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CNR—the new beamline for cold neutron imaging at the Swiss spallation neutron source SINQ

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Abstract

Based on the very good experience and knowledge gained with thermal neutron radiography at NEUTRA, novel capabilities can be predicted for a new beamline with cold neutrons: Micro tomography, neutron phase contrast imaging, contrast enhanced radiography, improved quantification of tracer elements and energy selective neutron imaging.

The two main conditions for high-quality neutron imaging—radiography, tomography and especially for neutron phase contrast imaging—are a high beam collimation and a sufficiently high neutron flux. In order to obtain as many cold neutrons as possible from the source, neutron guides are normally used. We have examined whether guides in the accessible parts of the beam channel for CNR could enhance the performance of the instrument. Our findings are (1) that the enhanced divergence provided by the guide is not matched to the collimation or L/D ratio planned for the instrument and (2) the extended image size provided by the guide is not homogeneously illuminated. It has therefore been decided not to use guides inside the target block.

The new radiography beam line CNR for imaging with cold neutrons will be installed at channel 52 of the spallation neutron source SINQ. It will have a direct view onto the liquid deuterium cold source. The installation is planned for the annual shutdown period—spring 2005. When operational, the CNR facility will be available for the NR community in the same way as the NEUTRA station.

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Keywords: Spallation source; Neutron radiography; Neutron tomography; Cold neutrons; Neutron beamline design

1. Introduction

The first steps in neutron radiography at the Paul Scherrer Institute (PSI) were made in the late 1980s of the last century at the swimming pool research reactor SAPHIR. The final shutdown of

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the reactor at the end of 1993 imposed a temporary stop to neutron radiography at PSI. A new neutron radiography facility (NEUTRA) [1] was designed for the spallation source SINQ. Together with the operational start of SINQ at the end of 1996, the first tests concerning beam properties and new detector systems could be performed. The last 7 years of NEUTRA show a successful story of development. The development is two-fold: One in imaging techniques, detector and camera systems and the other in an increasing number of internal and external users from universities and industries [2-4]. CNR—the new neutron imaging facility with cold neutrons will be a supplement and an extension to NEUTRA.

2. The spallation source SINQ

The neutrons in SINQ are produced by the so-called spallation process. A high-energy proton beam (590 MeV) provided by a ring cyclotron enters the spallation target, which consists of an array of horizontally oriented iron-clad lead rods (Fig. 1). When a proton in the high-intensity beam (1800 μA) hits a nucleus of the target material, this nucleus undergoes intranuclear collision processes and the Pb nucleus as a whole is "heated". The excited nucleus releases most of its energy by "evaporating" nucleons, mainly neutrons, from its surface. About ten high-energy neutrons are produced per incident proton with a kinetic energy of 590 MeV. These neutrons are slowed down in D_2O at room temperature. At a position outside the target where the thermal neutron flux has its maximum, a horizontal insert containing about 20 l of liquid deuterium D_2 at a temperature of 25 K is situated. This "cold neutron source" is providing cold neutrons, which are extracted to the neutron guide hall and in the opposite direction to the FunSpin and the new CNR area (Fig. 2).

3. The cold neutron imaging facility CNR

3.1. Introduction

The advantage of cold neutrons for imaging purposes is their higher contrasts for most of the

