The MEGAPIE operation synthesis

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Abstract. The MEGAwatt Pilot Experiment (MEGAPIE) was initiated by six European institutions (PSI, FZK, CEA, SCK-CEN, ENEA, CNRS), JAEA (Japan), DOE (US) and KAERI (Korea) with the objective to demonstrate the safe operation and to fathom the neutronic performance of a liquid metal (lead bismuth eutectic, LBE) target for high power spallation and ADS applications. The MEGAPIE target was operated at the Swiss Spallation Neutron Source SINQ starting mid-August 2006, for a scheduled irradiation period until 21st. December 2006. The continuous (51 MHz) 590 MeV proton beam hitting the target reached routinely an average current of ~1300 microA, corresponding to a beam power ~0.78 MW. The paper summarizes the main features of the target and the ancillary systems, and reports on the operational experiences made with this target during operation. The general performance is highlighted, including new beam and target safety devices, and the functional experience and lessons learned with the ancillary systems.

1. Introduction

The Swiss Spallation Neutron Source SINQ, operating since 1997, is driven by the 590 MeV proton beam from the PSI ring cyclotron with a power in the MW range [1]. The time structure (51 MHz) of the proton beam is lost after hitting the spallation target and releasing neutrons into the moderating systems, making SINQ a steady state (CW) neutron source for the users, with similar characteristics as a research reactor.

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. Having operated with a solid ‘lead-cannelloni’ target for many years, i.e. with an array of lead rods clad in steel tubes, the operation of the liquid metal target of MEGAPIE [2,3] in 2006 opened a widely unexplored field of experiences, new technologies and challenges. The goal of this experiment had various facets: accruing relevant materials data beyond STIP (SINQ Target Irradiation Program) [4] and related programs for a design data base for liquid lead-bismuth eutectic (LBE) targets, exploring the conditions under which such a target system can be licensed, gaining experience in operating the system under realistic beam conditions, and, last not least, exploiting the potential for enhanced neutron yield of a liquid metal target in comparison to the (standard) solid target of SINQ.

Meanwhile the MEGAPIE target has been operated in SINQ from mid August 2006 until December 21st, 2006. Over that period, the routine proton current received by MEGAPIE was at about 1300 µA, corresponding to a beam power of 0.78 MW.

The paper presents in brief the main features of the target and the ancillary systems and summarizes the general performance and the operational experiences, including new beam and target safety devices, the general functionality and lessons learned. For more details on design, operation and system performance we refer to [5].

Main features of the 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 [6]. In its interior it houses about 1 ton of liquid 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 twelve 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. Figure 1 shows two of the major target components, i.e. the 12-pin heat exchanger and the central flow guide tube.

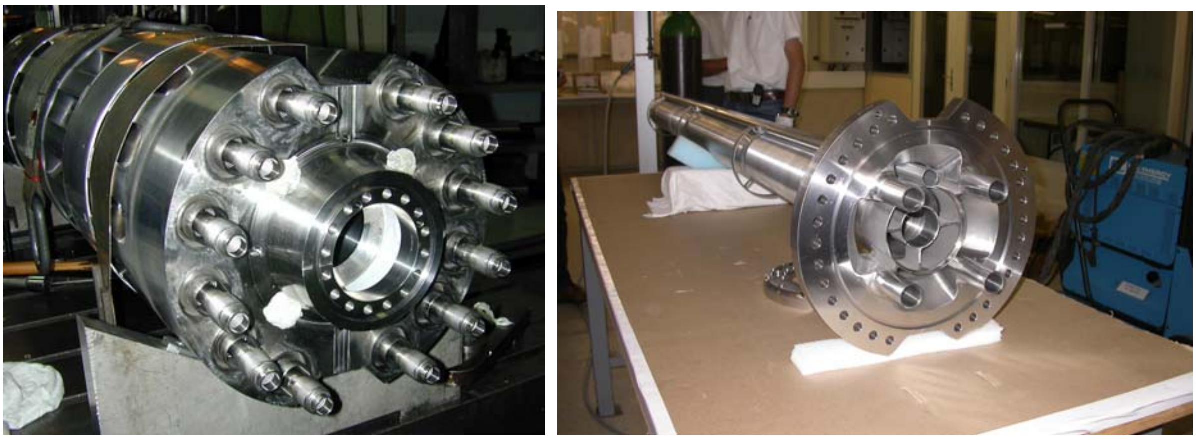

Figure 1: Two major target components prior to integration: the 12-pin heat exchanger (left) and the central flow guide tube.

