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The MEGAPIE 1 MW target in support to ADS development: status of R&D and design

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Abstract

The MEGAPIE project is aimed at designing, building and operating 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 been completed. The target configuration and the operating conditions have been defined and the expected performance assessed. A preliminary safety analysis has been performed considering normal, off-normal and accident conditions and a corresponding report has been submitted to the 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.

1. Introduction

Partitioning and transmutation (P&T) techniques could contribute to reduce the radioactive inventory of nuclear waste and its associated radiotoxicity. Sub-critical accelerator driven systems (ADS), which have as main components a proton accelerator, a spallation target and a sub-critical core, are potential candidates as dedicated transmutation systems. A particular favourable characteristic of ADS, i.e., sub-criticality, allows a maximum transmutation rate while operating in principle in a safe manner [1]. Following a first phase of R&D focused on the understanding of the basic principles of ADS, programs in Europe have been streamlined and focused on practical demonstration key issues. These demonstrations cover high intensity proton accelerators (beam current in the range 1–20 mA), spallation targets of high power (~1 MW, like MEGAPIE) and their effective coupling with a sub-critical core. The MEGAPIE (MEGAwatt Pilot Experiment) initiative was launched 1999 by CEA, PSI and FZK in order to design, build and operate a 1 MW liquid lead–bismuth eutectic (LBE) spallation target [2]. Presently,

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SCK-CEN, CNRS, ENEA, JAERI, KAERI and DOE are members of the project. Additionally, the EC jointed the initiative via the MEGAPIE-TEST project.

The present paper summarises the status of the MEGAPIE project by giving an overview on the target system and performance, on the ancillary systems and on the safety analysis and licensing process. Moreover, an important topic for the design of the target is the selection and characterisation of the structural materials, which is one of the main topic of this workshop. Particularly, the most susceptible part of the target is represented by the beam entrance window, which will be exposed to the proton irradiation and to the flowing liquid metal. Presently, the material selected for the beam window is the ferritic/martensitic steel T91 and a chapter of this work has been dedicated to the discussion of the state-of-the-art on the behaviour of this steel in presence of flowing liquid metal and irradiation.

2. Target system and performance

A sketch of the target and its main properties are shown in Fig. 1. It is designed to accept a proton current of 1.74 mA. The thermal energy (650 kW) deposited in the LBE in the bottom part of the target is removed by forced upward circulation by the main inline 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 Fig. 2. 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 to keep the LBE temperatures below 400 °C and the maximum flow speeds at about 1 m/s.

The target itself is conceived in nine sub-components, which are manufactured separately and finally assembled:

- Central rod inserted in the upward LBE flow path carrying a 20 kW heater and neutron flux meters
- Main flow guide tube separating the hot LBE up-flow from the cold down-flow in the outer annulus. The guide tube is equipped with a number of thermo-couples to monitor the temperature field above the spallation zone. Attached to the top of the tube is the
- Electromagnetic pump system, designed by the Institute of Physics (IPUL) in Latvia, which consists of a concentrically arranged bypass pump and an in-line main pump. Both pumps are equipped with electromagnetic, three-coil flow meters, respectively. A prototype of the main pump has been designed, built and tested to demonstrate its proper functioning [3,4]. In Fig. 3 a sketch of the pump system and its performance characteristics are reported. The pump system is surrounded by the

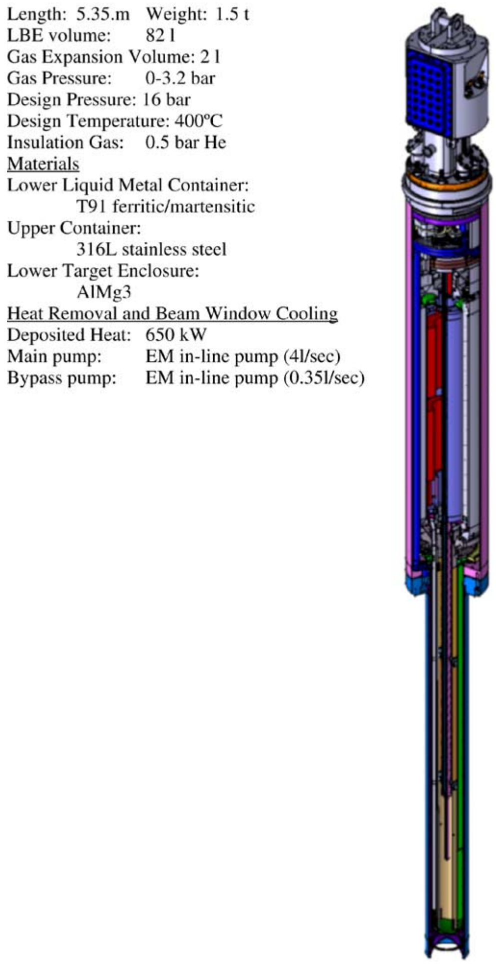

Fig. 1. Model of the MEGAPIE target and its main characteristics target and main parameters.

