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INSTRUCTIONS FOR TYPESETTING CAMERA-READY MANUSCRIPTS FOR PSI PROCEEDINGS

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ABSTRACT

Since the comissioning in 1997, PSI´s spallation neutron source SINQ has improved the neutron yield of the solid targets by a factor of 2,19 in 2009 by evolutionary development of the solid target concept.
This considers not the temporary maximum of 2,56 during the experiment with a liquid metal target in 2006. Motivated by its high neutron yield, exceeding the previous, solid lead-cannelloni standard target by about 80%, the standard target was further optimised by taking advantage of many experiences gained from the MEGAPIE experiment. These efforts resulted in the present standard target with very limited extra costs, but a gain factor of 2,19 in neutron yield compared to the day onetarget.
Combined with a 590 MeV proton beam increase from 0,85 mA to 1,5 mA on SINQ target and the high availability of around 99% the yearly integrated neutron production was improved by a factor 5,7 since the first year of full time operation in 1998.
The only eyesore in the success history of SINQ operation is a heat exchanger leakage in the moderator system, causing a 4% intermixture of H2O into the D2O moderator and a 3 month shut down for repair in 2007. Swapping the D2O inventories of different systems in a suitable manner prevented detoriation of neutron moderation after repair and restart of neutron production in 2008. Special measures were taken to prevent future H2O ingress into the D2O systems.

1. Introduction

The Swiss Spallation Neutron Source SINQ started operation in 1997, replacing PSI´s 10MW research reactor SAPHIR, which was shut down in 1994. SINQ is driven by the 590 MeV proton beam from the PSI ring cyclotron with a power in the MW range. In contrast to other spallation neutron sources the target of SINQ is hit by the proton beam from below. (Figure 1).

The nominal proton beam of 2,2 mA is passing two myon/pion production targets which consume 30% of the protons before the remaining 1,5 mA irradiate SINQ´s heavy metal spallation target. The spallation neutrons are released into the D_2O moderator and the D_2 cold moderator (Figure 2), making SINQ a steady state source for thermal and cold neutrons, with similar characteristics as a research reactor. Except for the yearly down time in winter, the operational beam time schedule is 24 hours per day during four weeks with 2 to 4 days of service, beam set up and accelerator physics per cycle.

