources are focussed on a time structure in the beams, means pulsed spallation sources. Due to the very high installation and operation costs, only few developed countries (or even regions) are able to build and host such facilities. Nevertheless, there is enough scientific interest and challenge to justify these huge investments.
Pulsed spallation sources will provide the following advantages in comparison to the strong reactor based research sources:

- With an averaged power of 1 MW (comparable to a reactor source of only 15 MW) the peak flux in the pulse will be higher by a factor 100 compared to strongest beams (e.g. at ILL).
- This pulse structure can favourably be used for a very effective energy-selection with TOF methods. Depending on the flight path and the energy of choice, the right timing at the detector position enables precise energy selection with unique intensity and resolution performance.
- The neutron spectrum can be tuned with dedicated moderator systems: cold, coupled, decoupled, poisoned

Most of these options fulfil the demands for many neutron scattering investigations perfectly, if the suitable experimental devices are build and installed. Nearly all state-of-the-art scattering methods and setups can be found at the new pulsed sources.

This is not the case yet for neutron imaging techniques and adequate installations. But there are some challenging new options also for neutron imaging options at pulsed sources, which are sketched in more detail below.

It was found out recently, that **energy selective neutron imaging** in particular in the cold energy range near Bragg edges becomes a very exciting research topic for applied material science [10, 11]. Although first preliminary tests were done for this topic already at a pulsed source installation (Osiris, Engine-X, ISIS, UK) under sub-optimal conditions, the most promising results have been obtained with a double-crystal mono-chromatizer setup at the CONRAD facility [12] for the moment.

Depending on the neutron energy of observation, scattering artefacts in bulk material combinations like welds becomes visible in the transmission mode, caused by the different crystallisation properties during solidification. Such a result is shown in Fig. 3 for the case of a stainless steel weld.

A future setup for neutron imaging at a pulsed source would deliver much higher performance and flexibility in the observation of such material phenomena. One the one hand, the field-of-view can be extended as much as the facility layout can deliver (e.g. 40 cm in diameter). One the other hand, any desired neutron energy can be chosen and the energy resolution in the same way. As shown in Fig. 4, the presently achievable energy resolution is in the order of 10% only, where sharp Bragg edges can still not be resolved most efficiently.

With higher energy resolution in future installations at pulsed sources the contrast variation can be improved and the scattering artefact will be increased.

In the same way, there is a chance to see directly differences in the internal stress within macroscopic structures. Although a quantification of stress parameters with the presently used diffractive approach [12] might require extremely high resolution (about 10^{-3}), a pre-scanning with lower resolution will deliver a global overview about the whole object, before a quantification of stress parameters can be performed within a more demanding procedure.

Because such a setup is not yet available [13], the amount of experience for such a challenging approach is limited for the moment.

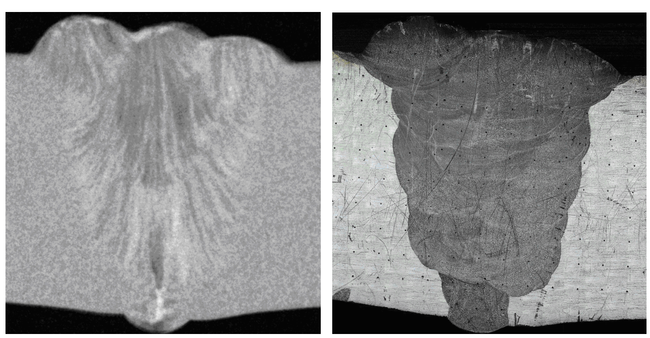

Fig. 3: Inspection of a stainless steel weld (image size 2.7 cm) with neutrons of 4 Angstrom in transmission mode. The neutronic features do not correspond to the optically visible structures at the polished surface and must be attributed to the crystal structure in the bulk. With the broad full neutron spectrum and in other energy regions than near Bragg edges the whole sample looks homogeneously. .

A second important feature with a pulsed neutron source based on spallation is the utilisation of the high intensity of the beam during the pulse. In a suitable setup, **time dependent phenomena,** in particular in repetitive mode, can be observed very sensitively and efficiently.

