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MEGAPIE at SINQ – The first liquid metal target driven by a megawatt class proton beam

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ABSTRACT

The lead–bismuth liquid metal target MEGAPIE (MEGAwatt Pilot Experiment) was operated at the Swiss Spallation Neutron Source SINQ starting mid-August 2006, for a scheduled irradiation period until 21st of December 2006. The continuous (51 MHz) 590 MeV proton beam hitting the target reaches routinely an average current of ~1300 μA, corresponding to a beam power 0.77 MW. This article illustrates the main features of the target and the ancillary systems specially needed for the liquid metal target operation. Further, the operational experiences made with this target during start-up and routine operation are summarized, besides the general performance highlighting new beam and target safety devices, and last but not least the neutronic efficiency in relation to the previously operated solid lead target.

1. Introduction

SINQ, the Swiss spallation neutron source, is driven by PSI's 590 MeV proton accelerator. Receiving a stable proton current of ~1300 μA, SINQ is the presently most powerful accelerator driven facility worldwide. Besides the primary designation of SINQ to serve as user facility for neutron scattering and neutron imaging, PSI seeks to play a leading role in the development of the facility, focusing to spallation targets and materials research for high-dose radiation environments. Serving these activities, SINQ has established several projects, the most prominent one being MEGAPIE (MEGAwatt Pilot Experiment), a joint initiative by six European research institutions (CEN-SCK (B), CEA (F), CNRS (F), ENEA (I), FZK (D), PSI (CH)), the EU, and JAEA (Japan), DOE (USA), and KAERI (Korea) to design, build, operate and explore a liquid lead–bismuth spallation target for 1 MW of beam power [1]. Such a target is under consideration for various concepts of accelerator driven systems (ADS) to be used in transmutation of nuclear waste and other applications worldwide. The goal of this experiment is to explore the conditions under which such a target system can be licensed, to accrue relevant materials data for a design data base for liquid metal targets, to gain experience in operating such a system under realistic beam conditions, and to ascertain the neutronic performance of such a target for the use in SINQ and other (future) accelerator driven neutron sources.

2. The MEGAPIE target

In shape and external dimensions, the MEGAPIE target has to match the given opening in the target block shielding, demanding a slim, about 5 m high structure [2]. In its interior, it is completely different as compared to the normal solid 'lead-cannelloni' target of SINQ (the latter being described in [3,4]): The MEGAPIE target houses 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 are two electromagnetic pumps for forced circulation of the LBE, a flow guide tube inserted into the lower liquid metal container to separate the annular LBE down-flow from the central up-flow, and 12 heat exchanger pins for removing the energy deposited by the beam and/or keeping the target at temperature when the beam is off. Further, the target is equipped with a variety of instrumentation, mostly thermocouples, for operational control, or serving safety features or experimental observation. Fig. 1 shows two of the major target components, i.e., the 12-pin heat exchanger and the central flow guide tube. Fig. 2 shows the fully assembled MEGAPIE target lifted before being inserted into the SINQ operation position.

3. Ancillary systems

The MEGAPIE ancillary systems directly necessary for the target operation are the heat removal system (HRS), the cover gas system (CGS), the insulation gas system (IGS) and the fill and drain system (F&D).

The HRS [5] consists of two subsystems: an intermediate cooling loop with oil Diphyl THT as heat transport medium, connected to the heat exchanger pins in the target, and a back-cooling water loop (WCL). The oil loop, operating between 160 °C and 230 °C, is primarily necessary to remove the about 0.6 MW of heat load deposited in the LBE by the proton beam. As a second function it must also be capable to manage a controlled hot-standby operation

