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WEBEXPIR: Windowless target electron beam experimental irradiation

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Abstract

The windowless target electron beam experimental irradiation (WEBEXPIR) program was set-up as part of the MYRRHA/XT-ADS R&D effort on the spallation target design to investigate the interaction of a proton beam with a liquid lead–bismuth eutectic (LBE) free surface. In particular, possible free surface distortion or shockwave effects in nominal conditions and during sudden beam on/off transient situations, as well as possible enhanced evaporation were assessed. An experiment was conceived at the IBA TT-1000 Rhodotron, where a 7 MeV electron beam was used to simulate the high power deposition at the MYRRHA/XT-ADS LBE free surface. The geometry and the LBE flow characteristics in the WEBEXPIR set-up were made as representative as possible of the actual situation in the MYRRHA/XT-ADS spallation target. Irradiation experiments were carried out at beam currents of up to 10 mA, corresponding to 40 times the nominal beam current necessary to reproduce the MYRRHA/XT-ADS conditions. Preliminary analyses show that the WEBEXPIR free surface flow was not disturbed by the interaction with the electron beam and that vacuum conditions stayed well within the design specifications.

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1. Introduction

A high power windowless spallation target is included in the design of the MYRRHA/XT-ADS, the European experimental accelerator driven system for the demonstration of transmutation [1]. It operates with liquid lead–bismuth eutectic (LBE) that will be irradiated with a 600 MeV proton beam at currents of up to 4 mA. To realise the design, a number of questions need to be addressed such as the stability of the free surface flow and its ability to remove the power deposited by the proton beam via forced convection, the compatibility of a hot LBE reservoir and the outgassing of the LBE in the spallation target circuit with the beam line vacuum. These items have been studied previously [1].

Another crucial point is the demonstration of safe and stable operation of the free LBE surface under the irradiation with a high power proton beam. As a first step, the windowless target electron beam experimental irradiation (WEBEXPIR) experiment was set-up to investigate the influence of LBE surface heating caused by a charged particle beam in a situation representative of the MYRRHA/XT-ADS. A compact LBE loop was constructed with flow characteristics and geometry at the irradiation point that are very similar to the MYRRHA/XT-ADS case. The loop was connected to a 7 MeV electron accelerator. During irradiation the effects of the surface power deposition on the flow stability and LBE evaporation were monitored.

2. Experimental set-up

2.1. Interaction chamber

The WEBEXPIR interaction chamber was made to represent the actual conditions in the target nozzle of MYRRHA/XT-ADS (see Fig. 1) as accurately as possible.

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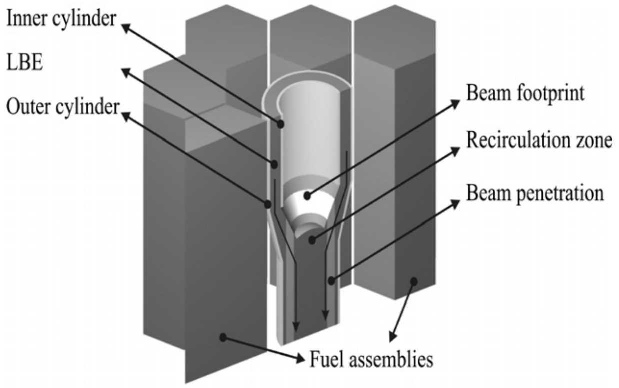

Fig. 1. Schematic cutaway view of the MYRRHA/XT-ADS spallation target and core.

In the latter, the proton beam goes through the inner of two hollow concentric vertical cylinders with the LBE target material flowing between the inner and the outer tube. At the bottom of this downcomer section, the outer cylinder end in a funnel shaped a nozzle, resulting in a confluent LBE target. In order to avoid overheating of the LBE recirculation zone present in the centre of the nozzle, the proton beam is painted along a circular path in between the recirculation zone and the inner cylinder forming an annulus shaped footprint.

To simulate these conditions in the WEBEXPIR experiment, a geometry that can be seen as an unfolded segment of the MYRRHA/XT-ADS nozzle, was chosen (see Fig. 2). It consists of a rectangular slide with a thickness corresponding to the 14.35 mm nozzle gap and with an inclination angle of 26°, being the angle of impact of the proton beam on the LBE surface. The slide was made sufficiently wide to ensure that the LBE velocity at the beam interaction zone was almost constant and equal to the 2.5 m/s LBE speed in the MYRRHA/XT-ADS target nozzle.

The section of the slide upstream of the interaction point is rib-roughened to prevent fluid acceleration and tearing. At the beam interaction point, the LBE flow is confined so that the impact of the beam can only be compensated in the direction perpendicular to the free surface.

