

Containment as a prime design goal for neutron spallation sources

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Abstract. Spallation neutron sources are increasingly becoming the mainstay for research employing neutrons. Besides important technical issues, one of their advantages is related to their public acceptance, which is much better than for reactors. In terms of their total radioactive inventory and the ensuing hazard potential spallation neutron sources simply cannot be compared to power reactors. In Switzerland and in many other countries, spallation sources are not nuclear facilities according to legal definitions. Nevertheless, spallation targets and their direct environment become radioactive, and this warrants precautions for safe enclosure. For both of the two target types so far employed at the PSI SINQ facility, i.e. solid state and liquid metal targets, an approach of staggered barriers and enclosures has successfully been implemented. The reliable safe enclosure of radioactivity in SINQ has been demonstrated also for cases of non-standard operational conditions. Experience accumulated at SINQ can shed some light on principal design options for new spallation neutron sources and their implications for licensing. A strong focus on safety and in particular containment from the start does not require concessions in terms of useful neutron flux for the experiments.

1. Introduction

There is no doubt, spallation neutron sources are built for reliably making available neutrons as probes in research. To an ever enlarging extent this is also what spallation sources do, taking over the task in former times predominantly served by research reactors. Among the various advantages, which are claimed for an approach based on spallation compared to fission, are the ease of implementing pulsed operation, and, of particular interest here, less problems with licensing and public acceptance as spallation sources are legally classified as non-nuclear facilities. There is no fissile material in current neutron spallation sources. Irrespective of this fact and the classification, some similarities exist between spallation neutron sources and research reactors. Relevant to the focus on containment, despite the differences in the nuclide inventory, an irradiated target of the PSI SINQ facility is about as radioactive as spent fuel from a nuclear power plant. Therefore it seems wise to adhere to safety approaches developed for reactors also for a spallation source, - with due scaling by the actually present risks. One very basic approach is to contain the potentially harmful substances in nested enclosures. A staggered arrangement of barriers is usually employed in order to guarantee safe containment also in accident conditions. In the following the containment approach at SINQ is shown, contrasting the standard effective for the solid state water-cooled targets with the special precautions required for the operation of the Megapie liquid metal (LM) target. Figure 1) shows in a historical document the originally planned lay-out for SINQ, at that time anticipating a LM target.

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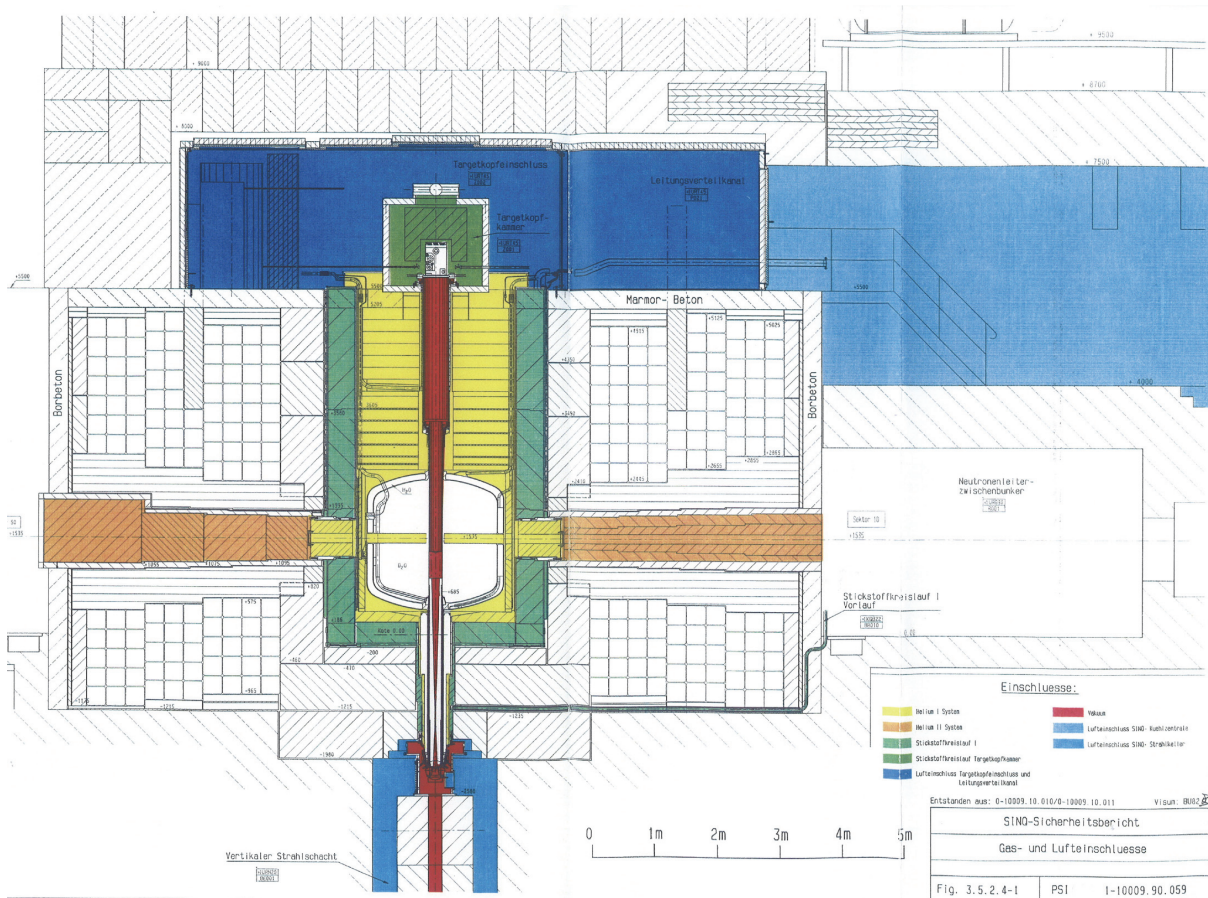