- Target heat exchanger (THX) consisting of 12 pins concentrically arranged. The performance of the pins has been experimentally investigated [5] and numerically assessed [6]. 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 has been 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. By this concept, any interaction of

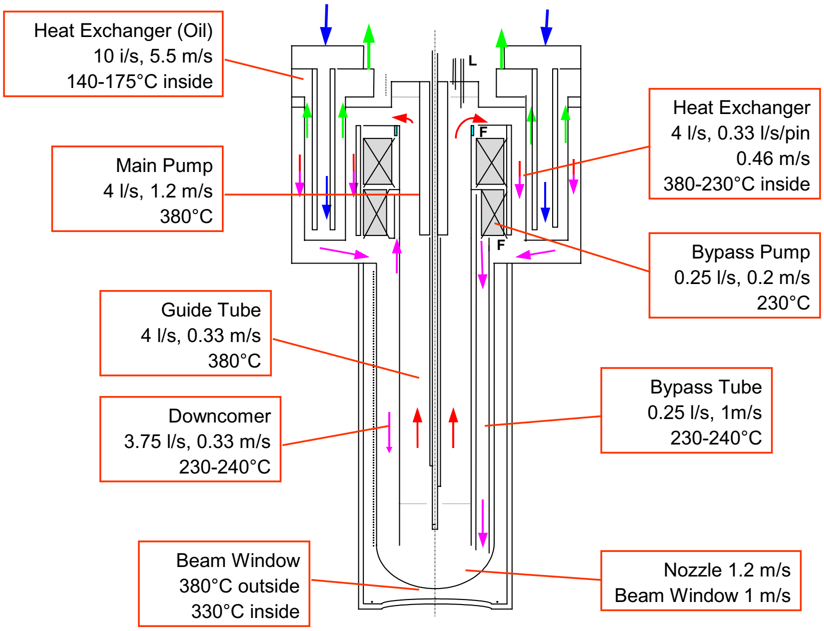

Fig. 2. Flow and temperature distribution at normal operation.

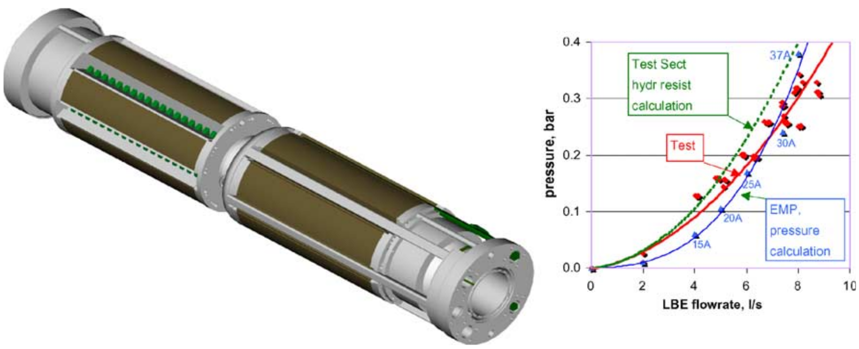

Fig. 3. Model of the EMP system and performance characteristics of the prototype.

LBE with cooling water is eliminated. The heat exchanger forms also the upper enclosure of the LBE and the gas expansion tank. The lower enclosure of LBE is formed by the

- Lower liquid metal container (LMC), which 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 EB welded to the tube, which is 2 mm thick in the spallation zone and 4 mm in the upper part. The energy deposited in the beam window by a 1.74 mA beam current calculated with CFX4 and the FLUKA codes is of the order of 5 kW (see Table 1). CFD modelling and FEM calculations were used to design the beam window cooling system, by considering specially the proper control of the temperatures and stresses in the material. Different designs of cooling systems 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. The temperatures calculated for the target

Table 1
Energies deposited in target components at 1.74 mA

Material	FLUKA (kW)	CFX-4.3 (kW)
LBE	705.8	709.9
Window	5.56	5.28
T91 Hull	2.68	1.21
Guide tube	5.55	6.03
Total	719.6	722.4

Table 2
Temperature in target components of reference design

Beam	Maj. axis	T_{peak} (C)			
		LBE	Guide tube	Central rod	Window
1.74 mA	= Bypass	422.7	368.2	386.8	370.2
	⊥ Bypass	424.1	363.1	389.5	360.3
1.4 mA	= Bypass	384.4	339.4	355.7	342.5

window, the central rod and the guide tube for this configuration are given in Table 2. Corresponding stress calculations using the above data as input yielded a maximum stress in the beam window and the guide tube of 55 and 63 MPa, respectively. An experimental validation of the cooling system is under preparation and will be performed in the near future [7].

