STATUS OF THE MEGAPIE PROJECT

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Abstract

The MEGAPIE project was started to design, build and operate a liquid metal spallation neutron target as a key experiment on the road to an experimental accelerator-driven system and to improve the neutron flux at the PSI spallation source. The design of the target system has now been completed and manufacturing has started. The target is designed for a beam power of 1 MW and 6 Ah of accumulated current. It will contain about 88 l of LBE serving as target material and primary heat removal fluid. The heat will be removed by forced convection using an in-line electromagnetic pump with a 4 l/sec capacity. The heat will be evacuated from the target through 12 mono-wall cooling pins via an intermediate oil and a water cooling loop. The beam window made of the martensitic steel T91 will be cooled by a jet of cold LBE extracted at the heat exchanger exit by a second EM pump from the LBE main stream.

A preliminary safety analysis has been performed considering normal, off-normal and accident conditions and a corresponding report has been submitted to authorities for licensing. The experience gained up to now shows that MEGAPIE may well be the first liquid metal target to be irradiated under high-power beam conditions.

Introduction

Based on an initiative of PSI, CEA and FZK, the MEGAPIE project was officially started in 2000 to design, build and operate a liquid metal spallation neutron target of 1-MW beam power as a key experiment on the road to an experimental accelerator-driven system [1]. The project is supported by an international group of nine research institutions (Figure 1) and is partially funded by the European Union within the Fifth Framework Programme.

Figure 1. The MEGAPIE partners

Objective of the project

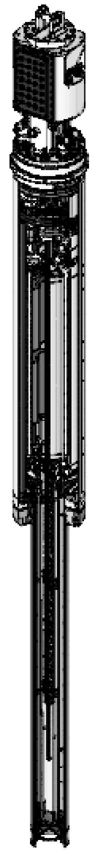
MEGAPIE is an experiment to be carried out in the SINQ target location at the Paul Scherrer Institute and aims at demonstrating the safe operation of a liquid metal spallation target at a beam power in the region of 1 MW. It will be equipped to provide the largest possible amount of scientific and technical information without jeopardising its safe operation. The minimum design service life will be 1 year (6 000 mAh).

Whereas the interest of the partner institutes is driven by the development needs of ADS, PSI is interested in the potential use of a LM target as a SINQ standard target providing a higher neutron flux than the current solid targets. Calculations of the undisturbed thermal neutron flux for the LBE target in comparison to the former zircaloy and current steel-clad solid lead target yield a gain of about 40% at the beam tube entrance positions (25 cm) [2].

Target system and performance

A sketch of the target and its main properties are shown in Figure 2. It is designed to accept a proton current of 1.74 mA, although the probable current in 2005 may not exceed 1.4 mA. The 65-kW thermal energy deposited in the LBE in the bottom part of the target is removed by forced circulation by the main in-line electromagnetic pump through a 12-pin heat exchanger (THX). The heat is evacuated from the THX via an intermediate diathermic oil and an intermediate water cooling loop to the PSI cooling system. The cooled LBE then flows down in the outer annulus. The beam entrance window is especially cooled by a cold LBE jet extracted at the THX outlet and pumped by a second EM pump through a small diameter pipe down to the beam window. The mass transport and temperature distribution is shown in Figure 3. The thermal-hydraulic system behaviour has been modelled with the RELAP5 code for normal and transient operations (beam trips and interrupts). The operating conditions were chosen in such a way to keep the LBE temperatures below 400°C and the maximum flow velocities

Figure 2. Model of the MEGAPIE target and its main characteristics



Dimensions

Length:	5.35 m	Weight:	1.5 t
LBE volume:	88 l	Gas volume:	2 l
Design pressure:	16/10 bar	Operating pressure:	0-3.2 bar
Design temperature:	400°C	Insulation gas:	0.5 bar He

Materials

Lower liquid metal container:	T91
Upper container	316L
Lower target enclosure:	AlMg3

Heat removal and beam window cooling

Deposited heat: 650 kW

Forced convection assisted by buoyancy

Main pump: EM in-line pump (4 l/sec)

Bypass pump: EM in-line pump (0.35 l/sec)

Liquid metal container

Upper container (316L, body of THX)

Lower container with beam entrance window (T91)

