The Swiss Spallation Neutron Source SINQ at Paul Scherrer Institut

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Introduction

The 'Paul Scherrer Institut' (PSI, http://www.psi.ch) operates three major user laboratories for condensed-matter research on one campus: a third generation X-ray synchrotron source (SLS), the world's most powerful continuous-beam µSR facility (SµS) and the only continuous spallation neutron-source worldwide (SINQ).

The Swiss Spallation Neutron Source SINQ (http://sinq.web.psi.ch) is a **modern and state-of-the-art user facility for neutron scattering and imaging experiments**. It is in full user operation since 1998 [1]. The thermal neutron flux close to the SINQ target is about $1.5 \cdot 10^{14}$ n/cm²/s, but SINQ was optimized for the delivery of **cold neutrons**: supermirror-coated neutron guides plus a cold D_2-source located in the flux maximum result in a cold-neutron flux exceeding that of other sources with comparable thermal flux. SINQ operates approximately 9 months per year. Proposals can be submitted twice a year (May 15 and November 15, http://user.web.psi.ch). Fast access is possible through dedicated director's beam time.

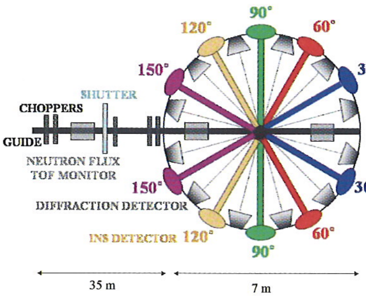

Figure 1. On the backscattering time-of-flight instrument **MARS**, the secondary instrument merges alternating diffraction and inelastic units.

SINQ instrumentation

SINQ offers **a full suite of modern instrumentation** for neutron scattering and imaging experiments. Detailed descriptions of the SINQ instruments can be found on the SINQ web pages: http://sinq.web.psi.ch/sinq/instruments.html. Below you only find a summary of **the unique, new and outstanding features**:

(a) **Diffractometers**: **DMC** is one of the very few powder diffractometers worldwide using cold neutrons, and hence being very well suited for solving magnetic structures. The second powder diffractometer **HRPT** uses thermal neutrons and is a high-resolution instrument competitive to world-class instruments at the ILL. **TriCS** is the only thermal neutron single-crystal diffractometer that can switch between a tiltable 2-dimensional and a tiltable single detector as well as between long and short wavelength mode. The thermal strain scanner **POLDI** (see other article in this issue) is designed as multiple pulse overlap time-of-flight diffractometer dedicated to internal strain and stress measurements.

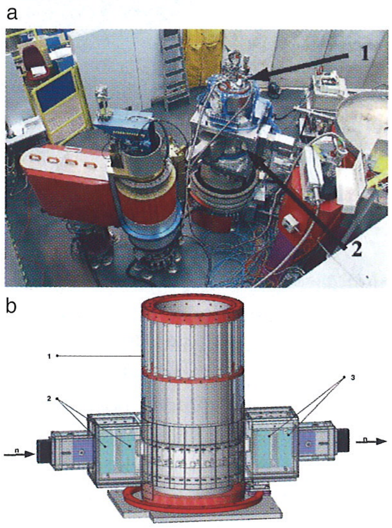

Figure 2. The spherical neutron polarimetry option MuPAD (arrow 2 in (a)) installed on the triple-axis spectrometer TASP at the Paul Scherrer Institut. A standard ILL orange cryostat (arrow 1 in (a)) can be installed inside the magnetic shielding; (a) complete setup mounted on TASP; (b) empty shielding of MUPAD: (1) μ-metal shielding, (2,3) turning coils.

(b) **Spectrometers**: **FOCUS** is a hybrid time-of-flight spectrometer covering a continuous energy range from 0.3 to 25 meV. Its open geometry allows for high flexibility in instrumental settings and sample environments ($T \geq 50$mK, $H \leq 9.5$T, $P \leq 1.2$GPa). In the framework of the cooperation with Risø National Laboratory the cold triple-axis spectrometer **RITA-II** was installed. With a

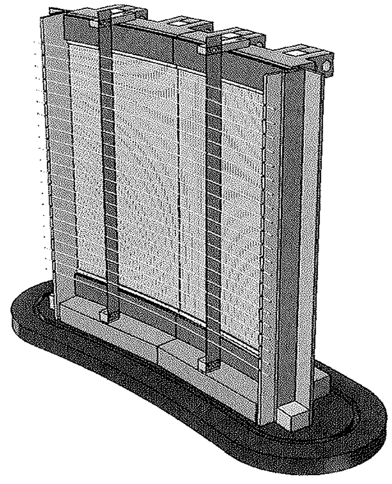

Figure 3. Design of one detector module for the new DMC-II detector. The module will cover a gapless area of 3260 mm (144°) by 300 mm.