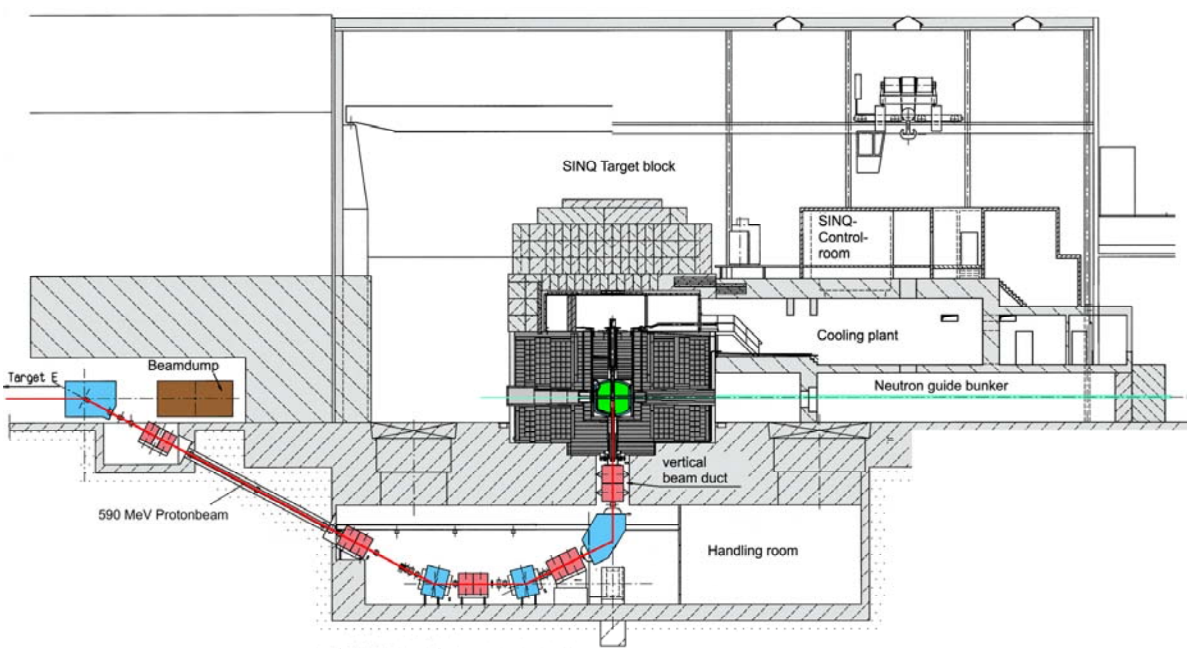


Figure 1: Vertical cut of the neutron spallation source SINQ

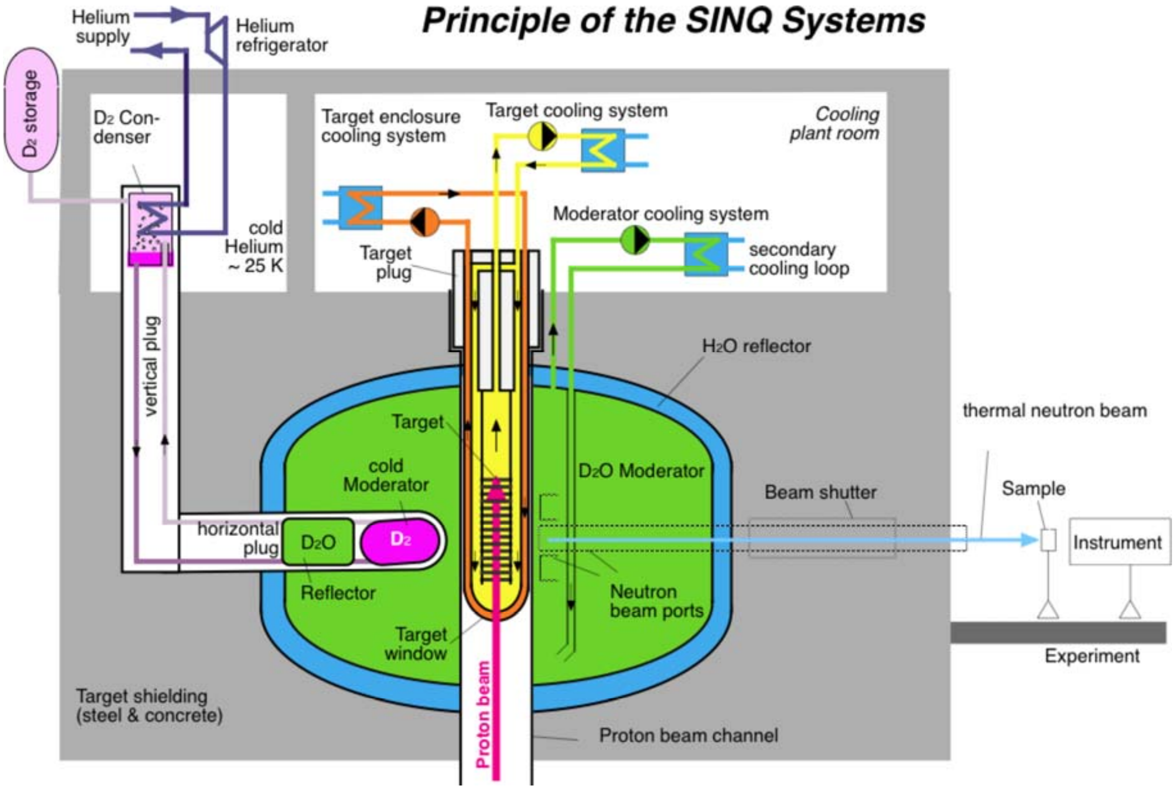


Figure 2: Schematic configuration of the target systems with thermal and cold moderator

