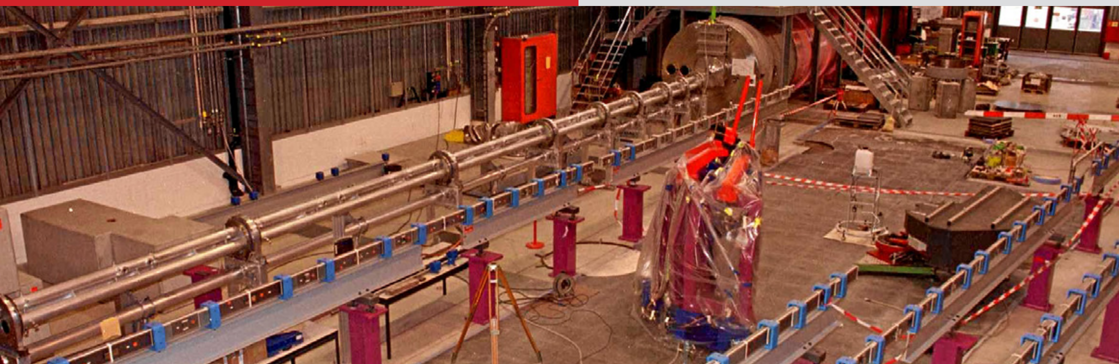
Number 49 | April 2017

SWISS NEUTRON NEWS



Schweizerische Gesellschaft für Neutronenstreuung
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The Swiss Spallation Neutron Source SINQ: From Idea to Realization

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Introductory Remarks

Switzerland has a long tradition in neutron scattering. Soon after the commissioning of the light-water reactor Saphir (1 MW thermal power) in the year 1957, Walter Hälg (professor at ETH Zurich) recognized the potential of neutron scattering for materials research. He started to build instruments at Saphir for neutron diffraction experiments. The situation was improved in the year 1960 with the commissioning of the heavy-water reactor Diorit (30 MW thermal power), which allowed to perform neutron spectroscopic experiments as well. 1977 marked the year of the final shutdown of Diorit. In the meantime, the reactor Saphir raised the thermal power up to 10 MW and the experimental hall was considerably enlarged, so that the neutron scattering activities could be successfully continued. At the end of the year 1993, however, the reactor Saphir had to be shut down, mainly for safety reasons. Was this the end of neutron scattering in Switzerland? The answer is no! The excellent conditions at both Diorit and Saphir created a strong national user community, which was able to exert a sufficiently strong pressure to maintain a permanent home base for neutron scattering experiments, and which was essential to get the green light for the construction of the spallation neutron source SINQ.

This report provides a chronological summary of the major steps in the development of SINQ. A short historical review is given in Ref. [1]. The initial sections describe how the project emerged from early ideas and technical concepts, which were repeatedly modified and finally led to the present SINQ. After the production of the first neutrons in the year 1996, the performance of SINQ has been permanently improved by upgrades and extensions as summarized in the final sections.

The Booster Concept (1972-1977)

Ideas about a Swiss spallation neutron source emerged soon after the successful commissioning of the 590 MeV proton cyclotron at the Swiss Institute for Nuclear Research (SIN) at Villigen in the early seventies. The spallation process typically provides a thermal neutron flux of the order of 10^{14} n · cm^{-2} · s^{-1} · mA^{-1}. Initially the proton current of the cyclotron was restricted to 100 μA, resulting in a neutron flux below an acceptable level. Therefore Walter Hälg, Beat Sigg and coworkers considered the so-called booster option based on a spallation target containing fissile materials, which produces an enhanced neutron flux by at least an order of magnitude. The booster option can be considered as an undercritical reactor assembly which, however, poses major safety precautions accompanied by considerable financial consequences, so that the booster study was not continued further, also in view of the continuous increase of the cyclotron's proton current to 200 μA in the year 1978 and finally to 2 mA in the year 2000, which made the concept of a truly spallation-based neutron source highly attractive.