multidetector it makes use of several analyser reflections simultaneously providing a significant efficiency gain. **TASP** is a highly versatile triple-axis spectrometer (at the end position of a cold guide) equipped for polarization analysis. The new backscattering spectrometer **MARS** is the only spectrometer presently available to deliver energy resolution around ~7 μeV at inelastic energy transfers of several meV. The thermal triple-axis spectrometer **EIGER** is under construction and will extend the accessible energy range to about 100 meV.

(c) **SANS/Reflectometry**: The **SANS-I** facility (collimation length: up to 20 m, detection length: up to 20 m) is mechanically a twin instrument of D22 at ILL. Beside its unique non-magnetic sample surrounding that allows for magnetic fields of 11T the instrument offers the option to polarize the incident beam and to perform time-resolved experiments. The new detector electronics of the **SANS-II** facility provides seven times more in the acceptable total count rate. Recently, a Halbach magnet (1T, permanent), *in situ* Dynamic Light Scattering and a solvent evaporation cell have been successfully introduced as sample environment for users. The reflectometer **AMOR** can be operated either in a time-of-flight or in an angle-dispersive mode. Special features are polarization analysis, the vertical scattering plane and focusing for small samples.

(d) **Imaging facilities**: The **NEUTRA** facility is a thermal neutron radiography and tomography beamline with imaging plates, slow scan CCD's, or a flat panel detector. A 230 kV X-ray tube is available for dual modality (neutron and X-ray) investigations. The new (2006) cold imaging beamline **ICON** (see other article in this issue) can be optimized in a wide range of beam collimation and intensity. Narrow energy can be obtained by a turbine type selector or with a Be filter. This highly flexible facility is equipped with a micro-tomography setup and a macro position with a sample table for up to 500 kg load.

New instrumentation development and sample environment options

The backscattering time-of-flight instrument **MARS** [2] is at the end of the commissioning phase. It is optimized for high resolution inelastic neutron scattering experiments. 5 Choppers select the narrow energy range of the incoming neutrons, which scatters at the sample. The secondary instrument merges alternating diffraction and inelastic units (Fig. 1). In the latter case the final energy is determined by the chosen reflection of the mica analyzers. The spectrometer boasts high resolution over a large neutron energy transfer range, reaching 1 μeV at the elastic line. The foremost distinguishing feature of the spectrometer is the moveable analyzer banks. These can be positioned at various angles perpendicular to the scattering plane, allowing resolution matching between the primary and secondary instrument. Further upgrades to increase the flux such as extended detector areas have just been started.

Another method implemented at SINQ, and highly used, is **spherical neutron polarimetry** (SNP), as complex magnetic structures are of great importance in a large number of condensed matter systems, e.g., frustrated and itinerant magnetic systems, multiferroics or superconductors. Due to the loss of directional and phase-information that is common to all scattering techniques the unambiguous determination of magnetic structures is in many cases not possible. However, the magnetic moment carried by the spin of a neutron can be used to at least partially recover the directional information about the magnetic structure that would be lost by only measuring intensities. In such an experiment the neutron beam is polarized, e.g., all the spins of the neutrons are aligned mutually parallel, and the change of the polarization direction upon the scattering process is measured. This method is generally called spherical neutron polarimetry (SNP) [3] and has been used successfully to identify magnetic structures that were intractable before, e.g., in multiferroics such as $LiCoPO_4$ and $MnGeO_3$ [4].

Since 2005, a **MuPAD** SNP device [5] – developed in collaboration with TU Munich - can be installed as an

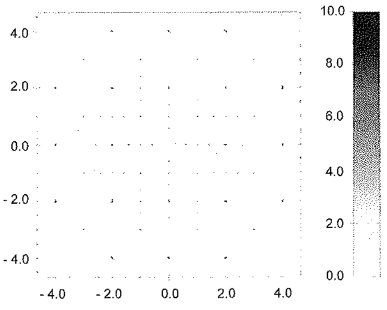

Figure 4. Transformation into q-space of the magnetic intensities of one layer from a single crystal. The measurement has been performed using the present linear detector of DMC.

option on the cold triple-axis spectrometer TASP (Fig. 2). It can be used in combination with a standard ILL orange cryostat down to temperatures of 1.5 K.