Operational experience

The first beam on Megapie was received on Aug. 14th, 2006 with a beam current of 40 μA, which corresponds to about 25 kW. 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). Normal user operation with MEGAPIE started on August 21st, and was continued until the normal annual winter shut-down starting on December 21st, 2006. All over this period the availability of SINQ, relating accepted to offered proton beam, was at satisfactory ~95%. The total proton charge accumulated at the end was 2.796 Ah.

During the MEGAPIE irradiation experiment the target experienced 5500 beam trips (<1 min) and 570 interrupts (< 8 h) with the consequence of temperature transients (see Figure 2) and related variable stresses. Even so the behavior was found excellent. The temperature distributions and -transients were as expected, very close to predictions.

Figure 2: Time history of relevant temperatures responding to beam trips from full power

The electromagnetic pumps operated stable and reliably, without any indication of degradation. For the operational experience with the MEGAPIE ancillary systems see the special chapter below. All in all, the MEGAPIE systems worked reliably according to specifications, exceeding our rather cautious expectations.

Ancillary systems – functional experience and lessons learned

The main 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). Figure 3 shows the systems installed in the target head enclosure chamber (TKE), shortly before final commissioning. For the basic functional requirements and the technical layout we refer to [7-11]. The present description mainly focuses on the experience gained during the design and operational phases.

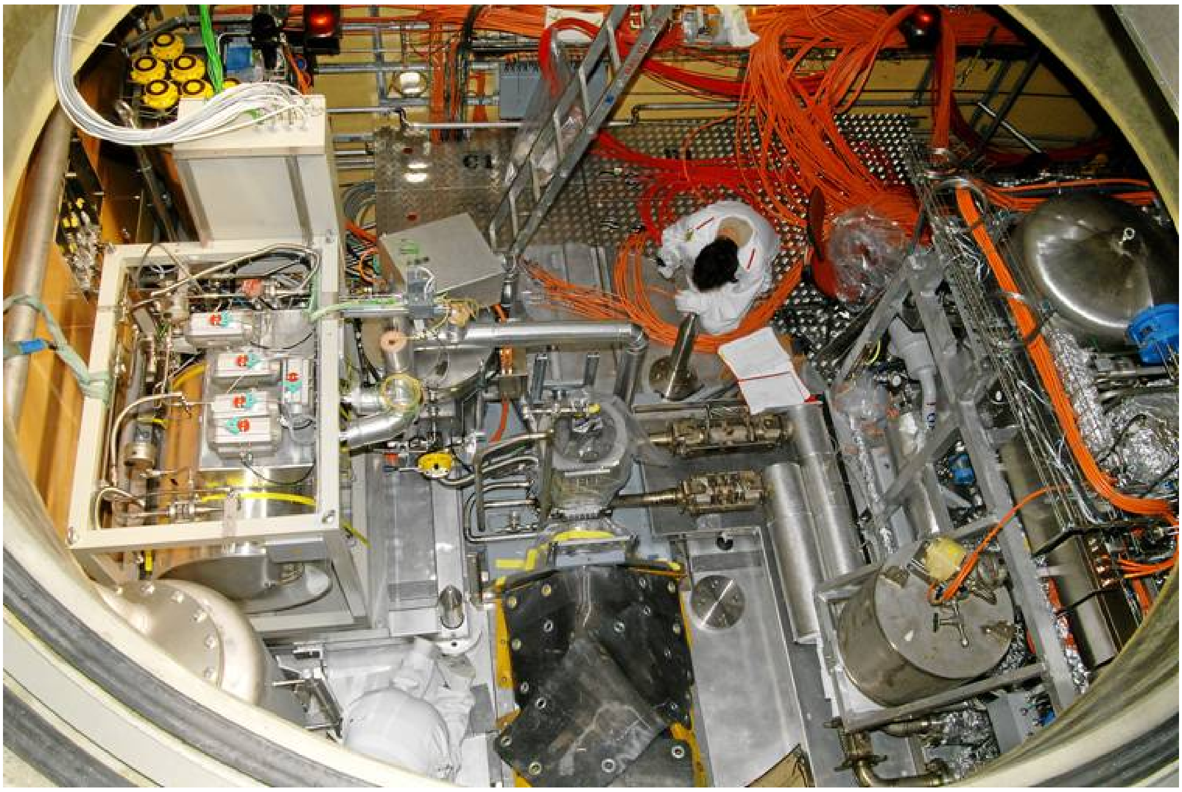

Figure 3: View into the TKE which is on top of the SINQ main shielding block (situation of April 2006). The target head is in the centre, still without the cables connected which are in preparation in the rear, the oil loop of the HRS is at the right, the F&D system at the left, and the CGS in the left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