2. Development of SINQ´s Spallation Targets

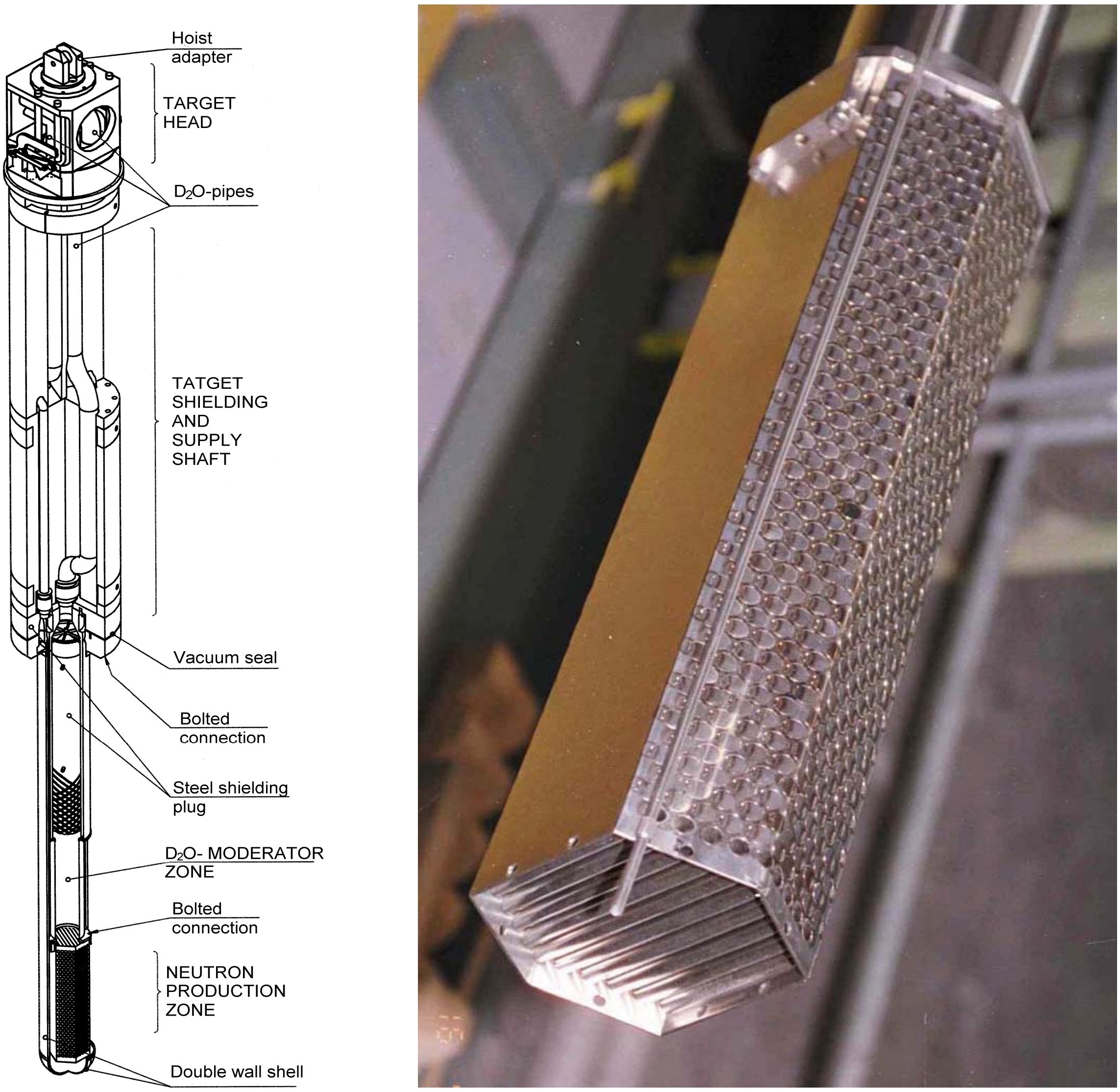
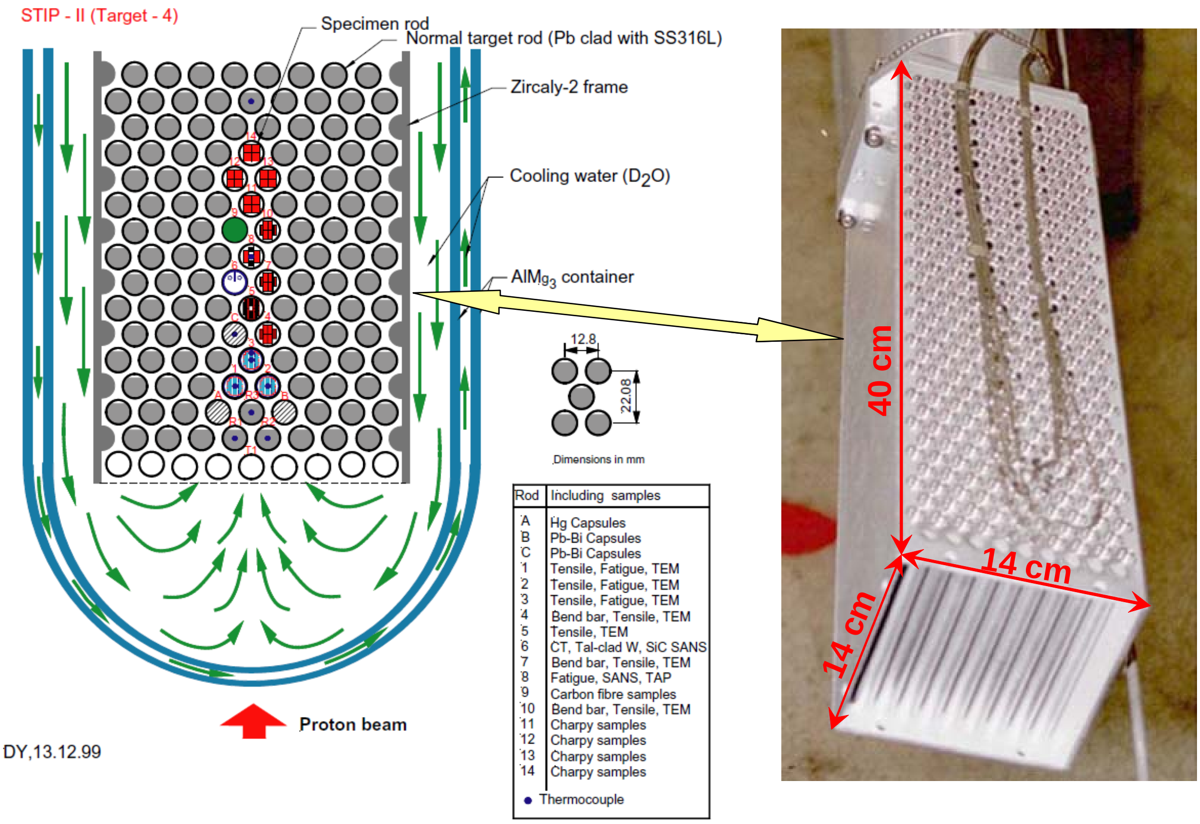