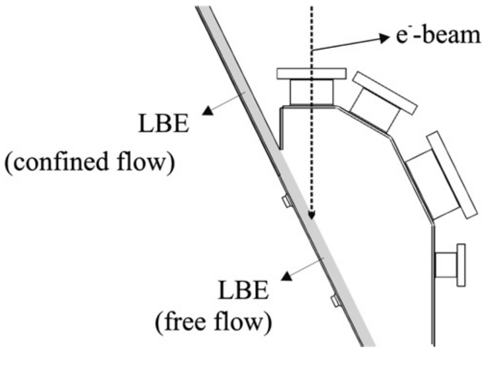

Fig. 2. Schematic side view of the WEBEXPIR interaction chamber, showing both the confined and free LBE flow sections. A number of viewports are used for instrumentation and the connection to the beamline.

2.2. Loop layout

The interaction chamber described above was integrated in a compact LBE loop in order to achieve the appropriate flow at the beam interaction point. Besides this, a number of spatial boundary conditions imposed by the configuration at the location of the IBA accelerator had to be taken into account.

Fig. 3 shows a schematic drawing of the loop. The LBE is circulated by a magnetically coupled 10 l/s, 5 bar centrifugal pump (**1**). Due to space limitations, the LBE/oil heat-exchanger (**2**), which evacuates the heat deposited by the electron beam was positioned on the exit side of the pump. A valve (**3**) was put placed behind the heat-exchanger to assure a stable pressure at the exit of the pump. A vortex type flow meter (**4**), which requires enough inlet and outlet tube length to reach the needed accuracy, is connected to a box at the top of the interaction chamber ramp (**5**). In the interaction chamber (**6**), several viewports were mounted to monitor the interaction between the electron beam and the LBE flow. At the drain of the interaction chamber an expansion volume (**7**) has been added to prevent flooding of the interaction chamber when the pump is not active. The top of the chamber is connected to the beam line (**8**), at the exit of the 270° magnet that bends the electron beam coming from the accelerator into the vertical direction. The connection consists of a set of flexible bellows, a gate valve and a beam collimator. Expansion joints have been incorporated at several positions in the loop to relieve thermal strain and to correct for misalignment errors.

2.3. Accelerator

The irradiation was conducted at the TT-1000 Rhodotron [2], which is a very high power electron accelerator available at Ion Beam Applications s.a. (IBA, Louvain-la-Neuve, Belgium). Table 1 shows its main accelerator characteristics.

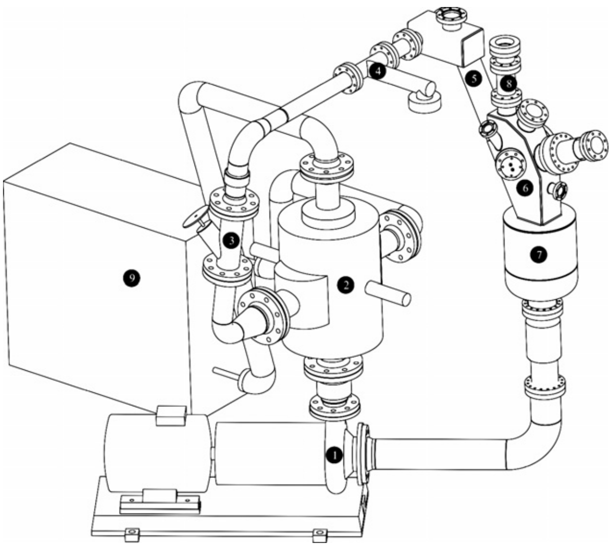

Fig. 3. WEBEXPIR loop layout (see text).

Table 1
TT-1000 Rhodotron characteristics

Energy	7 MeV e$^-$
Beam power range	0.5–700 kW
Beam spot	10 mm × 3 mm FWHM
Beam entrance	Vertical from top
Diameter	3.0 m
Height	3.3 m

The use of a 7 MeV electron beam allows to imitate the effect of a 350 or 600 MeV proton beam hitting the LBE surface without causing problems with induced radioactivity, safety and waste that would occur when using protons.

Fig. 4 compares the linear power deposition in LBE for a proton beam with an energy of 350 MeV and 600 MeV, respectively [3], and an 7.5 MeV electron beam, as calculated by Monte Carlo simulations. The inset of this figure clearly shows that the heating by the electron beam is concentrated near the lead bismuth surface. About 65% of the beam power is deposited in the first 2 mm below the LBE surface. This figure also shows that the linear power density per mA at the surface is very well comparable to that of a 350 MeV or 600 MeV proton beam.