LBE flow control

Main flow and bypass flow guide tubes

EMPS with in-line main pump and bypass pump

Target heat exchanger

Temperature control

Central rod with 20 kW heater

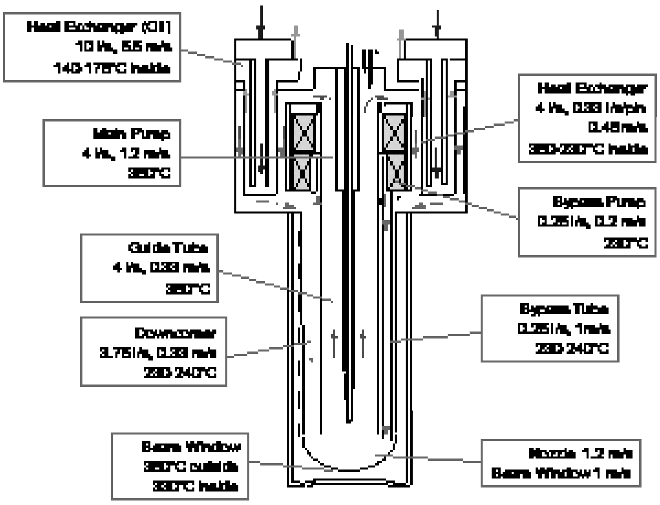
Outer enclosure (2nd barrier)

Target head

Upper target enclosure

Lower target enclosure with beam entrance window (AlMg3)

Figure 3. Mass transfer and temperature distribution in the target at normal operation



at about 1 m/s. Under these conditions, the corrosion rates in T91 and 316L steel remain low (<0.1 mm/year). This may, however, not be true for the beam entrance window, where interaction with the beam occurs. Specific investigations are therefore undertaken within the design support group to clarify this (LISOR and STIP) as well as the materials' susceptibility to liquid metal embrittlement [3-5].

The target itself is composed of nine subcomponents, which are manufactured separately and then assembled:

- Central rod inserted in the upward LBE flowpath carrying a 22-kW heater and a set of neutron detectors.

- Main flow guide tube separating the hot LBE upflow from the cold downflow in the outer annulus. The heat transfer across the tube wall raises the temperature of the downflowing LBE from 230 to 250°C. The guide tube is equipped with a number of thermocouples to monitor the temperature field in the spallation zone.

- Attached to the top of the tube is the electromagnetic pump system, consisting of the concentrically arranged bypass pump and the in-line main pump on top of it. Both pumps are equipped with electromagnetic, three-coil flow meters respectively. The Institute of Physics (IPUL) in Latvia designed the pumps and has built and tested a prototype of the main pump to demonstrate its proper functioning. While the pump performed according to predictions [6,7], the flow meter did not achieve the accuracy specified and failed during the test. Figure 4 shows a sketch of the pump system and the performance characteristics of the prototype pump.

- The pump system is surrounded by the target heat exchanger (THX), consisting of 12 pins concentrically arranged and 120 cm long. The pins' performance has been experimentally investigated [8] and numerically assessed [9]. Using the diathermic oil Diphyl THT as a cooling medium, it was necessary to implement a spiral in the oil path to increase the contact length. The main problem in the design of the THX was to comply with the complex thermal conditions and to limit the resulting thermo-mechanical stresses. This was accomplished by attaching the pins to the inlet and outlet oil distribution boxes by flexible bellows and inserting thin shrouds as heat shields. The heat is removed from the THX by an intermediate oil loop designed by Ansaldo. An intermediate water cooling loop designed and built by PSI then evacuates the heat from the oil loop. Using this concept, any interaction of LBE with cooling water is eliminated. The pressure in the oil loop is always kept higher than that of the water loop and that in the target. The oil is not significantly affected by interaction with LBE, except for the normal thermal and radioactive decomposition. The loops are also designed to serve during the target testing, which requires special operating conditions (see below). Table 1 provides the characteristic loop parameters. The heat exchanger also forms the upper enclosure of the LBE and the gas expansion tank. The lower enclosure of LBE is formed by the lower liquid metal container.

- The lower liquid metal container is made of the martensitic steel T91. The beam entrance window is hemispherical with a wall thickness tapered from 1.5 mm in the centre to 2 mm at the outer rim. The window is made of a forging and is EB-welded to the tube, which is 2 mm thick in the spallation zone and 4 mm in the upper part. Special attention is paid to the proper control of the temperatures and stresses in the beam window caused by the energy deposited by the proton beam. The current design relies entirely on CFD modelling and FEM calculations. Table 2 shows the amount of energy deposited in the different target components by a 1.74-mA current calculated with the CFX4 and FLUKA codes. The agreement is satisfactory. Different designs of beam window cooling have been investigated, finally leading to the reference design of a bypass jet flow along the long axis of the beam footprint and a 30° slanted guide tube. Figure 5 shows the reference design and the corresponding flow and temperature fields in the LBE as calculated by CFX-4. The design provides sufficiently low temperatures in all the components with respect to corrosion and thermal stresses as shown in Table 3.