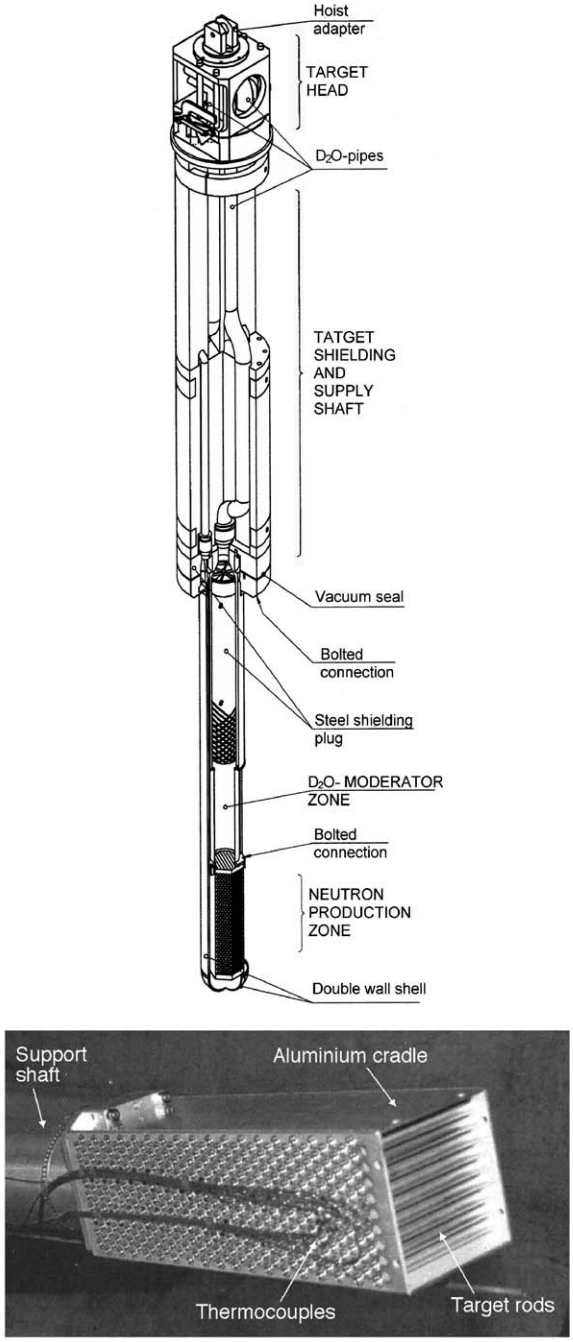

Fig. 1. Section view of SINQ target insert (top). Neutron production zone of the SINQ Mark III target with thermocouples in selected positions (bottom).

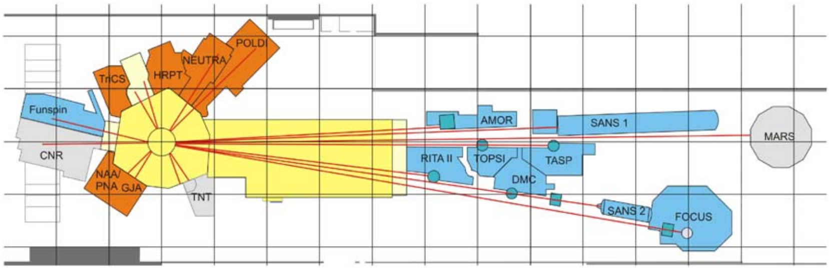

Fig. 2. Floor plan of the experimental facilities inside the SINQ hall. Experiments using cold neutrons are those located at the neutron guides to the right, and the FunSpin facility and the new project CNR to the left. The others grouped around the target block are using thermal neutrons.

sample materials and the higher detection probability. Therefore, thinner detectors can be utilized and higher spatial resolution achieved as a consequence. Tomography investigations (so called microtomography) are planned with the goal to approach the 10 μm resolution range.

Equipped with an energy selecting device, narrow energy bands can be cut out from the cold spectrum in those regions where the Bragg edges are located. This will enable the enhancement of contrasts for specific materials.

Phase contrast imaging will also be within reach with cold neutrons, since the phase shift is proportional to the neutron wavelength. A variable aperture device will be used to provide the best beam conditions for phase contrast imaging.

The comfortable space and infrastructure will enable complementary experimental conditions to the already existing thermal neutron radiography station NEUTRA.

The main prerequisites for high-quality neutron imaging in radiography, tomography and especially in neutron phase contrast imaging are high flux, low background and high beam collimation. The compliance of these conditions requires a compromise to be made between resolution and intensity. In order to extract as many neutrons as possible from the given source, the use of a neutron guide is often essential. The neutron guide transports neutrons of long wavelengths (slow or cold neutrons) by total reflection up to an angle of 0.1° per Ångstrom of neutron wavelength. For radiography, this inherent divergence of the neutron beam makes it difficult to obtain sharp images, for which a parallel beam is needed. The sharpness of an image is directly dependent on the L/D ratio. D is the diaphragm diameter and L is the flight path length, i.e., the distance from the diaphragm to the detector. An increase of the L/D ratio, in order to obtain a sharper image by closing the diaphragm (decreasing D) or by increasing the distance to the detector L, has the consequence of a decrease in neutron flux and therefore a longer exposure time. Whereas the increased divergence provided by the guide thus at first sight seems less attractive for imaging, there is a second effect of the guide which could enhance the efficiency of the instrument. If a neutron guide is extended to the cold source, this corresponds to extending the source dimensions and thus in a ‘pin-hole’-like geometry would result in a larger image size—or beam area at the sample.