The First SINQ Concept (1978-1982)

Spallation sources ideally operate with pulsed neutron beams triggered by pulsed proton beams, but the cyclotron at SIN provides a continuous proton beam due to the absence of a macro-timestructure. Therefore, the realization of a pulsed spallation source at SIN would have required to build an additional storage ring, but this option was soon given up mainly for financial reasons. Walter Fischer (see Fig. 1) and coworkers studied a new concept based on a continuous neutron beam. This concept was presented at a discussion meeting at Villigen on April 14, 1978, with more than 100 international participants. It was concluded that the realization of a continuous neutron source would be a most valuable extension of SIN's activities towards condensed-matter research, an opinion which was strongly supported by Sir William Mitchell and George Stirling (both were key persons to build the spallation neutron source ISIS in the United Kingdom). Moreover, such a neutron source would constitute an ideal parasitic use of the intense waste beam of the proton cyclotron which so far was directed - after having passed through some meson targets - to a beam dump without any further use. At the end of the meeting, Jean-Pierre Blaser (director of SIN) decided to initiate a detailed study of a continuous neutron source within a project group „SINQ" headed by Walter Fischer. SINQ is an acronym meaning „SIN-Quelle" in German („Quelle"=source) and „SIN-Queue" in French („Queue"=tail; the spallation target is positioned like a tail at the end of the proton beam).

Immediately after this meeting, an intense phase of international collaboration began.

Figure 1
The key persons of the SINQ project: Walter Fischer (left), Günter Bauer (middle), and Erich Steiner (right)

Together with experts from Jülich, Karlsruhe and Munich the installation of a mock-up target was planned in order to demonstrate experimentally the expected performance of SINQ. In addition, calorimetric measurements were performed at the accelerator in Vancouver to test the properties of both some target materials and the cold source under intense proton irradiation. All these efforts were essential for a high-risk project like SINQ to obtain a vigorous basis for the technical realization, to prove the physical parameters resulting from simulations, and to arrive at a reliable estimate of the project costs.

A budget of 32.58 MCHF was estimated for the SINQ project, and the ETH Board was approached for financial assistance. However, the ETH Board decided to first obtain expert opinions concerning the science policy associated with SINQ. The Swiss National Science Foundation (SNF) – based on a report of an international expert group – came to a positive recommendation in the year 1979. In particular, it was emphasized that the future scientific needs expressed by the Swiss user community would excellently be accommodated by a neutron source like SINQ. Based on the SNF report, the Swiss Science Council came to a similar conclusion in the year 1982 and recommended the realization of SINQ with high priority. Due to several circumstances, the Swiss Government included the SINQ budget in its financial planning only in the year 1986, which was approved by the National Parliament in spring 1987.

The Final SINQ Concept (1983)

In the course of the pre-studies some difficulties with the original SINQ concept became apparent. (i) Squeezing the SINQ into the already crowded experimental hall caused severe room problems for the maintenance of the target station as well as for optimally placing the instruments. (ii) The installation of instruments around the SINQ target was restricted to the lateral sites only, since the section of the incoming proton beam as well as the backside section were not accessible for instruments. (iii) There was simply no room to accommodate a modern neutron guide system. All these problems were solved by a new concept approved by the SIN management. First, placing SINQ into the experimental hall was given up, i.e., new buildings for both the SINQ target and the neutron guide system were foreseen. Second, and most importantly, the concept of a horizontal target was abandoned. Instead, the neutron source was to consist of a vertical target into which the proton beam is shot from below, allowing a coverage by instruments in a full angular range of 360°.

The new SINQ concept was presented at the second international discussion meeting on March 14, 1983, which took place at the ETH Zurich and gathered more than 200 participants from universities, industrial companies, and science organizations. There was an almost unanimous agreement that the realization of SINQ should be pushed with high priority, also in view of the so-called „neutron gap" threatening the worldwide neutron scattering activities towards the end of the century according to an OECD study report [2]. The meeting was continued on March 15, 1983, at SIN Villigen, where prospective SINQ users presented their scientific cases, giving essential information on the type of instruments needed for the corresponding neutron scattering experiments.

The Scientific Prospects of SINQ

Due to the provision of continuous neutron beams, the utilization of SINQ is very similar to that of a nuclear reactor. The thermal neutrons have a flux comparable to a medium-flux reactor. However, the big advantage of SINQ over a reactor is that, because it produces less gamma radiation per neutron, a cold neutron moderator is heated less. The cold source can therefore be installed at the position of the highest neutron flux. Cold neutrons can be transported by a neutron guide system – for the first time tailored to the needs of every instrument - over large distances essentially without loss, and a considerable reduction of unwanted background in the measurements is achieved. The combination of both the cold source and the neutron guides make SINQ competitive on an international level. This aspect was an essential criterion for the realization of SINQ, since cold neutrons became increasingly important to meet the scientific requirements of the national user community.