Figure 1. Original lay-out of SINQ enclosures for a LM target; color-code: yellow-helium1, orange-helium2, dark green-nitrogen1, light green-nitrogen2, dark blue-air (target head enclosure TKE), red-vacuum, light blue-air (cooling plant), blue-air (beam vault). When plans were changed during the already ongoing construction work at SINQ, and instead of a Lead Bismuth (LBE) liquid metal target a solid state one made from zircaloy was chosen, the light green separate enclosure around the target head was omitted.

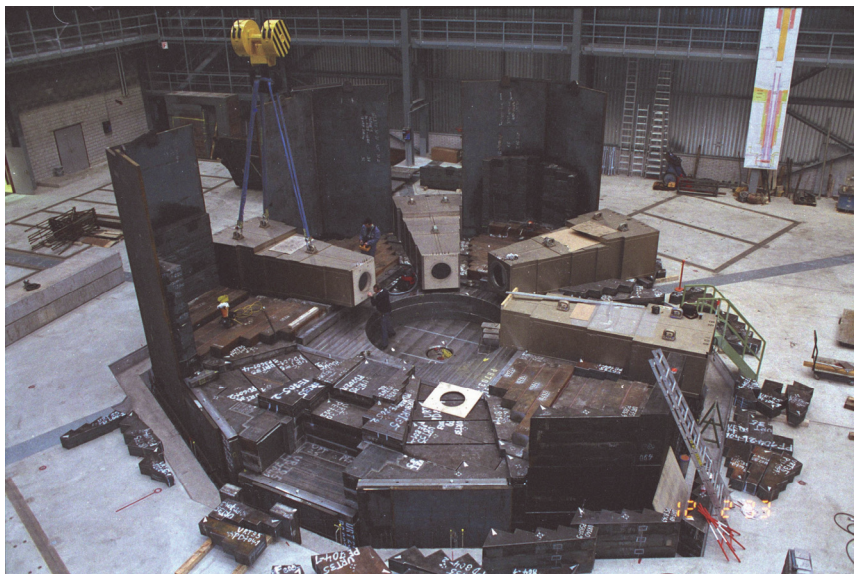


Figure 2. In an early phase during the construction of the SINQ target block beam ports and their enclosures “helium2” have been installed.

2. General Lay-Out

When building up the SINQ target block, barriers were installed in a succession from the outside to the inside. Enclosures around the neutron beam ports were about the first to be in place. Each port features a separate helium loop, all together making up “helium2”, see figures 2) and 4). Towards the target, the beam ports face corresponding extrusions of the inner helium tank (“helium1”), separated by double-walled windows. All around helium1 there is a nitrogen tank (“nitrogen1”), see figure 3).