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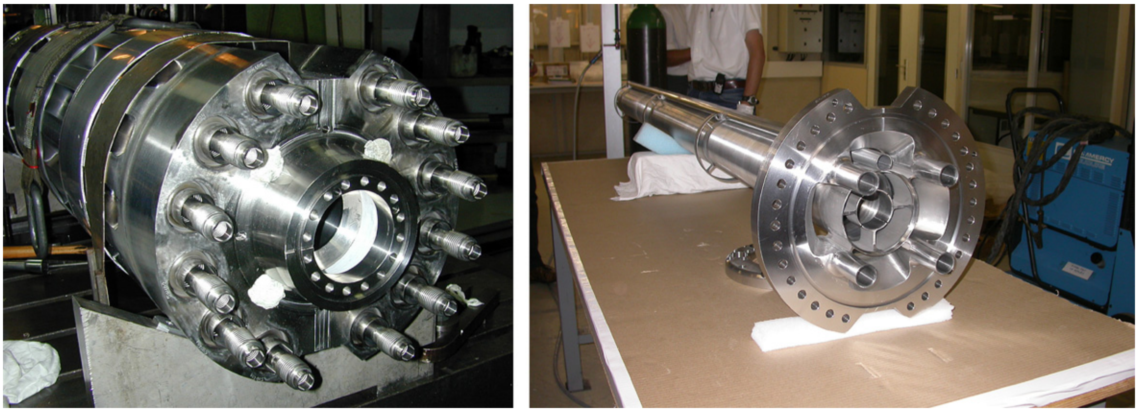

Fig. 1. Two major target components prior to integration: the 12-pin heat exchanger (left) and the central flow guide tube.

Fig. 2. The fully assembled MEGAPIE target before being inserted into the SINQ operation position.

after beam trips or scheduled beam interruptions to prevent freezing of the target.

The CGS [6] must handle the volatile, mostly radioactive inventory of spallation products released from the LBE in the target. Handling of radioactive gases and volatiles imposes stringent requirements on safe and remote operation, on retention of radioactivity, like second containment and tightness, and on shielding.

The insulation gas [7] fills the volume between the inner hot part of the target and the outer cold hull. Besides its function as thermal barrier it must safely cope with the potential incident of cooling water entering the insulation gap and getting into contact with the hot interior of the target.

The F&D system is needed to allow filling and draining of liquid LBE into or out of the target, respectively. Fig. 3 shows a view from above into the target head enclosure chamber TKE (situation of April 2006). The target head is in the centre, still without the cables connected which are in preparation in the rear, the oil loop of the HRS is at the right, the CGS in the left rear corner, and the F&D system at the left.

The initial baseline for the F&D system required draining of activated LBE from the target after the operation period. A detailed design for that was elaborated; however, the draining option was recognised to bear considerable risks, immediate ones, like possible contamination of the TKE, and more general ones related to licensing. Furthermore, it would have required considerable extra expenditure in its technical realization. In view of these difficulties the decision was taken to abandon the initial concept in favour of a draining option only in the non-activated state, prior to irradiation, and final freezing of the LBE in the target after completion of the irradiation experiment [8].

4. MEGAPIE irradiation start-up

The first beam on MEGAPIE was received on August 14, 2006: at a relatively stable and constant beam current of 40 μA, which corresponds to about 25 kW of beam power. The target accumulated a total charge of 60 μA h in this first phase. The second phase of the start-up procedure was successfully accomplished the following day, where the power was stepwise increased to 150 kW (250 μA proton current). The corresponding beam history is shown in Fig. 4. The goal of this phase was to check and verify the response of the heat removal system at power conditions comparable to those used when operated out of beam at the test stand in the autumn of 2005. The third and final phase of the start-up procedure was successfully accomplished on the 17th of August, when the power was stepwise increased to 700 kW (1200 μA proton current). The second graph of Fig. 4 shows the beam history during the ramp-up phase. At each power level the beam was interrupted after some 10 min with a stable proton beam, to verify the predicted temperature transients in the target. Most of the seemingly erratic beam behaviour was thus intentional.

5. New proton beam safety devices

For safe target operation a sufficiently broad footprint of the incident proton beam on the SINQ target is mandatory. If for any reason the protons were not scattered sufficiently in an upstream target (Target E) their footprint on the SINQ target could shrink leading to a rise in the maximum density of the beam by a factor of 25. At the resulting high current density it would take only 170 ms until a hole is burned through both the liquid metal container inside the target and the lower target enclosure (double-walled safety hull). The liquid metal would spill into the beam line and into the catcher vertically below the SINQ target. Such a failure would result in an extended shut-down period for SINQ.