Figure 3: Target insert (left) and its solid zirkaloy neutron production zone (right)

Besides general facility upgrades, the target development towards optimized neutron flux for the benefit of the SINQ users had high priority during the operational history. The solid targets are contained in a double walled, heavy water cooled aluminum shroud with a hemispherical beam entrance window, the so-called safety hull. Two heavy water loops actively cool the target rod array as well as the beam entrance window.

Two solid zirkaloy targets (Target 1 and target 2) were irradiated successfully from 1997 to 1999 with proton charges of 0,48 Ah respective 6,76 Ah. In 1997 operational time was limited by lack of personel on shift duty, due to a control system which was inadequate for remote operation. After implementation of a new control system remote operation of the SINQ facility was permitted by the swiss authorities after 1998. After solving some other initial problems, SINQ´s availability related to the available proton beam was raised beyond 95%.

The so called “cannelloni” target was developed in order to improve the neutron yield and to reduce the manufacturing costs. The target rods of uniform dimensions contained lead in stainless steel canning arranged in an aluminium cradle with square cross section as shown in figure 4 (right). In the center positions the target contained several rods with irradiation samples of candidate materials for components under high neutron or proton radiation exposures (figure 4, left). Selected rods were instrumented with thermocouples to monitor the temperatures inside the lead and some samples.



Rod	Including samples
A	Hg Capsules
B	Pb-Bi Capsules
C	Pb-Bi Capsules
1	Tensile, Fatigue, TEM
2	Tensile, Fatigue, TEM
3	Tensile, Fatigue, TEM
4	Bend bar, Tensile, TEM
5	Tensile, TEM
6	CT, Tal-clad W, SiC SANS
7	Bend bar, Tensile, TEM
8	Fatigue, SANS, TAP
9	Carbon fibre samples
10	Bend bar, Tensile, TEM
11	Charpy samples
12	Charpy samples
13	Charpy samples
14	Charpy samples

Figure 4: The „canneloni“ target with lead in stainless steel canning and sample rods

Substitution of lead for solid zirkaloy inside the target rods resulted in 42% gain of neutron yield. Targets 3, 4, and 5 were irradiated from 2000 to 2005 with high availabilities of about 99%. Another step in the improvement of the neutron yield was made by testing rods in selected positions with zirkaloy canning which replaced the steel canning with its higher cross section for neutron absorption compared to zirkaloy in target 5.