The *Heat Removal System* HRS [7] consists of two subsystems: an intermediate cooling loop with oil Diphyl THT as cooling medium (ICL), connected to the heat exchanger pins in the target, and second a back-cooling water loop (WCL). The ICL, operating between 160°C and 230°C, is primarily necessary to remove the about 0.6 Megawatt of heat load deposited in the liquid LBE by the proton beam. As a second function it must also be capable to manage a controlled hot-standby operation after beam trips or scheduled beam interruptions to prevent freezing of the target.

The general layout of the system proved to be sound. Oil as cooling medium turned out to be a reasonably good choice. The heat removal capacity of the system was rather over dimensioned. Oil degradation by radiolysis and pyrolysis was found to be much less than anticipated. The main drawback of using oil is the need for fire protection which was achieved by inertization of the atmosphere in the TKE and in the beam transport vault.

The *Cover Gas System* CGS [8] must handle the volatile radioactive and non-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 schematic layout is shown in Figure 4, together with a photo of the shielded decay tank box.

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 He leak tests according to specification a leak from the decay tank into the 2nd containment was detected by the very sensitive detector controlling the circulating gas. Although clearly detectable, the leak was sufficiently small such that the inventory could be released weekly by venting of the 2nd containment through the controlled exhaust system. A further lesson was to care for redundancy (if possible double) of vital sensors in such a delicate system: one pressure transducer inside the enclosure controlling and recording the plenum gas pressure failed, most likely due to radiation damage, although qualified for radiation resistance up to a total Gamma-dose of 1 MGy. Switching to the remaining redundancy solved the problem, but after that no redundancy remained.

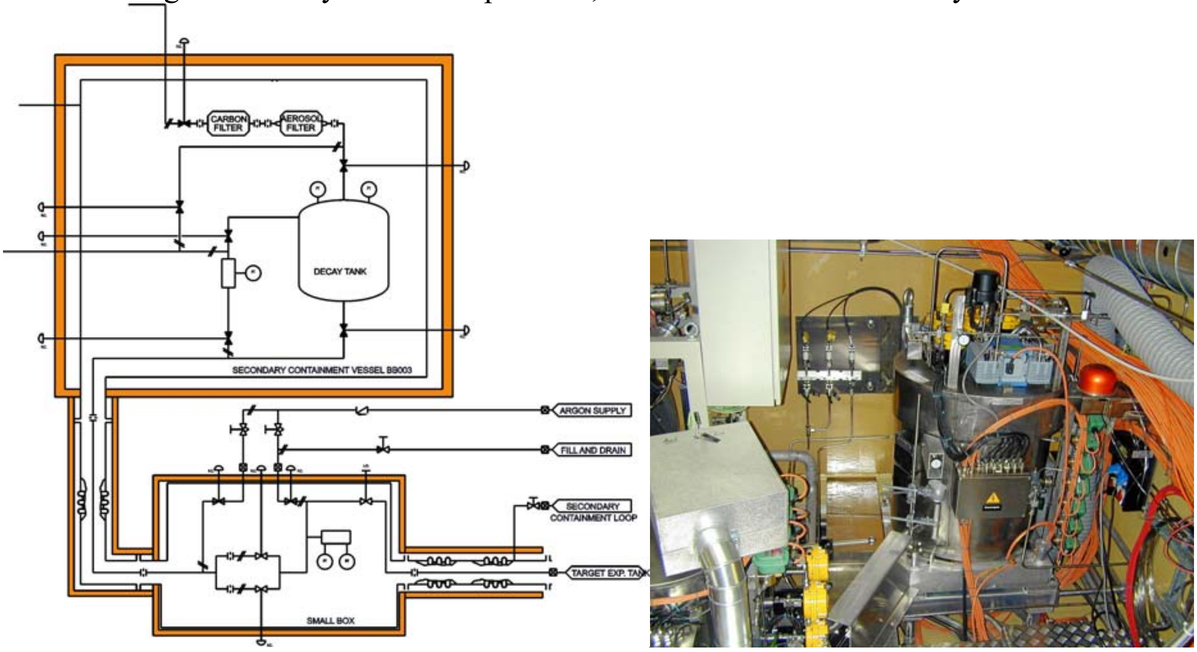

Figure 4: Schematic layout of the CGS, including second containment and shielding (left) and photo of the decay tank box in the TKE (right)

A further critical issue is gas sampling, indispensable to control the inventory before venting. Reliable and quantitative gas sampling is a difficult action and can be a hazardous job which needs special precautions, not at least to prevent or minimize radioactive exposure of the executive personnel. A qualified steel gas mouse with easy-to-handle valve and flange connection is a minimum requirement.