Figure 3. Steel shielding close to the center, around the inner helium tank (“helium1”) is sitting in a separate enclosure filled with a controlled nitrogen atmosphere “nitrogen1”.



Figure 4. “Helium2” as an example of the installations in the gas central for maintaining and monitoring the controlled atmosphere for the neutron beam ports.

The SINQ target itself sits in the very center of the target station, in a vacuum tube in extension of the proton beam line (red in figure1). The originally foreseen barrier around the target head inside the target head enclosure (TKE) still depicted in figure 1) had not been built when it was decided to start SINQ operations with a water-cooled solid state target built from zircaloy. When finally a Lead Bismuth (LBE) LM metal target was installed in SINQ, i.e. Megapie, the original requirements were valid again, and a second controlled enclosure was secured in the design of the target and the cover gas system [1].

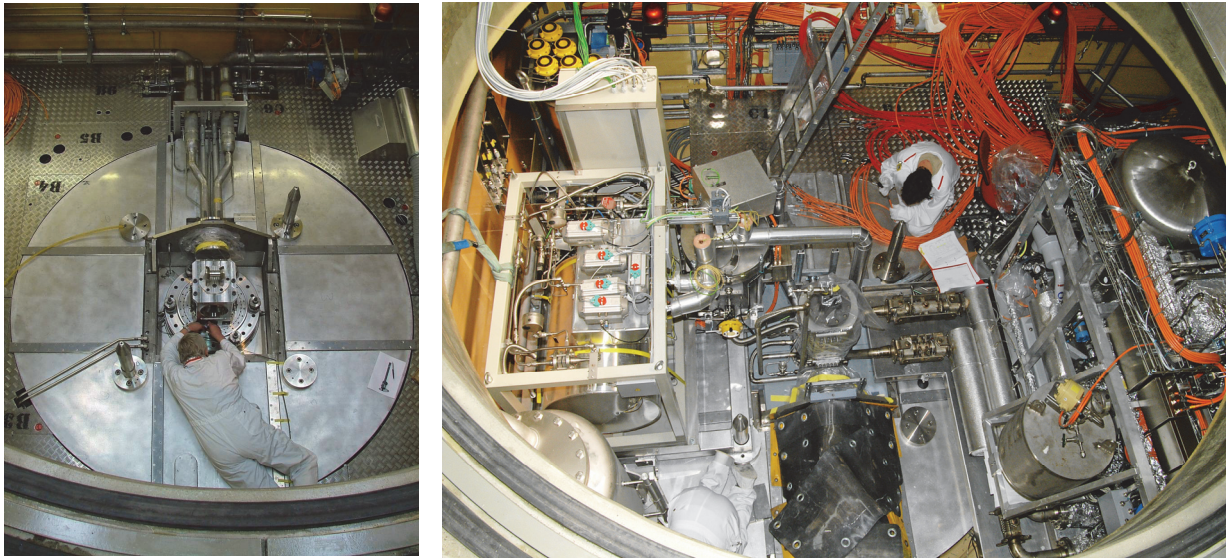


Figure 5. Left: the almost empty TKE when installing and, after the person had left, irradiating a standard solid state target; water connections at the top, both for the target cooling and the target window cooling are the only installations close to the target head in the center. Right: For the Megapie LBE target the TKE had to house delicate ancillary systems; from front left to front right, clockwise: expansion tank, fill system, cover gas system, heat removal system. The water connection pipes had not been removed but are covered by the temporary shielding visible in center front.

Contrasting the two situations in the TKE for water-cooling and liquid metal as shown in figure 5) one should bear in mind that the water cooling plant stayed unchanged, and was ready for operation all the time, immediately used again with the next solid state target after the end of the Megapie irradiation period. Nevertheless, it is obvious that the liquid metal target required additional installations and full-grown ancillary systems in addition to what is required for standard operations of the water-cooled solid state targets in SINQ. Only the fill system was in the TKE temporarily, all other systems, - and more outside the TKE - , had to stay there for the whole operational period. In particular, bridging the large temperature step from liquid metal temperatures (300 °C) to values better compatible with the cooling water (40 °C) required a complicated and expensive intermediate heat removal circuit (HRS), employing a special heat transfer fluid, i.e. oil (THT). Of even higher complexity, and also not without problems, the cover gas system (CGS) built in two parts deserves special mention. Both HRS and CGS had to address issues pertaining to containment. This was done in principal with success but at significant cost, some of them becoming visible only during decommissioning and dismantling of the then highly contaminated systems.