But also detector technique has highly improved since the mid-eighties and competition from modern diffractometers at other neutron centers is constantly growing. Therefore, we plan a major upgrade of the diffractometer DMC. Central work will be the replacement of the secondary instrument including the present linear detector. The design of the new cold-neutron diffractometer was motivated by attaining more intensity, resolution and versatility, as well as using special sample environments for high pressures and magnetic fields up to 15 Tesla.

The crucial point of the **DMC upgrade** is the large state-of-the-art detector. This means high efficiency through high gas pressure, large and gapless covered angle range in the scattering plane as well as perpendicular to it a pseudo-2D detection of scattered neutrons to resolve the curvature of the Debye-Scherrer cones. Compared to the present DMC this leads to ten times more total intensity, depending on wavelength and instrument configuration, but will also be a step forward in quality due to the 2-dimensional data recording. The new detector will be designed and built by the detector group at PSI. One module of the detector is shown in Fig. 3. The upgrade will also allow single-crystal measurements collecting more than one layer simultaneously, a technique already used at the present DMC (Fig. 4) for a single layer.

The thermal neutron triple-axis spectrometer EIGER is under construction and operation should start in 2010. EIGER aims to extend the energy range for the neutron spectroscopy accessible currently at SINQ: the incoming neutron energy at EIGER is variable from 5 meV to approximately 80 meV. A compact efficient monochromator shielding (Fig. 5) is calculated using MCNPX software. It will ensure proper biological shielding and should provide an excellent signal-to-background ratio. The monochromator shielding is designed from non- or weekly ferromagnetic materials so that our 15 Tesla cryomagnet may be used for the experiments. To suppress higher-order neutrons and to improve the background at the instrument a sapphire filter is installed before the horizontally converging neutron guide. At the end of the neutron guide there is a variable horizontal slit system, adjustable between 0–3 cm, which acts as a virtual neutron source. A large (20 cm height by 30 cm width) doubly-curved pyrolytic graphite monochromator is built to enhance the neutron flux at the sample. In the foreseeable future we expect to install a polarized neutron option using a Heusler monochromator. A neutron velocity selector is foreseen to be installed after the neutron guide. This option should add flexibility for EIGER allowing for a broader choice of the working final energy. In addition, the velocity selector is very helpful for the experiments where the secondary spectrometer consists of multi-analyzer/multi-detector. Initially, the secondary spectrometer of EIGER is a single analyzer with variable horizontal curvature and a single He tube detector. Further, it is planned to install a multi-detector option (MADbox [6]) in collaboration with TU Munich.

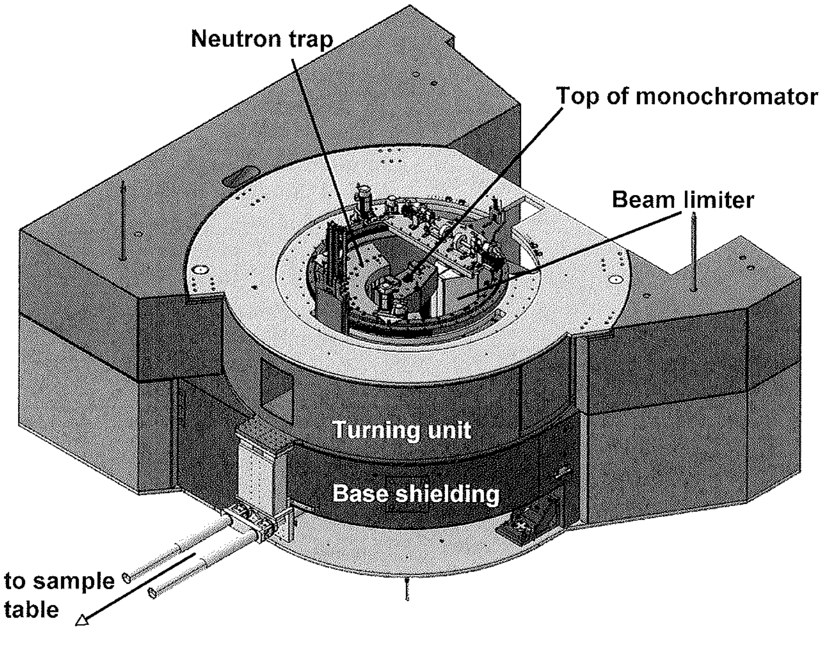

Figure 5. Base shielding and the turning unit of the thermal triple-axis instrument EIGER to be operational in 2010. The beam limiter and the neutron trap should decrease the background at the instrument.