It should be no problem to synchronize the interesting processes with the frequency of the source or its multiple. In the same way, the neutron detection system has to be synchronized.
Although such kind of studies have been done as pilot experiments at strong reactor sources [14], (see e.g. Fig. 5), there is no dedicated user lab available who serves industrial costumers with this kind of neutron imaging performance permanently and routinely yet. If well designed, a station at a pulsed source would be an important step forward in the study of time-dependent phenomena.

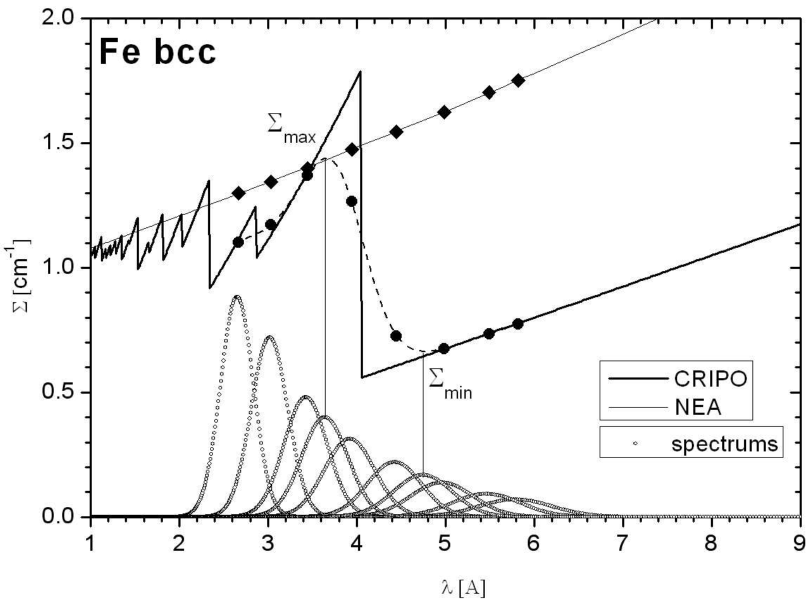

Fig. 4: Cross-section data in the cold region for iron (bcc): idealized (CRIPO) data are compared with experiments using a turbine based selector device (spectra below), which can resolve about 15% only. The challenge for a pulsed source would be to approach much closer to the Bragg edge, where the contrast variation is a factor of 2.5 about.

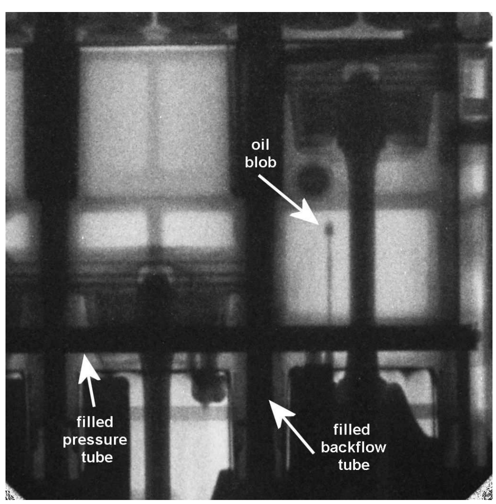

Fig. 5: Study of the lubricant distribution within a running automotive engine with low speed (about 800 rpm), where the continuous flow stops and the droplets do not reach the piston. This phenomenon was found in experiments at the neutron imaging facility ANTARES, FRM-2, TU Munich, for the first time.

Despite the use of the full beam intensity, integrated over the whole neutron spectrum in the pulse, which delivers highest brightness, there are also options feasible in a future installation to combine the energy selective approach with the study of the repetitive process. Both the transmission and the contrast can be adapted for the setup under investigation in the best possible way by choosing the relevant neutron energy. Certainly, such kind of studies will take longer accordingly.