In October 2005 a sudden increase of the radiation level in the SINQ cooling plant was measured and gamma spectroscopy of target coolant showed significant concentration of spallation products in the havy water samples, especially Xenon-127 which is the most volatile spallation product and therefore an indicator of leakage from the target rods.

In 2006 when target 5 was dismantled for recovery of the samples and inspection of the test rods with zircaloy canning, it was found that the zirkaloy canning of four rods in central positions with a high proton irradiation dose had remained in good condition.

Hoever, two other rods with steel canning at similar positions had burst and showed ballooning and cracks in the center section as shown in figure 5.

The proximate cause of the failure was an unintended beam overfocusing from normal 6 cm to about 1cm due to an incorrect set up of quadrupol magnets in front of the target for several hours, causing temperatures of more than 800 °C in target rods. The fact that the zirkaloy canning withstood this thermal and mechanical load led to the decision to apply only zirkaloy canning in all future solid targets.

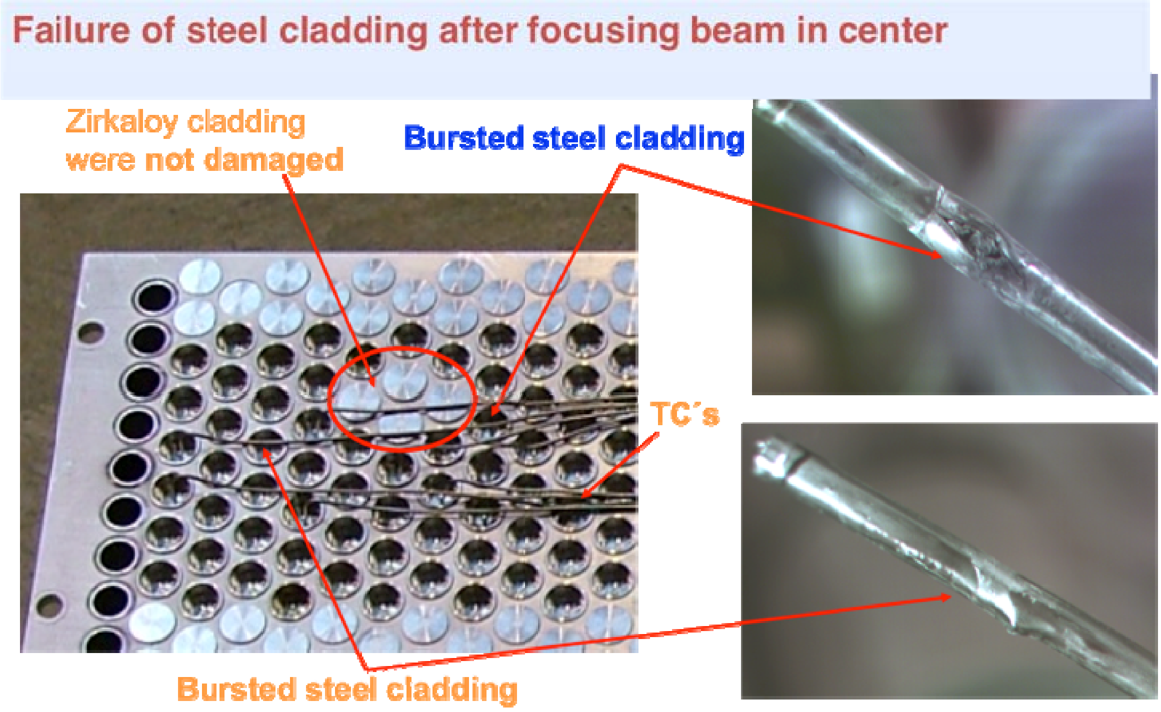


Figure 5: Target 5 steel and zirkaloy canning (left) burst rods with steel canning (right)

3. The Liquid metal target experiment (MEGAPIE)

In the framework of the MEGAPIE (MEGAwatt PIlot Experiment) motivated by the interest in Accelerator Driven Systems to transmute nuclear waste in the megawatt range, a liqid metal target with eutectic lead-bismuth (LBE) was irradiated with an average proton current of 1,35 mA during four months in 2006. During the experiment the target served as the source for the neutron scattering programme at PSI. The latter put very stringent demands on the availability of neutrons (full power >95% of the schedules operation time).