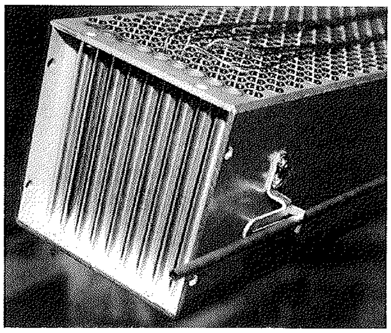

Figure 6. Rod array of SINQ solid 'lead-cannelloni' target.

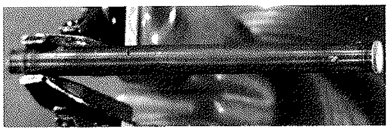

Figure 7. A visual inspection of one Zr-clad rod after 2 years of irradiation in SINQ showed no indication of damage or degradation.

SINQ target development

Besides general facility upgrades, the **target development** towards an optimized neutron flux for the benefit of the SINQ users was always an issue of high priority. From the beginning, SINQ operated for many years successfully with a **solid 'lead-cannelloni' target**, i.e., a target holding an array of lead rods clad in steel tubes (Fig. 6).

In 2006, the operation of a **liquid metal target** was tested in the frame of the **MEGAPIE** project, which opened a widely unexplored field of experiences, new technologies and challenges. The MEGAPIE target contained about 1 ton of liquid lead bismuth eutectic (LBE, melting point at 125°C) in a steel container, closed-end by a hemispherical beam window at the bottom. The main features inside were two electromagnetic pumps for forced circulation of the LBE, a concentric flow guide tube inserted into the lower liquid metal container, and twelve heat exchanger pins for removing the energy deposited by the beam and/or keeping the target at temperature when the beam is off.

During MEGAPIE operation the neutron flux, compared to the previously operated 'lead cannelloni' target, increased by as much as 80 to 90%. Motivated by this favorably high neutron yield a liquid metal target for permanent operation at SINQ has become a priority item and a corresponding development project has been launched. Before that becomes a real option, PSI seeks for improvements of the solid lead/steel 'cannelloni' target. One viable option is the replacement of the steel cladding by Zircaloy (Zr) tubes. Test rods of that type operated in 'SINQ Target 5' for two years confirmed the robustness of the Zr-cladding in our irradiation environment (see Fig. 7). This gave confidence to completely replace the steel cladding by Zr-tubes in 'Target 6' (after MEGAPIE), which rewarded a neutron flux increase between 10 and 13 %, very close to predictions.

Further options for an **improvement of the solid SINQ target** are now realized in 'Target 7', which started operation in April 2009: These improvements comprise a closer packing of the rods, a circular cannelloni support structure replacing the square-shaped frame, lead reflectors in the cooling water downcomer around the cannelloni structure, and inversion of the calotte of the safety hull to minimize the deceleration of the protons before entering the spallation zone. First measurements found an increase in neutron flux of 40% compared to the previous 'Target 6'.

All in all, since the start of SINQ the target efficiency has been improved by a factor of 2.2, and the proton current by 1.75, which is a factor 3.9 in total flux increase for the neutron users over 10 years.

The novel ultracold neutron source at PSI

In addition to SINQ, a powerful **source for ultra-cold neutrons** (UCN) is under construction at PSI. A large 2 m^3 storage volume can be filled with around $2 \cdot 10^3$ UCN per cm^3 about 100 times more than currently obtained at the most prominent UCN sources, e.g., at ILL. Neutrons are produced in a short (several seconds) pulse of the full 2 mA, 590 MeV proton beam on a separate spallation target. After being moderated, cooled, and finally down-scattered in solid ortho-deuterium, the UCN are extracted from the solid deuterium and guided into a DLC (diamond-like-carbon) coated large storage volume from which they can be extracted into experiments. After the proton beam pulse, the production and storage volumes are separated by a shutter, allowing for UCN storage times on the order of the lifetime of the free neutron. The UCN source is a user facility. The first experiment will be the search for an electric dipole moment (EDM) of the neutron. A sensitivity of better than 10^{-27}e·cm is envisaged for this EDM search, providing one of the most sensitive tests of the standard model of particle physics.

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