Figure 4. Sketch of EMP system and prototype main pump characteristics

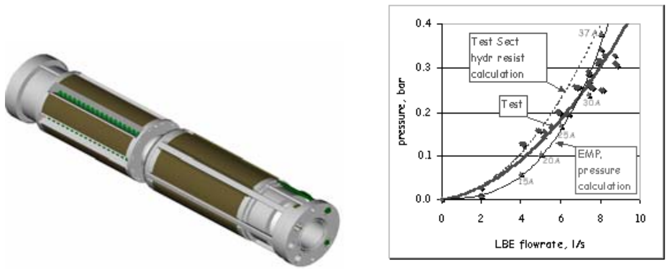


Table 1. Main parameters of the heat removal system

	LBE THX	Oil IHX	H_2O IHX
Inlet temp. [°C]	330	165	40
Outlet temp. [°C]	230	130	59
Oil loop			
Flow rate [kg/s]	9.28	Speed [m/s]	3.5
Pump head [m]	12	P drop [kPa]	626

Table 2. Energy deposited in the target components at 1.74-mA beam current

Material	FLUKA [kW]	CFX-4.3 [kW]
LBE	705.8	709.9
Window T91	5.56	5.28
T91 hull	2.68	1.21
Guide tube	5.55	6.03
Total	719.6	722.4

Figure 5. Temperature distribution in LBE in the spallation zone [11]

Table 3. Temperature in target components of the reference design as a function of beam current and bypass jet flow direction (parallel or perpendicular major axis of beam footprint)

Beam [mA]	Maj. axis	Peak temperature [°C]			
		LBE	Guide tube	C. rod	Window
1.74	= Bypass	422.7	368.2	386.6	370.2
	⊥ Bypass	424.1	363.1	389.5	360.3
1.4	= Bypass	384.4	339.4	355.7	342.5

Corresponding stress calculations using the above data as input yielded acceptable thermal and overall stresses in the beam window and the guide tube. For the optimum configuration, the maximum stresses in the beam window and the guide tube amount to 55 and 63 MPa, respectively, as shown in Table 4.

Table 4. Maximum temperatures and Mises stresses in the guide tube and beam window as a function of beam orientation to bypass jet flow for the reference design

Beam orient.	LBE weight	Peak temperature [°C]			
		Guide tube	Window	Guide tube	Window
0°	No	367	370	386.6	370.2
0°	Yes	367	370	389.5	360.3
90º	No	362	359	355.7	342.5

The lower liquid metal container, the flange of the guide tube and the heat exchanger constitute the boundary for the LBE, called the hot part. The second boundary is formed by three components, which are separated from the inner part by a gas space filled with either 0.5 bar He or Ar. The gas will stay enclosed during the experiment and only the pressure will be monitored. The components are the:

- Lower target enclosure, a double-walled, D_2O-cooled hull made of AlMg3. The containments of the current targets are made of the same material and experience on its radiation performance exists up to about 10 dpa. The enclosure is designed to contain the LBE in the case of a number of hypothetical accidents, which would lead to the breach of the inner container. Its proper functioning has been assessed by FEM calculations [12]. The enclosure is flanged to the upper target enclosure, formed by a stainless steel tube. This tube is welded to the target head.

- Target head, consisting of the main flange, which positions the target on the support flange of the central tube of the SINQ facility, and the crane hook. All supplies to the target and instrumentation lines are fed through the target head.

- Target top shielding, which connects the hot part to the target head. The LBE-containing part of the target is thus suspended from the target head and allowed to expand with the temperature. The component also contains tungsten to shield the target head area from the intense radiation of the LBE and the noble gases and volatiles collected in the gas expansion tank.

Ancillary systems

While the target is designed by CNRS-SUBATECH, the ancillary systems are designed and provided by PSI, ENEA and Ansaldo. The main components are the:

- Heat removal system already described above.

- Gas handling system for the cover and insulation gas. Although small in quantity (about 8 litres), the gases produced by the spallation process represent a high radioactive source term that must be properly handled to cope with the release limitations imposed under normal and accident conditions. The gases are collected in the target expansion tank and periodically evacuated via filters into a decay tank. The radioactive inventory accumulated in the target is so high that additional filters (active carbon) in the beam transport compartment and the TKE are required to retain all gases (except the noble gases) in case of a severe accident.