The target behaviour was satisfactory during stable operation and transients due to beam trips, and the liquid metal target delivered about 80% more neutrons than the pevious target 5. A drawback was a unexpected gas leakage into the insulation volume between the LBE-container and the outer safety hull, which required a weekly venting procedure to maintain the insulation vacuum. Mass spectrometry showed a high concentration of benzene and methane in the leakage. After dismantling the MEGAPIE target in 2009 a black, flaky smut was found in the bottom of the target window calotte, leading to the conclusion that a certain amount of oil (Dyphyl) from the heat exchangers inside the target must have leaked from the heat removal system into the thermal insulation volume.

Another surprising finding was a metallic shining fragment in the center of the calotte, which could be carbon, but also frozen LBE that had leaked from the LBE container into the gap between the beam window and the lower end of the LBE container. Since post irradiation examination has not been done, the origin of this fragment remains uncertain for the time beeing.

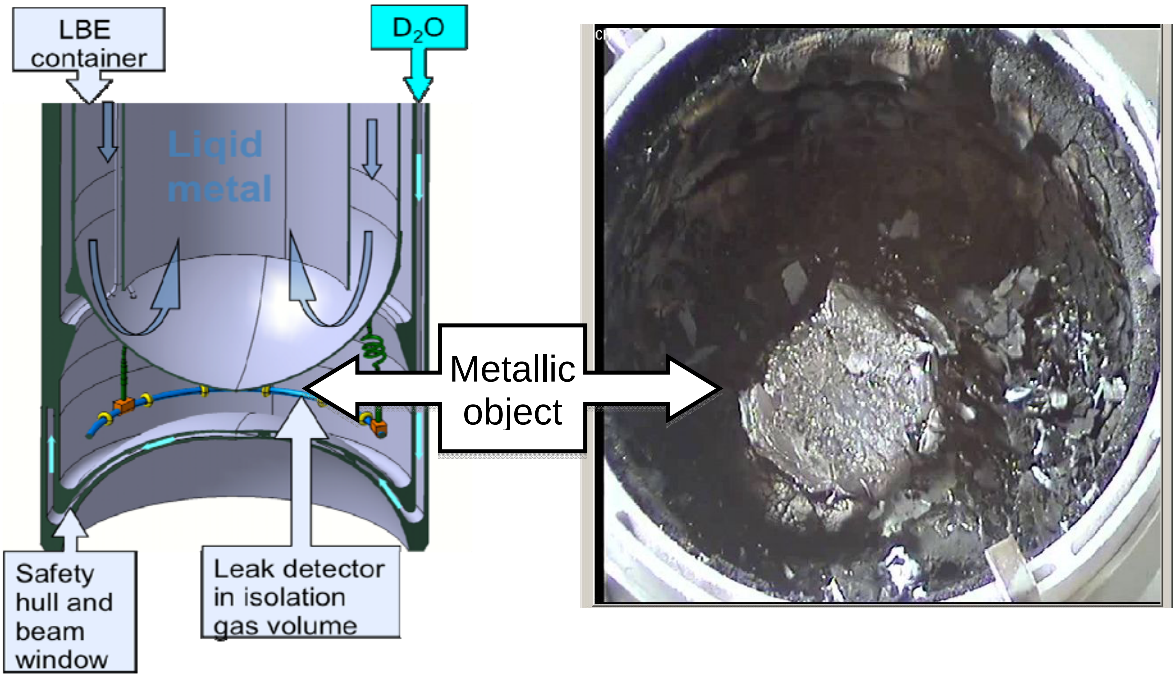


Figure 6: Lower configuration of the LBE target (left) and leakage remains inside calotte of the safety hull (right)

4. SINQ after the liquid metal target experiment

After deinstallation of the MEGAPIE target and its numerous auxiliary systems during the annual winter shut down 2007 a solid target with 100% zirkaloy canning was installed and irradiated, showing a 11% gain of neutron yield compared to the previous cannelloni targets with steel canning due to reduced neutron absorption of the zirkaloy canning. Unfortunately the users could only benefit from this increased flux until june 27 in 2007 when a sudden rise of radioactivity in the intermediate chill water system indicated a leak in a heat exchanger of SINQ´s heavy water systems. A continuous reduction of up to 30% neutron flux at the instruments indicated a degradation of SINQ´s D_2O Moderator by ingress of light water via the heat exchanger leak in the Moderator cooling system.