The Pre-Construction Time (1984-1987)

The new SINQ concept posed a myriad of additional technical questions which had to be worked out in detail. One of the most important activities was the verification of the neutron flux expected for SINQ with use of a mock-up target which was installed in baracks outside the experimental hall close to today's medicine pavilion. A schematic layout of the mock-up target is shown in Fig 2. The experiments were carried out in the year 1984 with a reduced proton current in order to keep the size of the biological shielding small. The neutron fluxes measured for several moderator geometries and even for a cold H_2 moderator confirmed the flux numbers resulting from simulations. In the late eighties,

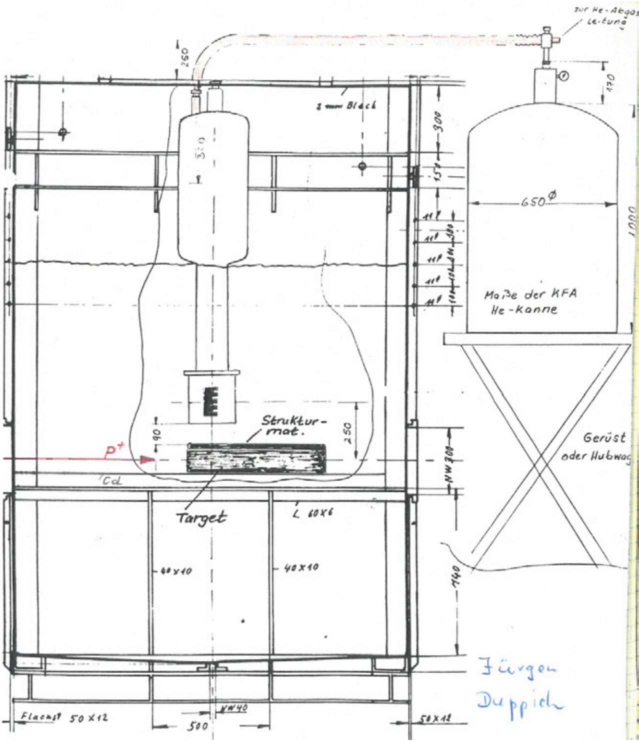

Figure 2
Schematic layout of the mock-up experiment (taken from Jürgen Duppich's laboratory notes).

Günter Bauer (see Fig. 1), the former technical director of the German SNQ project, joined the SINQ project group which profitted from his great experience with spallation sources. The number of people involved in the SINQ project continuously increased, so that the SINQ project group was later upgraded to a SINQ division headed by Günter Bauer. Also the prospective SINQ users met annually to update the requirements for the neutron scattering instruments. These meetings finally led to the creation of the Swiss Society for Neutron Scattering in the year 1992. Of course, all these detailed studies of the new SINQ concept had an impact on the total budget which was raised to 51.34 MCHF because of inflation, increased safety measures, and technological progress. In the year 1990, the additional funding of 18.76 MCHF was approved by the National Parliament.

Finally, the major parameters were frozen to enable the construction of SINQ. As schematically shown in Fig. 3, the target block and the plant service building are located in the target hall which has a floor area of 35×50 m^2. The accessible space around the target block is reserved for instruments using thermal neutrons. A set of seven neutron guides, running through a heavily shielded cavern in the ground floor of the service building, transport cold neutrons into the neutron guide hall, which measures 25×50 m^2 and is exclusively