In order to prevent an insufficiently scattered beam from reaching the SINQ target three independent safety systems have been installed: a dedicated current monitoring system, a beam collimating slit and a novel beam diagnostic device named VIMOS [9]. The latter

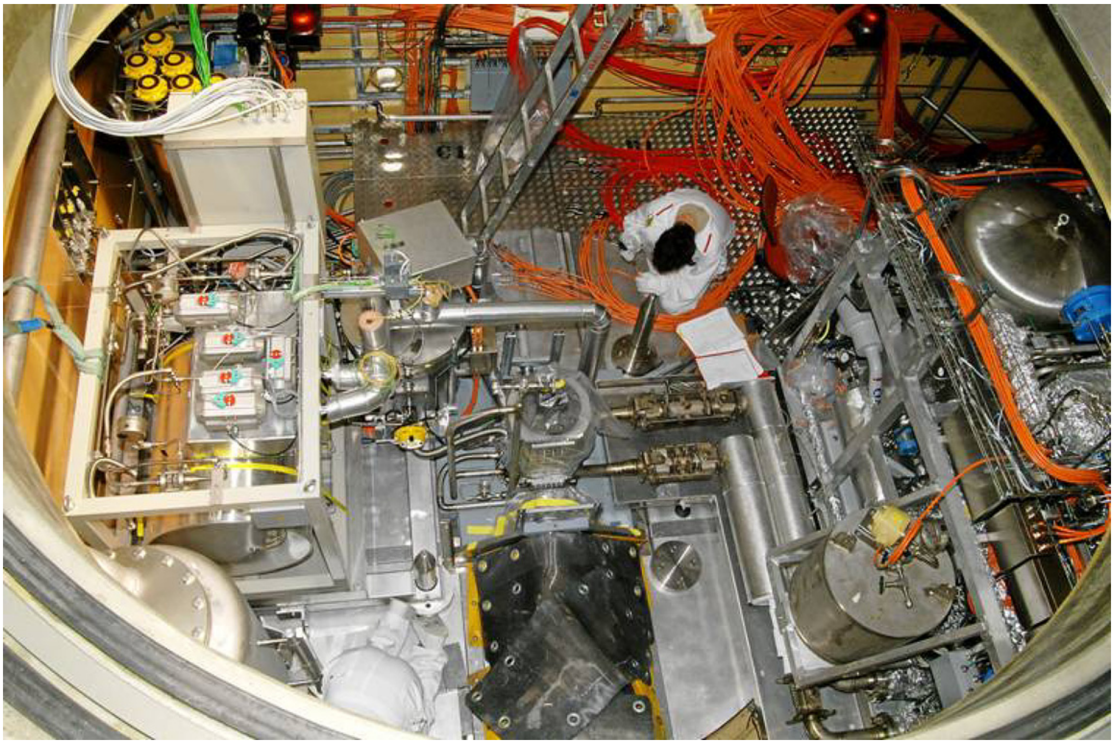

Fig. 3. View into the target head enclosure chamber TKE which is on top of the SINQ main shielding block (situation of April 2006). The target head is in the centre, still without the cables connected which are in preparation in the rear, the oil loop of the HRS is at the right, the F&D system at the left, and the CGS in the left rear corner (partly hidden behind the connector box of the F&D).

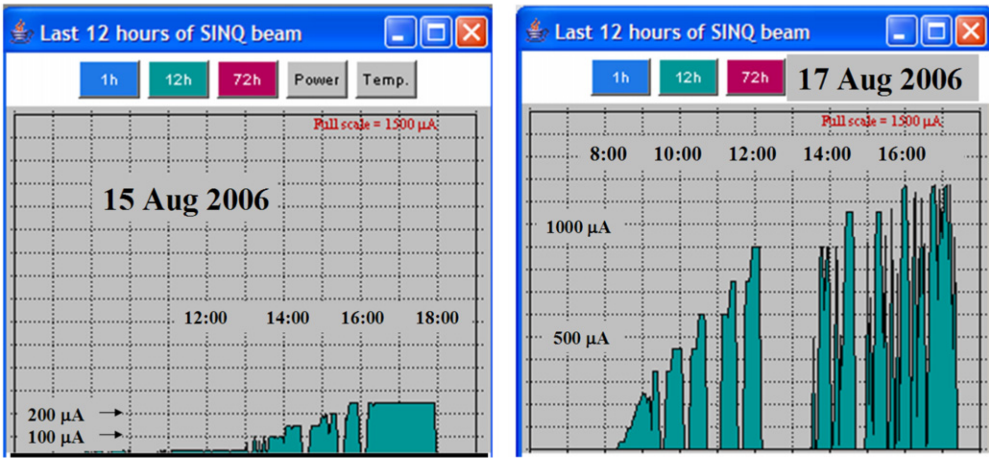

Fig. 4. Beam history during the second phase of the start-up procedure (August 15) where the power was stepwise increased to 150 kW, and the third phase (August 17) where the beam was ramped-up to full power. Most of the seemingly erratic beam behaviour was intentional.

monitors the correct glowing of a tungsten mesh closely in front of the liquid metal target. All these systems have to meet the basic requirement to switch off the beam within 100 ms when 10% of the protons by-pass Target E (corresponding to an increase in peak intensity by a factor of two). In an extensive collaboration amongst different groups at PSI the new safety devices have been installed.