After service, the heat transfer oil contained significant activity stemming from tritium, which had diffused through the stainless steel tubing (316L) at the elevated operating temperatures (300 °C).

As to the cover gas, the CGS had to be built to the same quality standards as the target itself, e.g. every connection welded and inspected by X-ray, wherever possible. A tiny leak in the order of 10⁻⁸ mbarl/s from the cover gas volume to the insulation gas between the liquid metal container and the lower target enclosure was properly detected during manufacturing. It was not considered an issue originally but necessitated the installation of an additional gas handling system during operations. The simultaneous occurrence of an oil leak into the same insulation gas volume and the ensuing production of substantial amounts of radiolysis gas made it necessary to vent this volume and contain the mixture for a decay period of one week before it could safely be released via the controlled PSI exhaust. This is a clear example of the usefulness of having diverse and well distinct barriers in a defense-in-depth approach by staggering containment shells.

3. SINQ, Solid State Target

Coming back to the target proper and the barriers there, figure 6) shows a principal sketch of a standard solid state SINQ target, cooled with water. This type of target has many features, which are very favourable in terms of safety. Here we shall concentrate on the inherent barriers relevant for normal operational conditions as well as for conceivable accident scenarios. Only two of the existing barriers are claimed as credited containment, see figure 6).

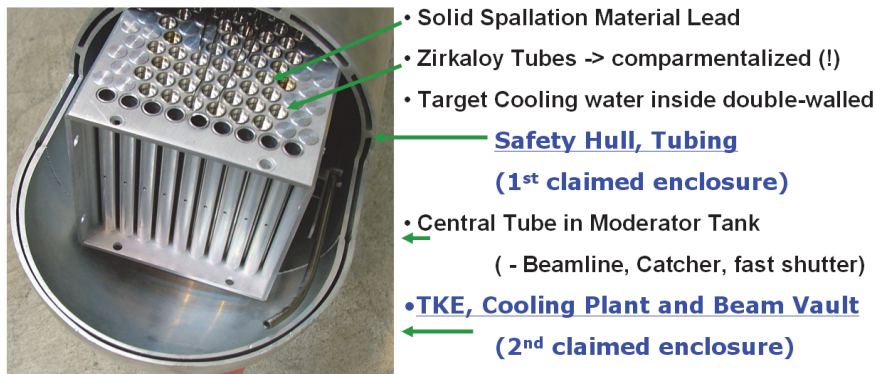


Figure 6. Cut-away showing the containment in a standard target; of the many barriers available with a water-cooled solid state target only the safety hull including the tubing and the rooms containing the installations (beam vault, TKE, cooling plant) are credited as enclosures.

The diverse barriers for a standard target are characterized by varying retention capability. In the order from the inside out, they start with the solid spallation material, lead in the case of the continuous source SINQ, see figure 6). Most of the lead in the cannelloni stays solid during normal operational conditions, and, much more important, immediately solidifies in case there is a rupture of one the „cannelloni“ containers made from zirkaloy. In the matrix of the solid material a significant fraction of the radioactive inventory is captured and prevented from spilling further out into the next shell.

Immediately after intrinsic enclosure in the (crystal) structure of the target material comes the packing into a large number of hermetic containers. The SINQ target features compartmentalization, which means the enclosure of all potential hazardous substances on a scale as small as possible, i.e. individual encapsulating tubes, “cannelloni”, rather than one big container. The safety consideration behind this statement can be exemplified in a telling, even if simplistic, comparison to fruit. A coconut needs a thick shell and an even thicker shock absorber to arrive safely and whole on the ground; one can cut an orange into halves without spilling more than a few drops of juice. In any credible accident scenario, and in particular for overheating by an involuntarily concentrated beam, which is a most likely event, only a (small) fraction of the tubes will be harmed and their inventory allowed to spill into the cooling water and the next layer of the containment.