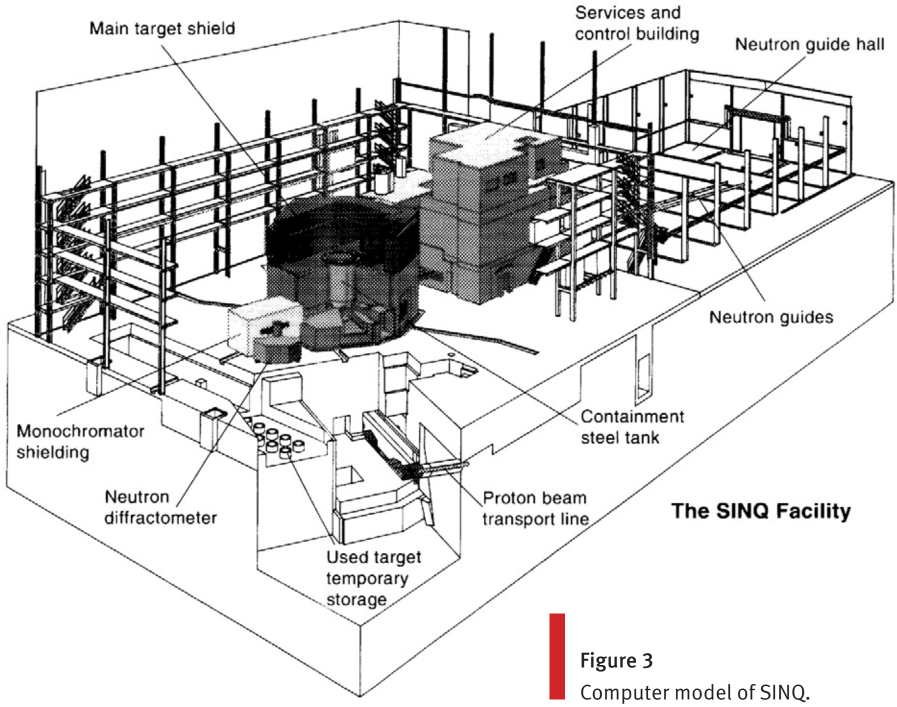

Figure 3
Computer model of SINQ.

reserved for neutron instruments and their ancillary equipment.

The Construction Phase (1988-1996)

On August 8, 1988, the construction of the buildings for SINQ started. In the very same year the Paul Scherrer Institute (PSI) was founded as a merger of the SIN at Villigen and the Federal Institute for Reactor Research (EIR) at Würenlingen. The SINQ was considered as a lighthouse project to bundle up some of the activities within the new organization. The PSI management appointed Erich Steiner (see Fig. 1) as project leader for the construction of SINQ. In the year 1990 the tunnel between the meson target E in the experimental hall and the SINQ was built in order to host the proton beamline over a distance of 54 m. Before entering into the spallation target, the proton beam is forced through a collimator system to prevent any focus on the target window. Successively, the construction of all the SINQ components was launched with the aim to complete the facility typically in the year 1993 (coincident with the final shut-down of the Saphir reactor). As an example, Fig. 4 shows the SINQ target block during construction.

The very ambitious time schedule, however, underwent some delays due to the technological complexity of the project. A particular challenge was the construction of the innermost target container which is a double-wall aluminum tank with 2 m diameter. It

Figure 4
The SINQ target block during construction.

contains the D_2O which is circulated for heat removal, and which is used to moderate the neutrons. It was quite hard to find an industrial company which dared to produce this item with the requested precision. Nevertheless, the D_2O tank was delivered and perfectly introduced into the target shielding, thereby relieving a major pressure from the project responsibles. Another challenge was the optimization of the target itself. Lead and bismuth are in this respect promising materials. Since they have relatively low melting points, it was even conceivable to use them in liquid form, which allows heat removal by circulation of the target material. However, the implementation of a liquid target requires considerable development. In order to avoid time pressure at the current project stage, it was decided to go for a solid target consisting of zircaloy rods, which – even though it is not optimal from the neutronic point of view - is not expected to present significant operational problems. Finally, the construction of the SINQ target station was successfully completed towards the end of the year 1996.

Education of the User Community

In order to make the international user community fit for future experiments at SINQ, annual summer schools were organized from 1993-2000 at the Lyceum Alpinum in Zuoz, nicely embedded in the beautiful Engadin Valley. Every school was attended by typically 100 participants (mainly Ph.D and postdoctoral students) who greatly profitted from the lectures and exercises presented by renowned scientists (e.g., by the Nobel Laureate Alex Müller in 1995). As a result, about two thirds of the participants became regular users of SINQ. A highlight of the first European Conference on Neutron Scattering held at Interlaken on October 8-11, 1996 (with a record attendence of more than 700 participants) was a one-day excursion to SINQ as part of the activities to attract prospective users, and several conference presentations were dedicated to SINQ [3].