Their proper functioning was verified early in the ramp-up phase as well as during routine operation. By deliberately producing slightly anomalous beam conditions at a sufficiently low current level not to endanger the target, the response of the whole interlock chain from sensors to effectors has been demonstrated, see Fig. 5: When slightly misaligning the proton beam, a non-zero current is measured on the jaws of the new collimating slit, arising at time point ‘0.96 s’ (see Fig. 5, bottom) and triggering a beam interrupt which effects a beam interlock after about 30 ms (time point ‘1 s’). Likewise, a beam interrupt triggered by VIMOS was intentionally actuated. By setting appropriate trigger levels these tests selectively demonstrated the correct performance of the novel devices without interfering with any other system or setting.

Similarly to an improper beam density also LBE leaking from the container requires tripping of the proton beam, with a longer response time in the order of one second being sufficient. Two different types of leak detectors have been developed: one employing thermocouples and an ancillary device monitoring the electrical impedance between special electrodes. During the operation of the MEGAPIE target the temperature-based leak detector proved its robustness and showed the expected response to beam-on operation and transients. Its response to a leak had been monitored

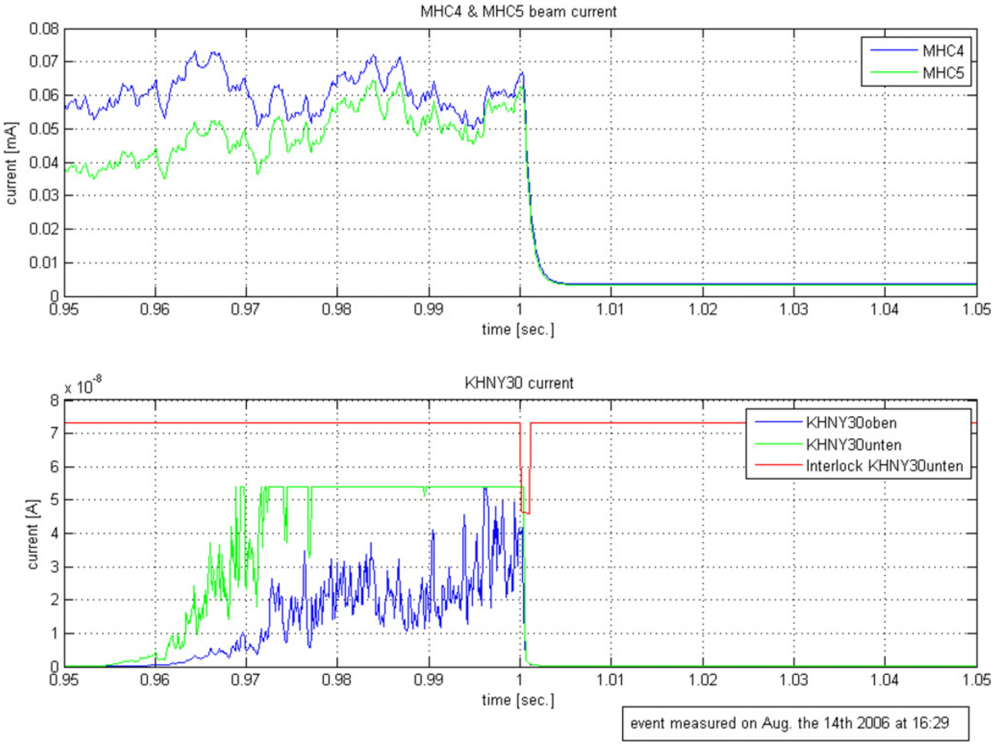

Fig. 5. End-to-end test @ 40 µA, total response time < 40 ms; top: beam current before and after Target E, bottom: current on the jaws of the new collimating slit and trigger signal. The narrowing of the current curves in the top part (starting at time point ~0.96–0.97 s) illustrates the reduced current loss in Target E when misaligning the beam. The simultaneously arising jaw current (bottom) triggers a beam trip effective after ~30 ms.

in an earlier full-scale leak test; in the *real* experiment, fortunately, no leak occurred.