Although the pressure gradient from chill water to moderator should avoid leake of radioactive D2O into the chillwater, about 150 liter tritiated heavy water contaminated the intermediate cooling system. A possible cause of the leak flow against the pressure gradient lies in the special geometry of the plate heat exchanger, creating local venturi jet effects. The possible cause of the leak was pressure oscillations which were induced by a dynamic instability in a automatic pressure regulator upstream of the moderator heat exchanger. It seams that plate heat exchangers are sensitive to pressure oscillations.

The repair of the heat exchanger caused a downtime of three month and a reduction of the availability in 2007. The contaminated chillwater system was refilled with deionized water.

To prevent future contaminations of chillwater as well as H_2O infiltration into the D_2O systems by heat exchanger leakage, an additional intermediate heavy water cooling loop was installed between the three SINQ heavy water systems and the chill water system of the accelerator facility during the winter shut down in 2008. To recover from the loss of neutron flux from the degraded moderator, the D_2O inventory from the target cooling system and the target window cooling system was exchanged with the degraded moderator inventory. The light water contamination of the present target- and target window coolant proved to have almost no influence on the neutron flux because of the fast neutron spectra inside the target. Measurements after the first start up in 2008 showed an almost complete recovery of the neutron flux.

Inspired by the gain in neutron production with the MEGAPIE liquid metal target further improvements for the solid target 7 have been elaborated and scrutinized by MC-simulations (figure 7), aiming at the utmost possible neutron yield from the cannelloni target concept. Since April 2009 an improved version of the solid target is in operation, with a 40% increase in neutron yield compared to its predecessing target 6, and 119% compared to the start-up target, falling only some 15% behind the liquid metal target of MEGAPIE. This was achieved by the following four modifications (figure 8).

1. Concave beam window calotte reduces proton losses in coolant
2. A 2 cm Pb blanket around the target shifts thermalisation of the fast spallation neutrons deeper into the moderator and reflects the thermal neutrons, increasing the thermal flux on the cold moderator and ports.
3. A reduction of the gaps between target rods from 1,5mm to 1,2mm
4. No irradiation samples in the target

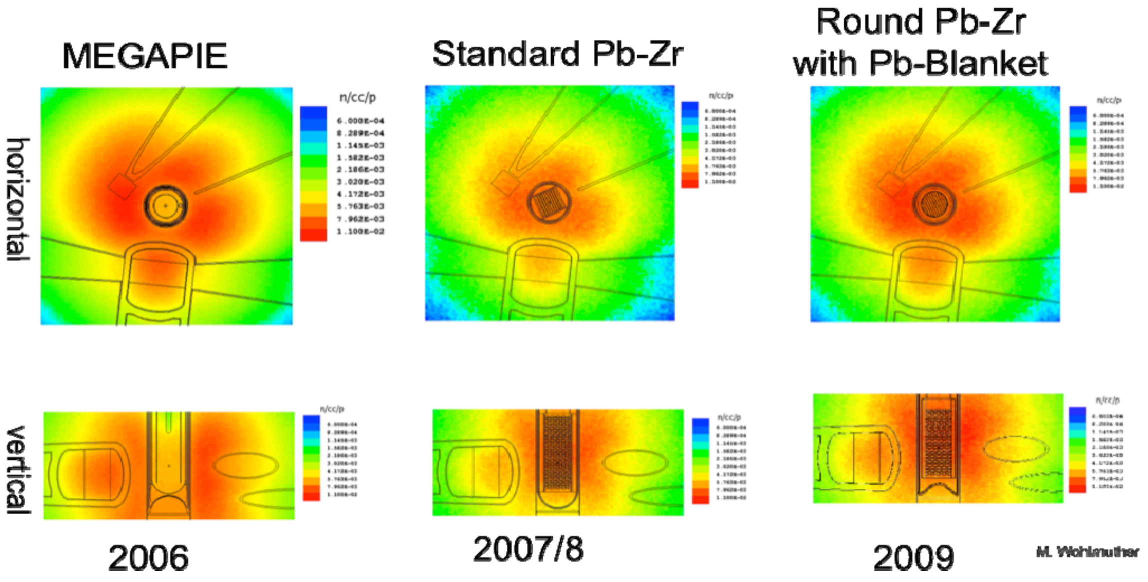


Figure 7: MC simulations of the LBE target from 2006, the standard canneloni target from 2007/8 and the present modified cannelloni target from 2009/10