3.2. Layout

In order to allow for an optimum choice between exposure time and image quality, the design of the new CNR facility must be versatile. In the layout (see Fig. 3), two positions for experiments are foreseen. At position 2, larger objects with high collimation can be imaged. If a higher neutron flux or shorter measuring time is required, the position 1 for smaller objects may be chosen.

The effect of a neutron guide in the inner part of the beam plug has been investigated by Monte Carlo simulation. For the simulation of the relevant neutron data (wavelength distribution,

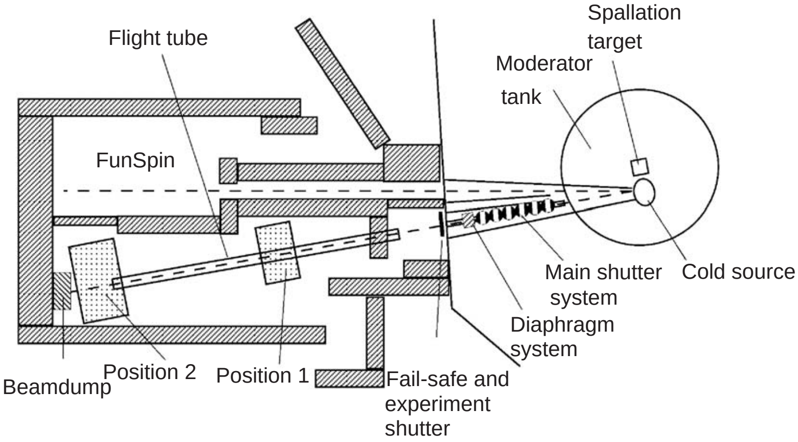

Fig. 3. Layout of the new cold neutron imaging facility CNR at the beam port = 1RNR52 in the sector 50 of SINQ. At the neighbouring beam port = 1RNR51 there is the existing FunSpin facility.

neutron flux, two dimensional spatial distribution of the neutrons at different positions of the beam path), the software package McStas version 1.7 [5] was used. Without the collimating pinhole (D), the expected gain in intensity at the sample position was found. The gain was about a factor of 3 and associated with a corresponding increase in divergence (Fig. 4).

The extended beam spot with the use of a guide is not homogeneous (Fig. 5 left) and it is furthermore wavelength dependent. The good homogeneity of the two-dimensional neutron distribution for the layout without neutron guide is shown in Fig. 5 (right). It has therefore been decided not to use guides in the design.

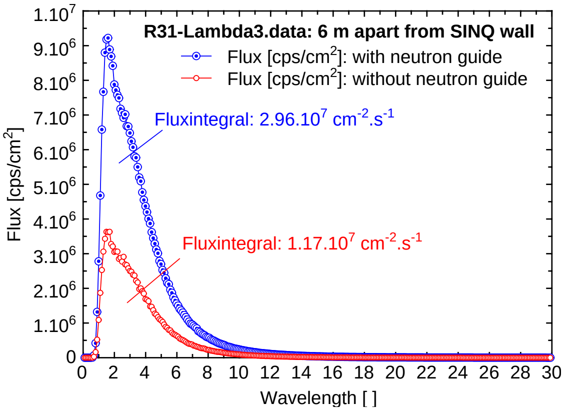

Fig. 4. Calculated wavelength distribution at position 1 (6 m from beam port exit) for the layout with (top curve) and without (bottom curve) neutron guide in the inner part of the beam plug.

3.3. The inner collimator

The target block inserts placed in the beam channel contain the inner collimator (Fig. 6). In a helium gas filled insert (length 1.2 m), the cold neutrons are extracted from the cold source to the front end of the collimator which has a square opening of 8 cm × 8 cm.[1] This collimator opening is surrounded by iron shielding throughout the whole length of the inner collimator (total length 4.9 m).