6. MEGAPIE in user operation

Normal user operation with MEGAPIE started on August 21st around 8:30 a.m., and was continued until the normal annual winter shut-down starting on December 21st, 2006. The chart of the first 12 h of proton beam is shown in Fig. 6. Since then SINQ with the MEGAPIE target was operating routinely and reliably. Mid September the goal current of 1350 µA has been reached. The statistics of weekly accumulated proton charge on SINQ is illustrated in Fig. 7, distinguishing charge delivered by the accelerator and charge accepted by SINQ. The ratio of both defines the availability of SINQ which, except for the starting week, was at satisfactory ~95%. The total proton charge accumulated at the end of week 51 was 2.796 µA h.

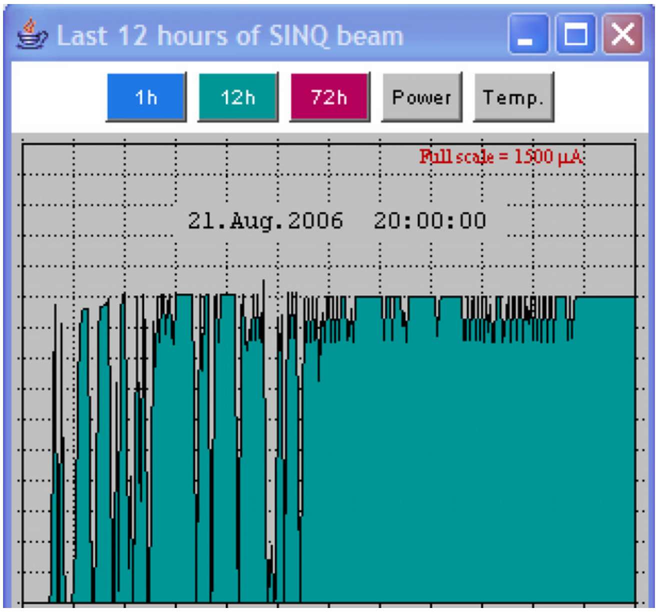

Fig. 6. Chart of the first 12 h of proton beam when normal user operation had started on August 21st.

During the entire MEGAPIE irradiation experiment the target behaviour was found excellent, both during stable operation and during transients due to beam trips or more extended beam interrupts. The temperature distributions and -transients were as expected, very close to predictions. The electromagnetic pumps operated stable and reliably, without any indication of degradation. For the main MEGAPIE ancillary systems directly connected to the target, i.e., heat removal system, cover gas system and insulation gas system, the experience is very positive, as well. All in all, the MEGAPIE systems worked reliably according to specifications, exceeding our rather cautious expectations.

7. Neutronic performance of MEGAPIE

During the start-up phases, several neutronic measurements were performed, i.e., measurements of delayed neutrons in the target head area, Bonner spheres and chopper measurements for spectral resolution at the ICON cold-neutron beam port, fission chamber measurements from inside the target and neutron flux measurements inside the D_2O moderator and at selected instruments and beam ports. The neutron fluxes of MEGAPIE in relation to the previously operated solid lead target were of particular interest. Based on earlier Monte Carlo simulations the liquid metal target was expected to yield a 40% increase in neutron flux (at identical current).