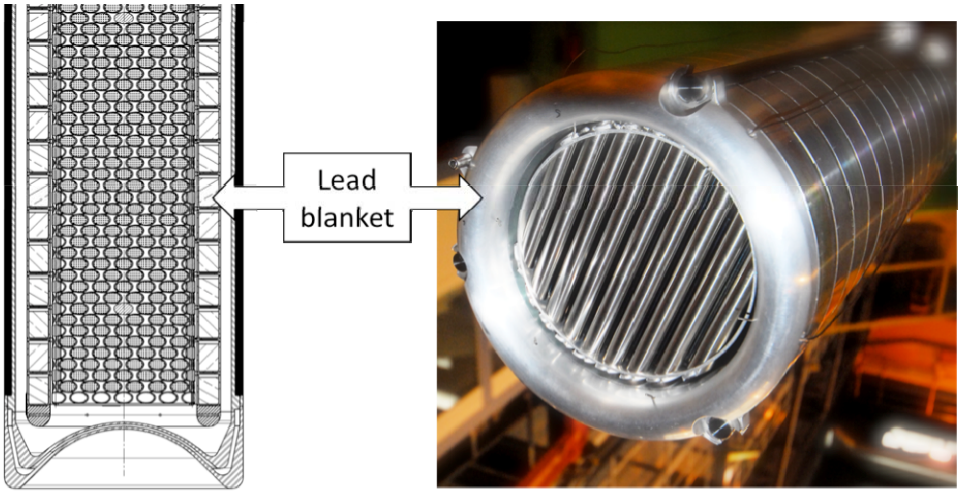


Figure 8: Modified cannelloni target 7 with concave beam window calotte, lead blanket, and reduced coolant gaps

Summing up the neutron production history of the 12 years since the start up of SINQ figure 9 shows the benefit for our users of about 300% more neutrons resulting from target development together with a 75% upgrade of the proton beam since 1999. The availability of the target station was around 99%, whereas the average availability of the accelerator was 90% during the last years.

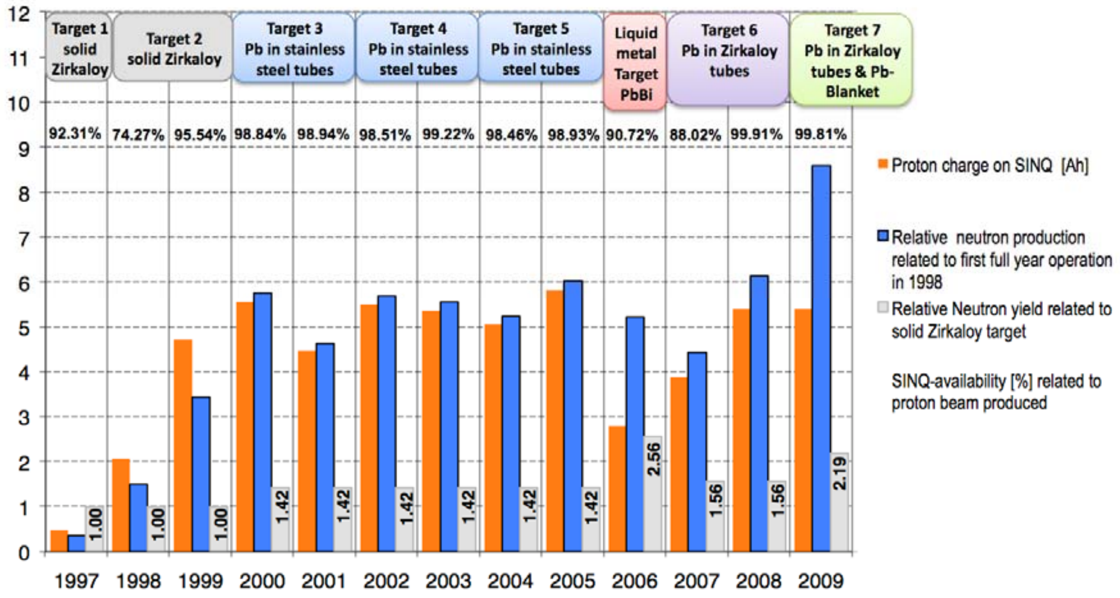


Figure 9: History of yearly accumulated proton charge and related neutron yield. The numbers in the top row indicate the availability of SINQ (for most years >98%).

5. Outlook into SINQ´s future

SINQ will share from 2010 on 1% of the protons with the new ultra cold neutron source UCN. The proton beam on target is planned to be upgraded to 2mA and the target development is ongoing towards optimization , also considering an alternative liquid metal target for higher proton beam currents.