The central part of the collimator is equipped with *six revolving drums*, which are used as a shutter to switch off the beam. The first and the last half drum are filled with boron carbide to increase the shielding performance of the shutter against low-energy neutrons (thermal and cold neutrons). The other four drums are made of steel

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[1] The calculated two-dimensional neutron distribution showed in Fig. 5 has an opening of 8 cm × 15 cm (from a former layout).

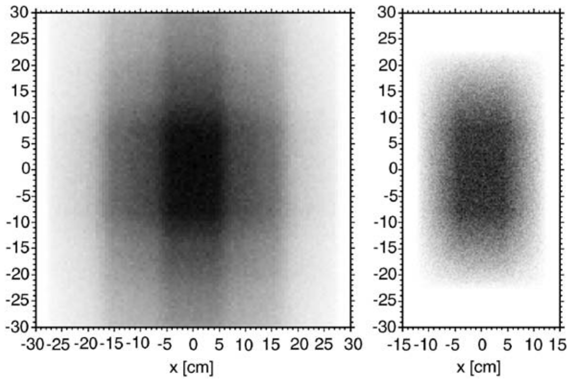

Fig. 5. Calculated neutron distribution at position 1 (6 m apart from the beam exit) for a collimator opening of 8 cm × 15 cm. Left with and right without neutron guides inside the SINQ target.

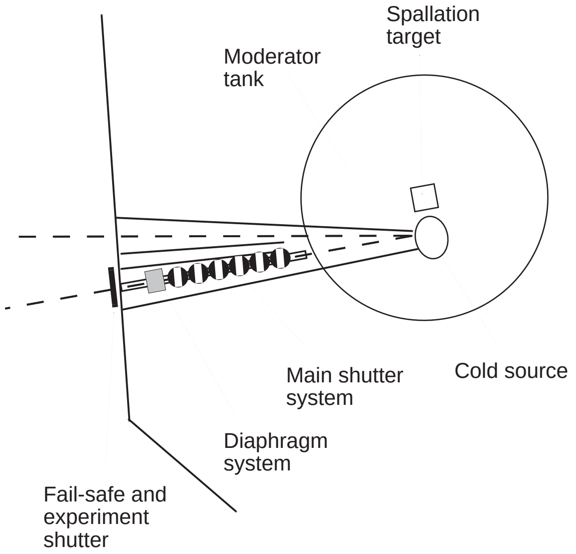

Fig. 6. Inner collimator with moderator tank, cold source and spallation target.

in order to shield high-energy neutrons and gamma-rays.

In the last part of the inner collimator (just after the revolving drums), a rotating *diaphragm system* (Fig. 7) is situated. Four of the six different apertures (8, 4, 2, and 1 cm) can be chosen depending on the required L/D ratio or the two small apertures (0.1 and 0.05 cm) for phase contrast imaging.

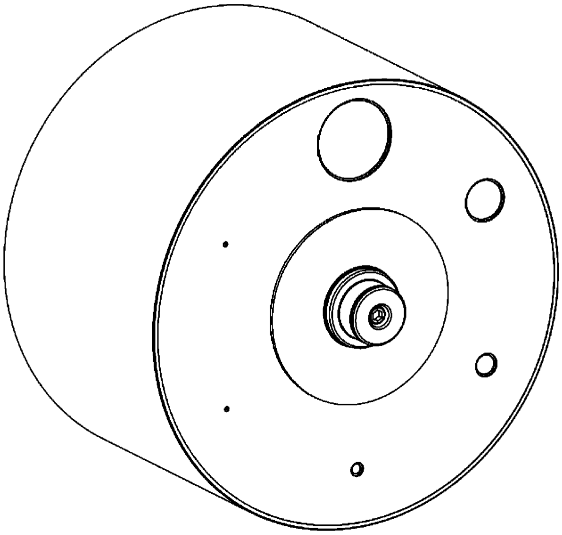

Fig. 7. Rotating diaphragm system with six different apertures (8, 4, 2, 1, 0.1 and 0.05 cm).