The *Insulating Gas System* IGS [9] fills the volume between the inner hot part of the target and the outer cold hull by an insulating gas. The concept envisaged was filling with He at a pressure of 0.5 bar, benefiting from lower activation on the expense of a higher heat loss compared to filling with Ar. During preheating the empty target it turned out that evacuation was necessary to prevent excessive heat loss. After the target was filled with liquid metal, during refilling the isolation volume with He we experienced that 4 out of 7 electric heaters in the lower central target were damaged, probably caused by electric discharges. The loss of heaters did not hamper or inhibit further operation, but another draining and refilling with liquid metal would not have been possible any more.

One of the accident scenarios which needed to be safely handled was water ingress from a leaking safety hull into the insulating gas volume with the consequence of steam production and possible pressure built-up. This was accomplished by installing a 40 mm exhaust pipe combined with a rupture disk and a steam condenser vessel outside the insulation volume.

Designed as closed volume the pressure in the IGS was expected to remain constant during target operation, only reacting to temperature variations. Instead, starting with the first beam a continuous gas pressure increase of about 5 mbar/h was observed. Thorough analysis gave evidence that most likely oil from the HRS was leaking into the IGS volume and decomposed by radiolysis during beam operation. The gas produced further contained small amounts of (radioactive) cover gas, entering through a second (small) leak. The gas production urged a weekly venting of the IGS. The measures taken to cope with this problem were the installation of a 180 l decay vessel in the cooling plant and regular (weekly) venting into the exhaust system after a sufficient decay period and gas sampling. The lessons learned: do not rely on closed volumes, expect radioactivity everywhere and provide devices to handle that.

The initial baseline for the *Fill and Drain System* F&D required draining of activated LBE from the target after the operation period. A detailed design for that was elaborated; however, the draining option was recognized to bear considerable risks, immediate ones for accessing the TKE and more general ones related to licensing. As well, it had required considerable extra expenditure in the technical realization: the active draining option would have imposed the need of radiation shielding, second containment, radiation-hard components and remote operation, similar to the CGS.

Viewing these difficulties the decision was taken to abandon the initial concept in favour of only inactive draining and final freezing of the LBE in the target after completion of the irradiation experiment [10,11]. The inherent final freezing imposes mechanical stressing of the hull and window material due to the well-known volume expansion of solidified LBE. Hence, post-irradiation alterations of the materials properties are not completely excluded. This drawback is handled by controlled slow freezing of the LBE in the lower target volume.

The finally realized concept is sound; the system is reasonably safe and easy to operate. The experience during commissioning recommends providing sufficient trace heaters and place controlling thermocouples at the coldest points to prevent clogging. The missing oxygen control did not impose a problem.

New safety devices: beam monitoring and LBE leak detection

Systems which make sure that no liquid metal can leak out of the target are of utmost importance for the safety of the MEGAPIE experiment. In the case of breaking the integrity of the lower target enclosure in the SINQ, LBE would spill into the beam line and cause a major accident. While the impact to the environment could be kept within acceptable limits, the situation for the PSI SINQ installations would be very serious.

For safe target operation a sufficiently broad footprint of the incident proton beam on the SINQ target is mandatory. With a focussed beam 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) with the fatal consequences cited above. 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 [12]. The latter monitors the correct glowing of a tungsten mesh closely in front of the liquid metal target. Figure 5 shows a Photo of this device taken before installation. All these systems have to meet the basic requirement to switch off the beam within 100 ms when they respond to off-normal situations.

Similarly to an improper beam density also LBE leaking from the container requires tripping of the proton beam. Two different types of leak detectors have been developed: one employing thermocouples and an ancillary device monitoring the electrical impedance between special electrodes. The assembly at the lower end of the liquid metal container is shown in Figure 6. 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 in an earlier full-scale leak test; in the *real* experiment, fortunately, no leak occurred.