- LBE fill and drain (F&D) system. Draining of the active LBE had originally been envisaged and a corresponding engineering concept had been worked out. The installation of the complex and expensive equipment in the TKE (heavily shielded container permanently installed) turned out to be difficult and the operation was judged very risky with respect to radiation protection. Due to a better understanding of the LBE freezing process, it seems feasible to sufficiently control the LBE expansion (roughly 1.5% in the solid state with time) to avoid damage to the structural materials, which would jeopardise PIE. Freezing of the LBE in the target at the end of the experiment was therefore chosen as reference design and a F&D system to handle only un-irradiated LBE is now worked out. Its main purpose is to condition the LBE before filling, fill and drain the target during testing and fill the target in the TKE. The LBE expansion process has been modelled by FEM, showing that the stresses on the containers can be limited, if the LBE is solidified in a special procedure, which allows the LBE to creep [14].

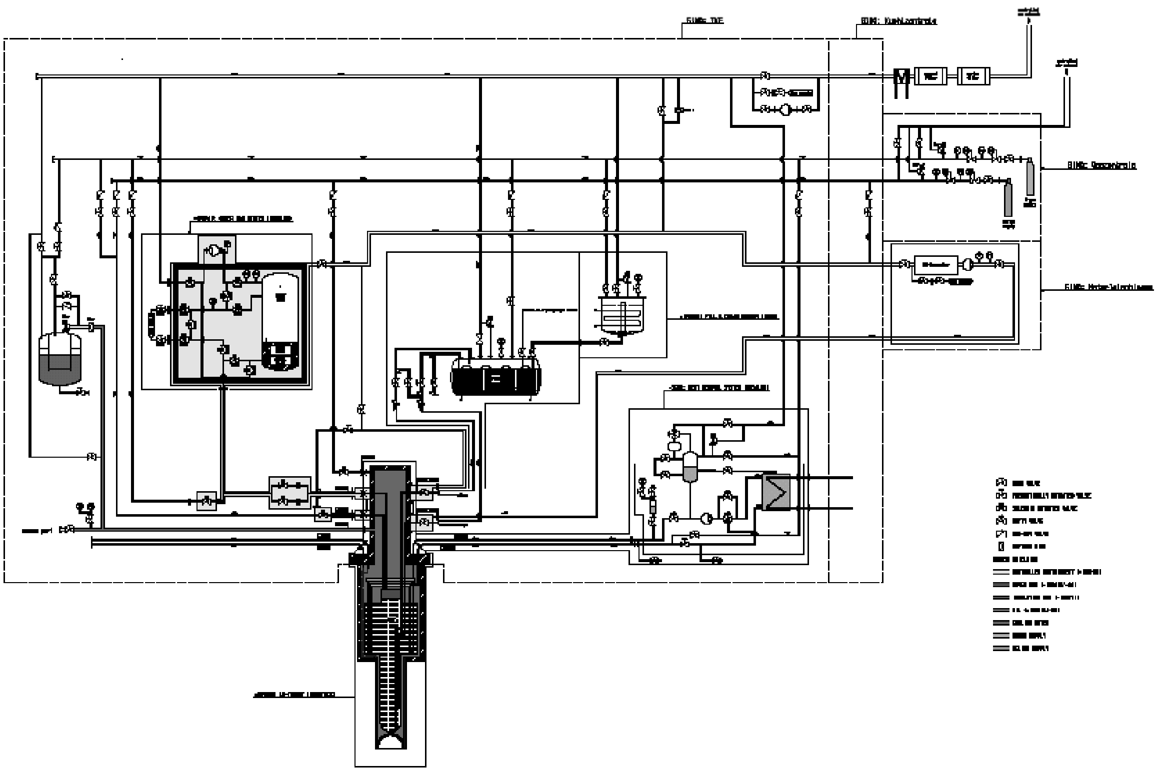
- Beamline adaptations including advanced beam monitoring.

- Handling devices for the target decommissioning, storage, dismantling and disposal.

- Control system with the adaptation of the SINQ infrastructure.

Figure 6 shows the layout of the main ancillary systems. All connections to the target have to pass by the target head. Components handling radioactive products under normal operation are placed in a second containment filled with He at a pressure below ambient. Activity is continuously monitored.

Figure 6. Layout of the ancillary systems with, from left to right: insulation gas system, cover gas system with double containment, fill & drain system and heat removal system



Manufacturing and quality assurance

The target system has been designed and is now manufactured at different sites in Europe. The assurance of the appropriate quality is therefore a key issue. The following modules are currently employed to assure proper quality:

- *Design validation*. Verification of the design and compliance with accepted standards by an independent, second member or group of the project team.