All free space around the components inside the target is filled with a *helium atmosphere* to avoid the activation of air. At the exit of the target block, there is a helium-tight Al window, which can be penetrated easily by the collimated neutron beam.

3.4. The experimental area

The experimental area (Fig. 8) is a well-shielded concrete construction (bunker), which contains the whole experiment setup. It is controlled by an admission safety system, the Local Access Control (LAC) system.

The first 2 m in the bunker will be separated from the rest by concrete shielding blocks and a closed door, also controlled by the safety interlock system LAC. In this part, activated components like the fail-safe shutter, the experiment shutter and (in the future) the velocity selector are placed.

A horizontally movable *fail-safe shutter* is placed directly at the beam port exit. It is a sandwich construction consisting of 10 cm thick borated polyethylene, 0.5 mm Gadolinium and 1 cm lead. The closing time is estimated to be about 2 s. A pressure accumulator, whose nominal value is controlled, guarantees the fail-safe condi-

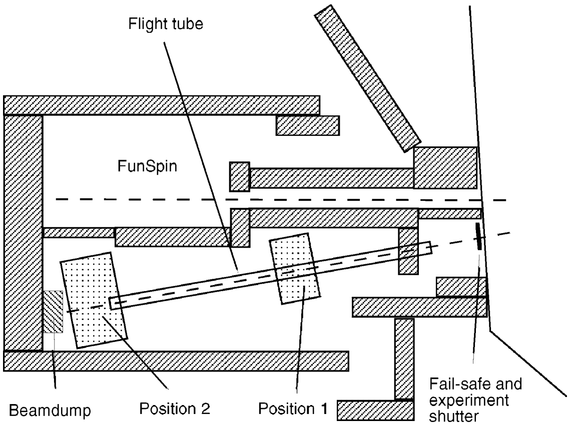

Fig. 8. Experimental area with the two experiment position.

tion. Behind the fail-safe shutter, a fast (closing time about 200 ms) *experiment shutter* is placed.

Two *beam limiters* (motorized diaphragms) are foreseen: one in a fixed position at 1.8 m from the beam port exit and the other in front of the respectively probe position.

A versatile *support system*, on which all components like the flight tubes and the imaging system can be mounted, is under construction.

At experimental *position 1*, a scanning table with a micro-tomography setup will be mounted. Position 1 can be chosen according to the experimental conditions between 2.5 and 6.5 m from the beam port exit and is meant for smaller objects. The calculated homogeneous flat region of the neutron beam at 6 m distance ranges from 5 cm × 5 cm to 14 cm × 14 cm depending on the chosen aperture of the diaphragm system. The corresponding L/D ratio ranges from about 90 to 700.

At *position 2*, a scanning manipulator for large objects is planned. Position 2 is at a fixed distance of about 10 m from the beam port exit. It is suitable for large objects of up to 1.5 m in linear dimension. The calculated homogeneous flat region of the neutron beam at 10 m distance ranges from 8 cm × 8 cm to 22 cm × 22 cm depending on the chosen aperture of the diaphragm system. The corresponding L/D ratio ranges from about 130 to 1100.

Behind position 2, a neutron and gamma absorbing *beam dump* is placed.

Neutron radiography images will be recorded by a high performance 2048 × 2048 pixel CCD camera system Andor DV 436 from Andor Technology (http://www.andor-tech.com/), looking on to a ^{6}Li based neutron scintillator screen. The camera and a custom-made lens optic system will be mounted on a common bench. For dynamic neutron radiography, imaging with either an intensified CCD camera system or an amorphous silicon-based flat panel will be used. Static radiography with the inherently highest possible resolution will be performed with the imaging plate technique (BAS-2500). Some promising other imaging techniques based on CMOS technology are under consideration too.

In this way, a high flexibility and optimal performance is guaranteed for cold neutron imaging in as many applications as possible.

4. Conclusion

A Cold Neutron Radiography facility will be established at the spallation source SINQ at PSI during the next few months. It will be an efficient and versatile tool for industrial non-destructive testing as well as for basic scientific investigations. The new CNR facility will together with its heavily demanded and successful “thermal sister facility” NEUTRA provide PSI with a complementary set of state of the art neutron imaging stations.

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