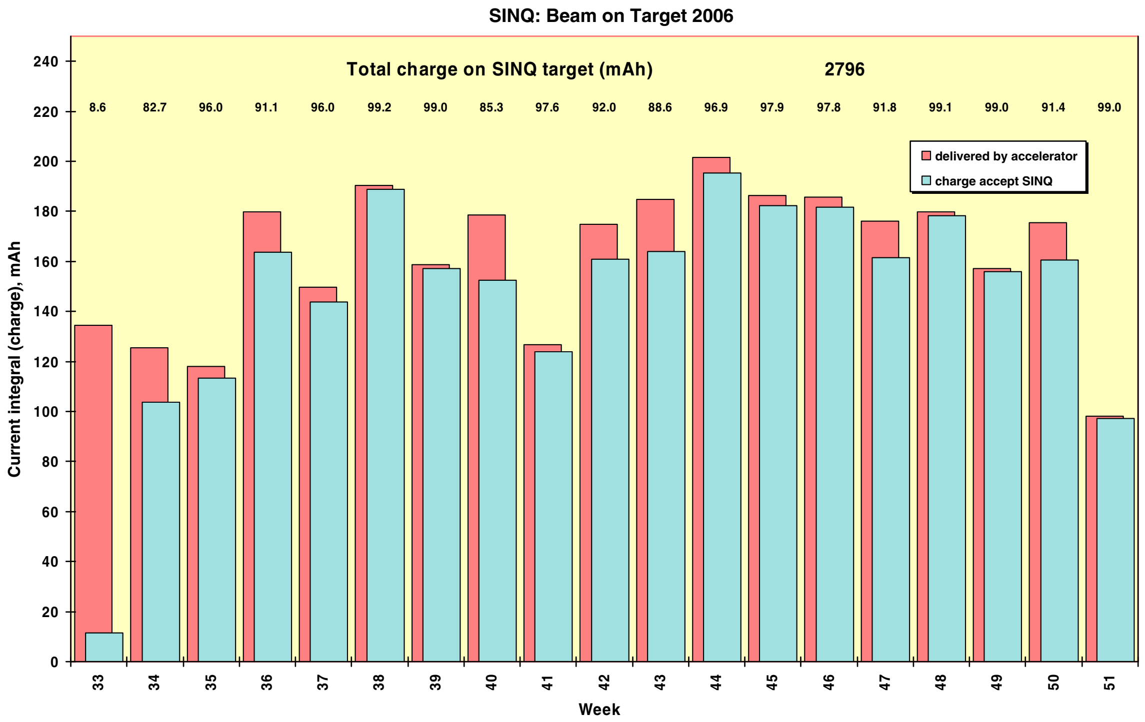

Fig. 7. Statistics of weekly accumulated proton charge on SINQ during MEGAPIE operation. The availability of SINQ, even with the complex MEGAPIE systems and various additional beam interrupt channels, was at the satisfactory level of ~95%.

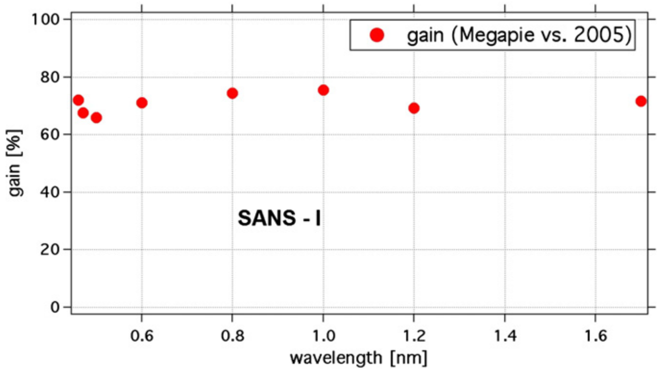

Fig. 8. Neutron flux increase by MEGAPIE in relation to the standard steel–lead cannelloni target, measured during the start-up phase of MEGAPIE at the SANS-1 instrument placed at a cold-neutron guide. Gold foil activation measurements during stable operation at full beam power confirmed flux increases between 80% and 85% at thermal and cold beam ports.

First measurements during the start-up phase at the cold-neutron guide of the SANS-1 instrument quoted a flux increase as high as 70–80% (see Fig. 8). Later, during stable operation at full proton beam power, gold foil activation measurements have confirmed flux increases between 80% and 85% at both, the thermal beam port of the radiography station NEUTRA and the cold beam port of the ICON instrument. Revised calculations with more detailed target and moderator geometry reproduce these results.

8. Summary and conclusion

MEGAPIE, the first liquid metal target driven by a megawatt class proton beam, was successfully operated at the Swiss spallation neutron source SINQ in the second half of the year 2006. The goals of the experiment were fully accomplished: four months of reliable and essentially uninterrupted operation (beam trips and short beam interruptions permitted) at a power level as high as the accelerator was able to deliver (~0.75 MW), excellent performance of the target and the dedicated ancillary systems, the prove of functionality of advanced proton beam safety devices and, last not least, a superb neutronic efficiency delivering about 80% more neutrons for the users compared to our previously operated lead-cannelloni target.

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