The lower liquid metal container, the flange of the guide tube, the heat exchanger and the flange of the central rod 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 surveyed. The components are the

- Lower target enclosure (LTE), a double walled, D_2O cooled hull made of $AlMg_3$, which is designed to contain the LBE in the case of a number of hypothetical accidents leading to the breach of the inner container. Its proper functioning has been assessed by FEM calculations [8,9]. The enclosure is flanged to the
- Upper target enclosure, formed by a stainless steel tube. This tube is welded to the
- 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.

The last component is the

- 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.

3. Ancillary systems

Whereas the target has been 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 only small in quantity (about 8 l), the gases produced by the spallation process represent a high radioactive source term, which has to 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. The gas system is enclosed in a second containment filled with He.

- LBE fill and drain (F&D) system

Draining of the active LBE was originally envisaged and a corresponding engineering concept was worked out. The installation of the complex and expensive equipment in the TKE (heavily shielded container permanently installed) turned out to be difficult and very risky with respect to radiation protection. Freezing of the LBE in the target at the end of the irradiation experiment was therefore chosen as reference design and a F&D system to handle only not irradiated LBE is now worked out. This design choice is accompanied by experimental results aimed at characterising the expansion of the solid LBE and the LBE freezing process. 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 [10].

4. 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

- ‘Inside events’: beam focussing, LBE leak, LMC fracture, D_2O leak, gas leak.
- ‘External events’: like earthquake and airplane crash.

The safety concept has to take the operability of the SINQ into account, relying on the two inner barriers (the LM container and the target enclosure) being part of the target system. The safety concept cannot rely on the integrity of the first barrier alone, with the LMC made of T91 steel. The present knowledge on the effect of irradiation, LBE and mechanical loads on the structural materials under conditions representative for the MEGAPIE experiment is limited mainly to single effect studies (i.e. LME, corrosion, irradiation) and will be discussed in the next paragraph. Moreover, one of the goals of the MEGAPIE experiment is the assessment of the behaviour of the T91 steel in the real MEGAPIE conditions, where the coincidence of the different effects occurs.

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. A leak in the gas phase will be detected by a pressure rise and by monitoring the radioactivity in the He gas of the second containment. 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 [11]. Although the $AlMg_3$ 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.

The perforation of both beam entrance windows would send the LBE down the beamline. The LBE will then be collected in a specially designed catcher, but the beamline will be heavily contaminated. The beamline will, however, withstand the pressure increase caused by the LBE/D_2O interaction as shown by simulations with the MATTINA code [12]. 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 [13] show that the activity is sufficient to exceed the dose limit imposed by law. It is set at 1 mSv for the public, whereas the target is designed to withstand a safety earthquake (probability of 10^{-4}/year) we have to assume that the target and the beamline 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 I-125, 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.

5. State-of-the-art on the T91 steel characterisation under MEGAPIE relevant conditions

As previously mentioned, an important topic of the MEGAPIE project is the characterisation of the chosen beam window material, i.e., the T91 steel. This component will be exposed during the spallation target operation to the high power proton beam and the flowing liquid LBE. The predicted maximum damage at the window after 1 year irradiation at 6 Ah is 14.5 dpa and about 1600 appm of He will be produced [14], the LBE highest temperature will be about 350 °C and the flow rate about 1 m/s. Further, beam trips occurring normally at the SINQ facility as well as accelerator maintenance periods cause temperature transients to the system.

Therefore, the materials characterisation should be aimed to assess the corrosion and mechanical resistance under these given conditions. Up to now a large effort has been devoted to the characterisation of the T91 steel in terms of corrosion resistance [15,16,22], mechanical degradation in presence of the liquid metal [15–18,20] and evaluation of the effect of proton/neutron irradiation on the mechanical properties [16,19].

5.1. Corrosion resistance

Corrosion rates estimated experimentally at 400 °C are between 40 μm/year [21] for a LBE flow rate of 1 m/s, and 86 μm/year for a LBE flow rate of 2.2 m/s [22]. Both these results were obtained in experiments where the oxygen content in the LBE was less than 10^{-7} wt%, therefore no protective oxide layer was produced on the steel surface. This oxygen content has been considered representative for the MEGAPIE conditions, since no oxygen control and monitoring system has been foreseen in the target. The estimated corrosion rates indicate that in the given testing conditions the corrosion resistance of the steel does not represent a critical issue.