Figure 5: VIMOS head with a Tungsten wire mesh to be installed close in front of the target entrance window

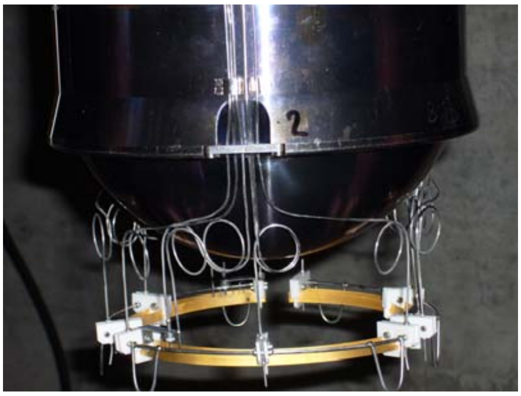

Figure 6: MEGAPIE leak detector mounted at the beam entrance calotte of the liquid metal container

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 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. Stimulated by these early measurements, a new campaign of simulations started to calculate the neutron fluxes at the actual positions were the measurements were performed. The main results are given in Table 1. Results for the solid target Mark IV are also included in the table. The data show that: *i*) the agreement between absolute flux values is rather good for most of the measurements. This indicates that the fluxes with the MEGAPIE target model are correctly calculated; and *ii*) the measured increase of the flux performance is of a factor 1.78-1.85, which is somewhat higher than the predictions. The difference is mostly understood in light of the newer calculations of the *solid* target, which include the STIP samples and the fact that the lead occupies only 90% of the volume inside a rod.

Complementary to the external flux measurements, the inner neutron flux was measured and monitored during the whole target irradiation by an array of miniaturized fission chambers placed in the central rod right above the spallation zone. First results are reported in [5].

Table 1: Calculations and measurements for relevant thermal neutron flux (n/cm2/s/mA) in the beam lines at the exit from the SINQ target shielding block (about 6 m from the centre of the target) and at the NAA station (at about 80 cm from the center of the target) with the MEGAPIE target (2006) and SINQ target 6 (2005). Calculated values are the integral between 0 and 1 eV. Systematic uncertainties on the experimental fluxes are of the order of 10%. Uncertainties on the experimental data are of about 8%.

	SINQ target 6 (2005)		MEGAPIE (2006)		RATIO	
	EXP	CALC (E<1eV)	EXP	CALC(E<1eV)	EXP	CALC (E<1eV)
NEUTRA (30)	$2.55\ 10^{7}$	$2.43\ 10^{7}$ (3%)	$4.80\ 10^{7}$	$3.81\ 10^{7}$ (2%)	1.85	1.57
ICON (50)	$4.27\ 10^{8}$	$4.77\ 10^{8}$ (1%)	$7.73\ 10^{8}$	$8.0\ 10^{8}$ (2%)	1.81	1.68
NAA	$5.06\ 10^{12}$	$6.43\ 10^{12}$ (2%)	$9.01\ 10^{12}$	$1.14\ 10^{13}$ (2%)	1.78	1.77

10. Summary and Conclusion

The very challenging milestone to operate a representative, high power heavy liquid metal spallation target on the road towards a possible ADS development has been effectively achieved. Indeed, the MEGAPIE target, which is of significant power, has been operated successfully from August 2006 to December 2006 in the SINQ facility at PSI, producing innovative know-how and expertise on the different components and materials of a heavy liquid metal spallation target.

The results achieved so far within the MEGAPIE project clearly indicate that a step forward has been made in the neutronics and thermal-hydraulics code validation for HLM systems. Moreover, an increased confidence has been gained in the procedures needed to assess structural material performances, in the area of component (e.g. pump systems) testing and on the crucial issue of the beam window coolability.

For instance, the analysis of the neutronics data gathered during the irradiation of MEGAPIE confirmed the expected increase in neutron flux obtained with the MEGAPIE target with respect to the performance of previous solid targets irradiated in SINQ.

Moreover, the integration of the target and of the ancillary systems, the execution of the integral test, the first operation and the irradiation, allowed getting confidence with the start-up and routine operation of this innovative system.

As next steps of the MEGAPIE project, after the dismantling of the target, an extensive PIE is foreseen to complete the evaluation on the components and materials performance under irradiation completing the assessment of a first-of-a-kind high power liquid metal spallation target.

Acknowledgement

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