The cooling medium, (heavy) water could be seen as a means of enclosure because in the accident case of lead leaking out of a tube the water readily freezes the material and thus immobilizes its inventory. Of course, the water itself carries radioactive constituents also in normal conditions, i.e. tritium and beryllium, and therefore requires suitable containment, even if at a lessened level of risk. The water installations, i.e. the tubing, act as the first credited enclosure in SINQ. Beryllium settles on the walls and gaseous tritium is collected in an expansion volume, released occasionally. At the moderate temperatures ensured by water cooling no problems with leakage of tritium through the steel due to diffusion occur at SINQ. The cooling circuits for the target, the target window and the moderator tank are connected to the facility cooling circuit only via a hermetically sealed intermediate cooling loop, also operating with water as medium [2]. The connected tubes of beam vacuum and the central tube in the big moderator tank form an additional complete enclosure. In the proton beam line a fast-acting shutter-valve upstream of the target towards the accelerator is tested yearly in the course of a formal procedure before starting SINQ operations.

The target head enclosure TKE, cooling plant and beam vault establish the second credited barrier at SINQ for standard targets with water cooling.

4. SINQ, Liquid Metal Target

When the LM Megapie target was inserted in SINQ in 2006 an additional credited barrier on top of the water- related precautions had to be foreseen: the liquid metal container and the volumes connected to it inside the target, see figure 7).

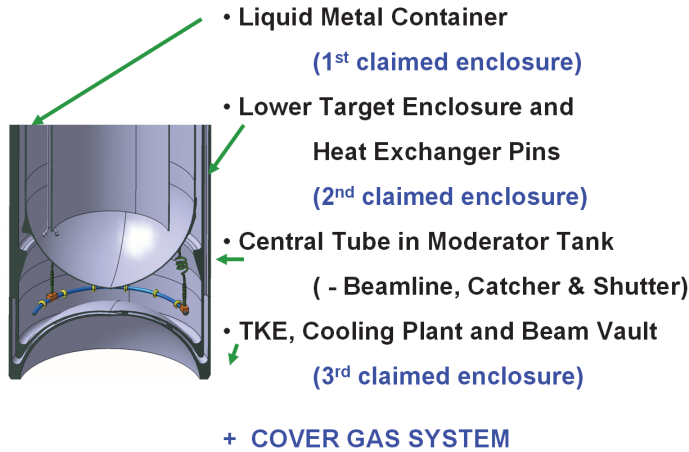


Figure 7. Principal sketch of containment in the Megapie target; liquid metal container, safety hull including the tubing and the rooms containing the installations (TKE, cooling plant and beam vault) are credited as enclosures. The succession of layers for the cover gas ran in parallel, in principle, but made necessary dedicated and expensive installations.

It is important to note that the precautions necessary for establishing the safe and reliable containment of the spallation material proper, i.e. LBE with Megapie, had to be accompanied by equivalent installations for the highly radioactive cover gas, see figure 8). All gas-carrying tubing had to be double-walled, fabricated with the adherence to very stringent quality standards. In practice, the CGS required substantial design effort and still suffered from a failing pressure sensor and rather awkward operational procedures, e.g. during sample taking in full heavy protections suits with external air supply.