5.2. Mechanical properties in LBE

A number of tensile and fatigue tests have been performed on the T91 steel in LBE [16,17,20,23]. These tests were conducted under very dissimilar conditions among them and generally they were of qualitative type. For these reasons, it is not possible to combine numerically these results for the estimation of the MEGAPIE window performance. However, some trends can be observed from these experiments: generally all experiments showed that the surface condition of the steel has an influence on the mechanical properties degradation when the material is in contact with the liquid metal. For instance, by creating an 'intimate' contact between the LBE and the steel surface a reduction of the tensile properties have been observed [16,20]. It seems that the presence of the native oxide layer can delay the occurrence of this intimate contact, preventing the degradation of the tensile properties [20]. Thus, the specification and survey of the surface conditions (roughness, presence of microcracks and eventually a pre-oxidised state) are important parameters, which can affect the performance of the beam window. Moreover, the reduction of the low cycle fatigue lifetime in LBE might not have consequences on the MEGAPIE system provided that there are no localised stresses [17].

5.3. Mechanical properties under irradiation

As far as the behaviour of the T91 steel under proton/neutron irradiation, samples irradiated at SINQ up to 9 dpa at 275 °C exhibit an increase of DBTT with dose. An attempt to estimate the window lifetime gave a value of 3–6 months in the MEGAPIE conditions, using the DBTT results as a criterion [24]. This assessment has been done without taking into account LBE effects.

Moreover, a linear elastic fracture mechanics evaluation [25] shows that the presence of a surface crack will not lead to sudden brittle failure of the window under normal operation conditions, since T91 steel should retain sufficient toughness even after months of irradiation in a spallation spectrum. This study is encouraging as far as the resistance of the irradiated T91 steel, though a worsening of the mechanical properties of the irradiated steel, due to the presence of the liquid metal cannot be excluded.

5.4. LBE – irradiation combined effect

The proton irradiation and liquid metal combined effect on the mechanical behaviour of the T91 steel will be tested with the LISOR experiment. Preliminary LISOR results have been obtained on T91 steel after a short (1 h) irradiation, showing essentially no difference with respect to not irradiated samples [26].

Presently, the experimental campaign on the T91 steel is going on. Further experiments are underway at PSI (STIP and LISOR experiments) and SCK-CEN (neutron irradiation experiment) to assess the combined effect of irradiation and LBE on the mechanical properties of the steel.

In summary, with the present experimental results available, it can be assumed that the corrosion rate of the T91 steel in the MEGAPIE conditions does not represent a critical issue. Further, it has been shown that the T91 steel should retain sufficient toughness in its irradiated state and it can be assumed that the degradation of the mechanical properties of the steel due to LBE can be, at least, delayed by a controlled surface preparation. Concerning the LBE – irradiation combined effect, more experimental results which will be available in the next future will help to the clarification of the performance of the T91 steel in the window condition of the MEGAPIE target.

6. Summary and perspectives

In this report the status on the MEGAPIE target and ancillary systems as well as the safety analysis have been summarised. Emphasis has been given to the state-of-the-art of the T91 characterisation in flowing liquid metal and under proton irradiation, since this Workshop is related to this topic. The analysis of the results obtained up to now, shows that the corrosion resistance of the materials in the MEGAPIE conditions is fairly good. Moreover, the tests performed on the T91 steel in LBE have evidenced the importance of the condition of the steel surface. The surface should be free of microcracks and a pre-oxidised state or the presence of a protective layer can delay the degradation of the mechanical properties of the steel due to LBE. Concerning the irradiation effect on the properties of the steel, a window lifetime estimation showed that the T91 steel can withstand in the MEGAPIE conditions at least 3–6 months. This evaluation was performed without taking into account the LBE effect. The LBE-irradiation combined effect will be assessed after the completion of the experimental campaign at PSI and SCK-CEN.

In parallel to the materials assessment, the manufacturing phase of the target and the ancillary systems has started. Test programmes to assess the component and sub-systems and to validate the overall target performance, out of beam, are going on and before irradiation these experimental programs will be fulfilled.

The planning of the irradiation phase, the post-irradiation phase and the decommissioning are presently at a conceptual level and they will be worked out in the next future.

Finally, the target irradiation in the SINQ beam is presently foreseen for mid 2006.

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