The First Neutrons from SINQ (1996)

On December 3, 1996, the SINQ was taken into operation and produced its first neutrons. After a test of the beam elements, a proton current of 20 µA was successfully kept on the target for about 10 hours. On the next day, the proton current was stepwise raised up to 900 µA. Some of the results of these tests are shown in Fig. 5. Of particular importance is the fact that the measured flux spectrum is significantly higher than calculated, especially for wavelengths larger than 4 Å. This demonstrates that for cold neutrons SINQ is competitive with the world-leading neutron sources, keeping in mind that the neutron flux of SINQ will be considerably enhanced in future both by neutronically improved targets and by a substantial increase of the proton current.

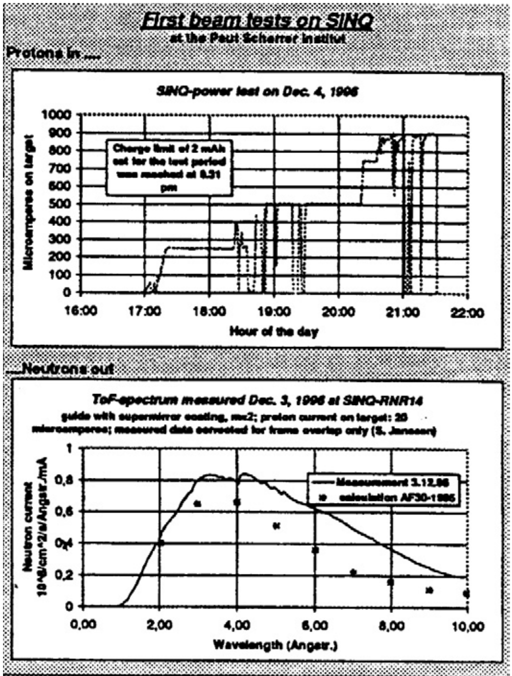

Figure 5
Results of the first beam tests at SINQ. The upper part shows the proton current on the SINQ target. The lower part displays the measured neutron spectrum taken at the guide RNR14 (solid line) in comparison with the estimated values (squares).

Inauguration of SINQ (1997)

The official inauguration of SINQ took place on January 17, 1997. During this event, Meinrad Eberle (director of PSI) expressed his satisfaction about the successful outcome of the SINQ project, which was achieved thanks to the exemplary efforts of PSI experts in a truly interdisciplinary collaboration. The Federal Councillor Ruth Dreifuss (see Fig. 6) and other speakers put emphasis on the significance of SINQ to strengthen both the Swiss and the European research areas in broad fields of science. Finally, Joël Mesot (see Fig. 6), representing the generation of young scientists, pointed out the role of SINQ as an important facility to contribute to a successful scientific career, a vision which became reality for himself, since he has been director of PSI since the year 2008.

Figure 6
The Federal Councillor Ruth Dreifuss (left) inaugurates the SINQ. Joël Mesot (right) presents the young scientists' case during the inauguration ceremony.

The Real Costs of SINQ

The budget of 51.34 MCHF allocated by the Swiss Parliament was by far too low to realize a technically challenging project like SINQ, so that additional funding was necessary, and several activities had to be economized in order to relieve the budget. A typical example for the latter aspect is the neutron guide system which was offered by an industrial company at a price of approximately 8 MCHF. The most expensive part of a neutron guide is the supermirror coating of the glass channels. It was therefore decided to perform the coating at PSI, which was a considerable technological challenge, since the proper techniques for supermirror coatings were not yet established at that time. Nevertheless, Peter Böni and coworkers developed this technique shortly after the purchase of a dedicated sputtering plant to perfection. From this highly successful endeaver the spin-off company SwissNeutronics arose in the year 1999.

The PSI invested more than 80 MCHF out of its yearly budgets mainly for internal manpower and for the experimental infrastructure including the first generation of neutron scattering instruments. In addition, the D_2O necessary for the moderator (14 MCHF) was readily available at PSI as a result of the decommissioning of the reactor Diorit. For the biological shielding of the target station dozens of tons of iron (10 MCHF) were taken from the Swiss war reserve stored at the PSI campus. In total, the real costs of SINQ amounted to typically 160 MCHF.