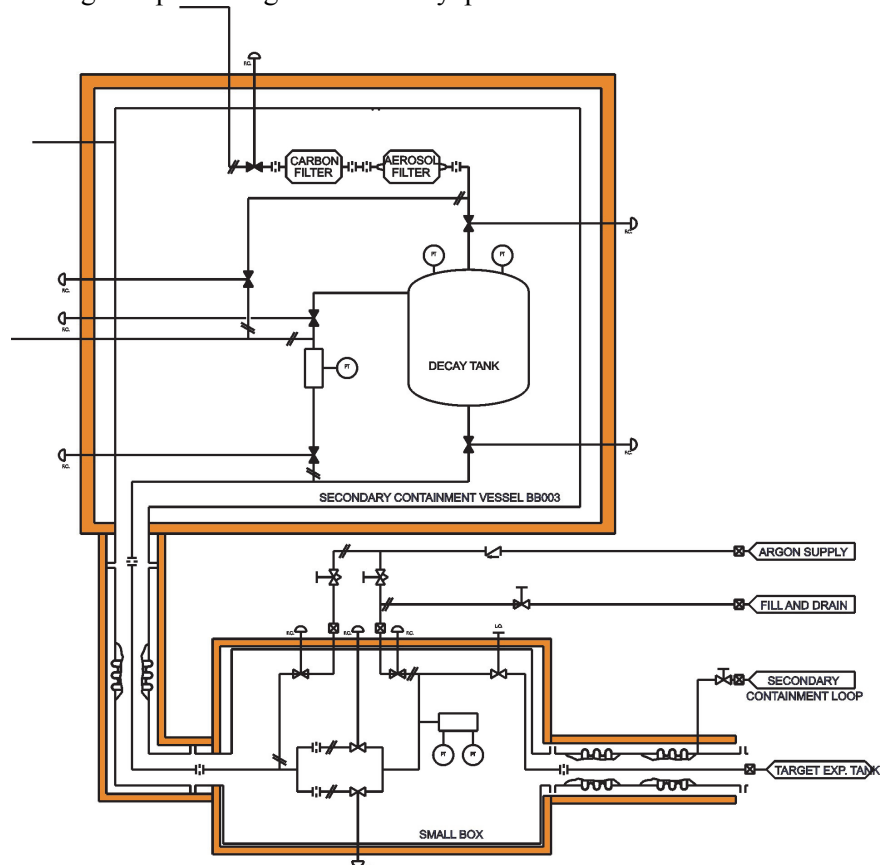


Figure 8. Schematic layout of the Megapie cover gas system (CGS); a section containing valves “small box” had to be installed very close to the target head, whereas the big part with the decay tank was put into a corner of TKE, all in permanently monitored second enclosure and shielded to the outside.

5. Lessons Learned

The chosen design, in principle, proved sustainable; in practice, meeting the stringent requirements, turned out to be rather complex and expensive. One lesson learned with the system was, that 'leak-tightness' for gases in the conventional definition is not the same as for radioactive gases: in spite of successful helium leak tests according to specifications a leak from the decay tank into the 2nd containment was detected by the very sensitive detector monitoring the circulating gas. Although clearly detectable, the leak was sufficiently small in order to release the inventory weekly by venting of the 2nd containment through the controlled exhaust system.

Some more lessons learnt, both, during the extensive and successful operation of the standard solid state targets with water cooling and with the much more demanding liquid metal megapie target can be summarized.

Most important for the issues of safety and containment is to NOT focus solely on the target; - ancillary systems easily suffer from a lack of attention compared to the target itself but they can turn out to pose more problems and to demand more effort than the target itself. Examples are the dedicated heat removal system and the cover-gas system, which had to be built during the Megapie project. These systems in the end were more expensive than the target, and they required manifold un-anticipated care.

The use of the heat transfer oil THT as a bridging medium between the high temperatures of the LBE in the target and an interim water cooling loop made it necessary to reduce the oxygen content in the SINQ beam vault and the target head enclosure chamber (TKE). This was required by the licensing authority in order to prevent inflammation, which necessitated the expensive hiring of special equipment in operation during the whole operational period of the Megapie target in SINQ.

The Megapie cover gas contained as expected a whole plethora of volatile substances amounting to very high activity. The system for controlled handling of the cover gas was more expensive and proved in a sense more demanding in its operation than the Megapie LBE target.

Unexpectedly, a complete additional system had to be improvised during the actual irradiation of Megapie. This was made necessary by the added effects of an oil leak plus a previously known tiny leak from the cover gas into the interstitial space between target and safety hull. This insulation gas volume, meant to contain stagnant helium at half a bar pressure turned out to fill up quickly with a radioactive gas mixture, collecting radioactive species from the cover gas and big amounts of hydrocarbons from the radiolysis of leaking heat transfer oil.

After having operated the LM target of Megapie at SINQ; one can appreciate the relative easiness of standard water cooling. Focusing on the target first, from a rather naive point of view and the perspective of safety and containment, one should try starting with the least dangerous materials and only opt for more problematic ones in case the absolute need to do so surfaces. Quite generally, one can argue that everything, which can be built from solid material should in fact be done so. Just the same, what can be accomplished with a liquid should not rely on gas.

It can be stated that the initial focus on containment resulted in a solid and safe basis for SINQ. Following an evolutionary approach and setting small development steps one after the other, in particular with respect to materials' choices, reliable performance from the start as well as a significant increase in performance has been achieved at SINQ over the last 15 years [3].

6. References

- [1] Wagner W., Gröschel F., Thomsen K., Heyck H., "MEGAPIE at SINQ – the first liquid metal target driven by a megawatt class proton beam", *J. Nucl. Mater.* **377** (2008) 12.
- [2] Wagner et al. "Ancillary systems at SINQ", this conference ICANS XX.
- [3] Wagner et al. "SINQ facility report", this conference ICANS XX.