- *Manufacturing quality*. Establishment of a quality plan by the manufacturer, approval by the project QM, surveillance of the tests and assessment of the results by the manufacturer, the project quality manager or a certified body according to the Q-plan.

- *Materials*. Application of referenced materials with Q-certificate.

Safety analysis and licensing process

The safety concept is based on the defence-in-depth approach to contain the LBE, using four barriers for the liquid metal and three barriers for the gas phase. Accident scenarios have been established, analysed and countermeasures have been elaborated considering:

- Internal forces, such as beam focusing, LBE leak, LMC fracture, D_2O leak, gas leak.

- External forces, such as earthquake and airplane crash.

The safety concept must take the operability of the SINQ into account. In this case, we rely on the two inner barriers being part of the target system. The safety concept cannot rely on the integrity of the first barrier alone. The knowledge concerning the interaction of irradiation, LBE and mechanical loads with the structural materials is not sufficiently established (it is one of the goals of the experiment). The possible failure of the first barrier is detected by different sensors, which will trigger the stop of the beam and the transition of the target into a safe condition. The key element for LBE leaks is a sensor placed in the bottom of the target. A leak in the gas phase will be detected by monitoring the radioactivity in the He gas of the second containment. A breach of the first barrier and containment within the second barrier will cause no contamination of the SINQ environment. The target can be extracted and replaced without severe delay.

The two barriers may be breached due to malfunctioning of the proton beam. The target is hit by a fully or partially focused beam, if the target E fails or is bypassed. The peak current density is increased by more than 20-fold. Calculations show that the LMC beam entrance window can only withstand for less than a second [15]. Although the AlMg3 LTE itself supports the high local energy deposition, it will fail soon afterwards when contacted by LBE, if the beam is not switched off. Although devices exist to detect malfunctioning of the beam, two new monitoring devices are under development, given the high risk of such an incident. The beam slit is intended to block those protons bypassing the target E. These protons deviate from the normal path due to their slightly higher energy. The VIMOS device monitors the temperature distribution of the beam footprint on a tungsten grid just ahead of the target. Both devices were installed during the shutdown 2004 and shall prove their functionality before installation of the MEGAPIE target. The perforation of both beam entrance windows will send the LBE down the beam line. The LBE will be collected in a specially designed catcher, but the beam line will be heavily contaminated. The beam line will, however, withstand the pressure increase caused by the LBE/D_2O

interaction as shown in simulations with the MATTINA code [16]. Extraction of the target will require special measures and the operation of the SINQ is interrupted for several years. The reliable detection of beam malfunctioning is therefore a key requirement.

The protection of the public is a major concern. Source term and spreading calculations [15] show that the activity is sufficient to exceed the dose limit imposed by law. It is set at 1 mSv for the public. It had been reduced to this value from 100 mSv with the decision to release PSI from the emergency organisation. Whereas the target is designed to withstand a safety earthquake (probability of 10^{-4}/year) it must be assumed that the target and the beam line will fail during severest accidents. The inventory of the target will spread out in the beam transport channel compartment and the volatile components will be released. Calculations showed that the iodine isotopes, in particular ^{125}I, make the highest contribution to the dose outside PSI, which may reach 230 mSv. Upgrading of the ventilation system with earthquake resistant carbon filters and retention of the iodine brings the dose down to 66 μSv, which is acceptable. A similar upgrading is required for the target head compartment.

Licensing of the experiment by the authorities requires clearance for the following steps before the start of irradiation:

- Operation of the heat removal system.
- Operation of the gas system.
- Inactive operation of the target system.
- Dismantling, transport and waste disposal.
- Active operation of the target system.

Conclusions

The manufacturing of the target has started. Some details, like detectors, still have to be elaborated and the final design has to be validated. The progress on the ancillary systems is according to plan. PSI has managed to complete the installations in the beam line and the piping and cabling during the shutdown 2004. Assessment of the beam monitoring devices is now underway. The start of irradiation in May 2006 is still within reach.

Acknowledgements

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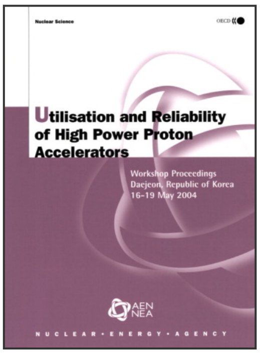
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