Commissioning of the First Generation of Instruments (1997)

In order to define the first generation of instruments, a user meeting took place on March 24-25, 1992, at PSI which was attended by more than 100 participants. In turn an international expert group chaired by Tasso Springer (director at FZ Jülich and former director of the ILL) recommended the presented instrument concept for realization, which included two powder diffractometers (DMC and HRPT), a single-crystal diffractometer (TriCS), a small-angle scattering instrument (SANS), a multi-purpose instrument (TOPSI, which includes a USANS option), a reflectometer (AMOR), two three-axes spectrometers (DrüchaL and TASP, the latter for polarized neutrons), and a high-resolution time-of-flight spectrometer (FOCUS). In addition to this programme, the SINQ division was preparing a neutron radiography station (NEUTRA) and a diffractometer for residual stress measurements (POLDI). Since no financial contributions were foreseen within the official SINQ budget, the necessary funding came to a large extent from the annual PSI budgets, but significant financial support was also obtained from external organizations (notably from the University of Saarbrücken for FOCUS through a grant provided by the German government). Furthermore, the ancillary equipment for sample preparation and sample environment as well as some instrument components were already available from the former activities at the reactor Saphir, which contributed to a major relief of the financial pressure.

In the second half of the year 1997, SINQ was operating typically for two days/week and allowed the successful commissioning of four instruments (DMC, DrüchaL, TASP, TOPSI) at the neutron guide system and one instrument (NEUTRA) at a thermal beam tube. The commissioning of the remaining instruments followed in the two following years.

Start of Routine Operation (1998-1999)

The SINQ started its regular operational schedule with a proton current of about 1 mA by mid-1998. The first call for proposals launched in April 1998 received an unexpectedly large response. 136 proposals involving more than 200 scientists were submitted by national and international user groups, and the available beam time was already overbooked by a factor of 2.5. The novel category of „long-term proposals“ was particularly advertized to allow the execution of coherent programmes in neutron scattering. This possibility was extremely well received by the users especially for the performance of long-term experiments in the framework of Ph.D studies. In the following years, the requests for beam time were gradually increasing due to the excellent conditions at SINQ, resulting in a doubling of external users already in the year 2000. The status of SINQ in the year 2000 was described in Ref. [4].

Upgrades and Extensions of SINQ (2000-2006)

In the year 2000, the original zircaloy target was replaced by a target consisting of lead rods in zircaloy tubes, which was called „cannelloni target“ (cannelloni is an Italien dish made from dough reels filled with minced meat). At the same time, the length of the meson target E was reduced from 6 cm to 4 cm, and the proton current was increased up to 2 mA. Some years later a new, geometrically improved cold D_2 source was installed, which doubled the flux at the cold neutron guides. All these measures resulted in an enhancement of the neutron flux by almost an order of magnitude, which was extremely beneficial for the users and allowed to perform novel classes of neutron scattering experiments at SINQ. In fact, an expert commission of the European Union funding the user programme 2001-2004 at SINQ made the following comments: „Recent scientific highlights resulting from experiments at SINQ are impressive in quality and range of topics covered.“ This was indeed a highly gratifying statement! Some highlights resulting from experiments at SINQ during the first five years of operation are summarized in Ref. [5].

In the year 2001, the Danish neutron scattering group moved its experimental facilities from Risö National Laboratory to SINQ. A second small-angle scattering instrument (SANS II) was installed, and DrüchaL's analyzer and detector parts were exchanged against the RITA system. Moreover, a major fraction of experimental devices (magnets, cryostats, dilution inserts, etc.) were moved to SINQ, which ideally complemented and improved the existing sample environment.

Soon after the commissioning of SINQ the limited space in the SINQ buildings caused severe problems for the technical operations as well as for the realization of the second generation of instruments. It was therefore decided to extend the neutron guide hall by an additional 22 m. In the year 2004, the extension of the guide hall was completed, which greatly improved the operations of the technical sections (sample environment, electronics, mechanics) and allowed the on-site sample conditioning as well as IT activities for the users. In addition, it hosted the new backscattering spectrometer (MARS) which became operational in the year 2007.