5. Status world-wide

Projects for neutron imaging installations at the pulsed spallation sources are on the way in several directions. As shown in Table 3, there are activities and projects to bring neutron imaging capability to the new sources. Despite the dominance of the neutron scattering community, the new options at the pulsed source should be motivation enough to go into this direction. Maybe, a combination of the imaging and the scattered information from interaction with the sample can provide some completely new approaches in the near future.

TABLE 3: STATUS OF NEUTRON IMAGING INSTALLATIONS AT THE NEW PULSED SPALLATION SOURCES

		neutron imaging project
SNS (Oak Ridge, USA)	in operation since 2006	VENUS
J-PARC (Tokai, Japan)	in test operation since 2008	considered
ISIS-TS2 (Rutherford Lab, UK)	under construction	IMAT
ESS (Europe)	under consideration	probable

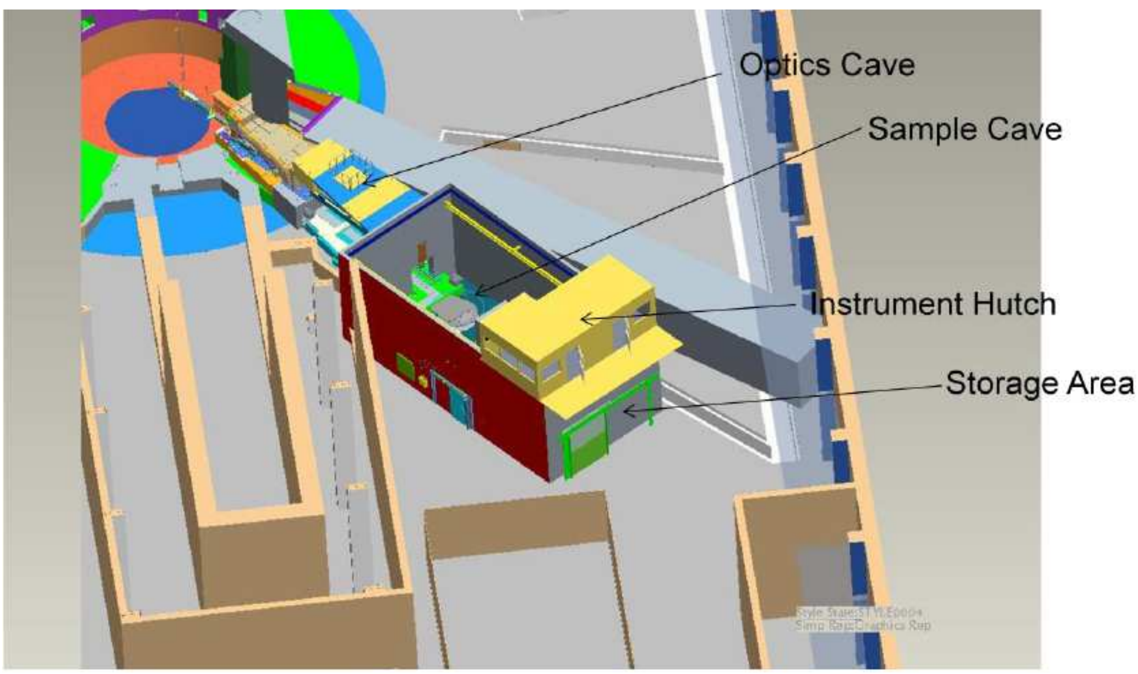

Fig. 5: Areal view of VENUS's (SNS, Oak Ridge, USA) project downstream area with the sample and optics cave, the instrument hutch and the sample equipment storage area: source [15]

6. Conclusions

It was demonstrated by the installations at SINQ (PSI), that spallation neutron sources can host neutron imaging facilities similar to those at reactor based sources if they are well designed and installed. The background from gamma radiation and high energy neutrons are minor problems which can be handled adequately.
Therefore, it will be possible to implement neutron imaging capability at the new pulsed sources from the technical point of view. The challenge there is the perfect tuning option for energy selective imaging investigations in the best possible way with a high flexibility in resolution.
Stroboscopic studies with superior performance and the combination with the energy selective option will create unique applications for scientific and industrial customers in the near future.

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