In the second half of the year 2006, test experiments were carried out with use of a liquid lead bismuth target in the framework of the European project MEGAPIE (**MEGA**watt **Pi**lot **E**xperiment) [6]. Such a target has been under active consideration for various concepts of accelerator driven systems (ADS) to be used in transmutation of nuclear waste and other applications worldwide. For SINQ it has the potential of increasing significantly the thermal neutron flux. The temporary insertion of a liquid metal target had major technical consequences, i.e., the containment as well as the cooling system existing for a solid target had to be considerably modified, and enhanced safety precautions had to be implemented. As expected, the measured increase of the thermal neutron flux turned out to be of a factor of 1.8. After these successful test experiments, the MEGAPIE target was removed in early 2007 and exchanged against the previously used cannelloni target mainly for safety reasons.

The Consolidation Phase (2007-2016)

The last ten years have seen a very stable operation of SINQ without any major technical incidents. Most importantly, the reliability and availability of SINQ, relating to the delivered proton beam from the accelerator, has been routinely above 98%. This excellent figure of merit has been highly appreciated by the international user community which continuously increased up to about 900 visitors per year to carry out neutron scattering measurements. On the experimental side, the existing instruments for neutron scattering have been permanently improved and partly renamed (DrüchaL→RITA-II, TriCS→ZEBRA, TOPSI→MORPHEUS), and new instruments were installed (EIGER, a three-axis spectrometer for thermal neutrons; NARZISS, a polarized neutron reflectometer; ORION, a two-axis diffractometer for cold neutrons). In addition,

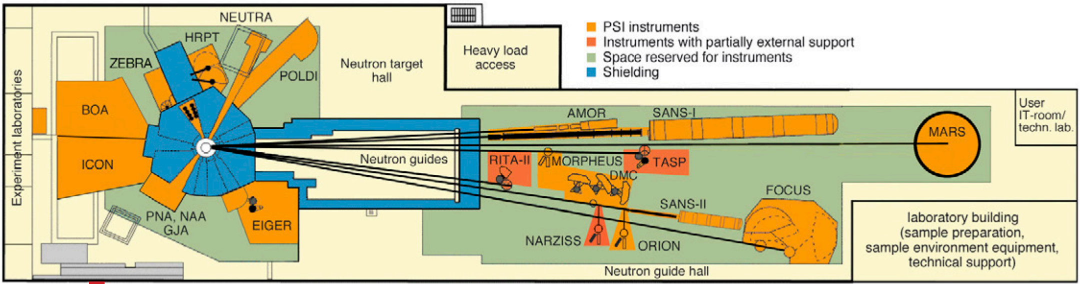

Figure 7
The present state of the SINQ instrumentation.

several beam lines were equipped with instruments for non-diffractive applications. An overview of the present state of the SINQ instrumentation is shown in Fig. 7.

The Upgrade of the SINQ Guide System (2017-2020)

The aim of the symposium *20 years SINQ* held on April 18, 2017, at PSI was not only to look back at past achievements, but also to launch a neutron guide and instrument upgrade project in order to strengthen the performance of SINQ for the next 20 years. The completion of the upgrade programme is expected for the year 2020, and the overall costs are estimated to be 16.7 MCHF. The essential part of the upgrade concerns the neutron guide system which will be replaced by guides with tailor-made supermirror coatings according to the specific instrument needs, resulting in flux gains up to an order of magnitude. The international user community can therefore look into an extremely bright future of SINQ!

[1] A. Pritzker, in *The Swiss Institute for Nuclear Research SIN* (BoD, Norderstedt, 2014), p. 115 (ISBN 978-3-7386-0820-5).

[2] T. Riste, in *Neutron Beams and Synchrotron Radiation Sources* (OECD, Paris, 1994), p. 63 (ISBN 92-64-14249-5).

[3] See, e.g., W. Fischer, *SINQ – The spallation neutron source, a new research facility at PSI*, Physica **234-236**, 1202 (1997).

[4] P. Allenspach, *The Continuous Spallation Neutron Source SINQ*, Neutron News **11**, No. 3 (2000), p. 15.

[5] P. Fischer and A. Furrer, in *Swiss Neutron News No. 47* (March 2016), p. 6 (http://sgn.web.psi.ch/sgn/snn/snn_47.pdf).

[6] C. Fazio et al., *The MEGAPIE-Test Project*, Nuclear Engineering and Design **238**, 1471 (2008).