Table 2 compares the characteristics of the flow and the beam profile for the MYRRHA/XT-ADS and the WEBEXPIR case. In order to obtain at least the same surface heating conditions during the WEBEXPIR experiment, the nominal beam current was set to 0.25 mA.

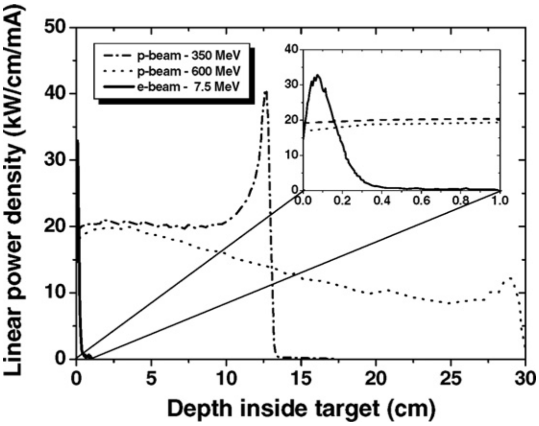

Fig. 4. Linear power deposition.

Table 2
Comparison of flow and beam characteristics

	XT-ADS target	WEBEPXIR target
Target material	LBE	LBE
Beam energy	600 MeV p	7 MeV e$^-$
Linear power at surface ($d < 2$ mm)	1.8 kW/mm/mA	2.2 kW/mm/mA
Flow velocity	2.5 m/s	2.5 m/s
Beam shape	~Gaussian (10 mm FWHM) painted along annulus (54 mm Ø)	~Gaussian (3 mm FWHM γ flow, 10 mm FWHM//flow)
Beam current	4 mA	0.25 mA

2.4. Instrumentation

A number of diagnostic devices have been installed on the interaction chamber in order to study the two main effects mentioned before, i.e. free surface distortion and enhanced evaporation. Additional devices were used to monitor the electron beam and the LBE flow.

An electron beam collimator with a current read-out was used to monitor which fraction of the beam is stopped by the beam collimator. Together with the total current measurement from the accelerator, the total beam current on target was deduced. The exact position of the interaction spot and its shape was periodically verified with a beam monitor consisting of a thin Al_2O_3 layer deposited on a water cooled copper support. The interaction between the Al_2O_3 and the electrons creates visual light that is easily observed.

Visual observation of the interaction zone was also provided by an optical camera mounted at angles both perpendicular and parallel to the LBE surface.

The temperature of the LBE surface was measured without disturbing the flow with a dedicated infrared camera. In addition, for verification purposes, a thermocouple array was periodically inserted into the LBE flow downstream of the beam interaction point. A set of Pt-100 resistive sensors was employed to accurately measure the LBE bulk temperature before and after beam interaction.

For diagnostic purposed, thermocouples on the loop were used to measure the temperature of the main loop components, the temperature of the top and sides of the interaction chamber and the temperature of the beam collimator. The LBE flow was determined with a calibrated vortex flow meter.

A dedicated shieldless active ionisation pressure gauge was installed to determining the enhanced evaporation at the beam interaction point while additional Bayard-Alpert pressure gauges were used to monitor the vacuum conditions in the interaction chamber and the beam line.

Finally, pressure transducers were put around the interaction zone to monitor possible shockwaves underneath the LBE flow and to measure the LBE pressure at the entrance and exit of the main pump.

3. Measurements and discussion

A set of measurements were performed at different electron beam currents to determine the experimental conditions and to address the beam-LBE interaction issues discussed above. Table 3 shows the nominal conditions of the LBE flow with the electron beam turned off.

Table 3
Nominal LBE conditions with beam off

LBE flow	3.8 l/s
LBE velocity at interaction point	2.5 m/s
LBE bulk temperature	200 °C
Total LBE mass in loop	800 kg
Vacuum in interaction chamber	5×10^{-8} Pa

3.1. Beam profile measurements

The distribution of the current along the beam profile was determined prior to the actual irradiation experiments. For this, a stack of electrically insulated collimators with decreasing diameters was mounted at the exit of the 270° bending magnet. The fraction of the beam current caught by each of the collimators was read out. The remaining fraction of the beam was deposited in a water cooled beam dump. Since the profile of the beam might change as a function of the total beam current, the beam profile was measured for currents of 100 μA up to 4 mA.

Apart from this, the beam position and profile were also visually checked by inserting an Al_2O_3 coated and water cooled copper support in the electron beam at the position of the beam interaction point (see Fig. 5). The interaction with the 7 MeV electrons produces visual radiation which can be detected with an optical camera.

The combination of both measurements resulted in a beam profile with an average full width at half maximum (FWHM) of 10 mm in the direction parallel and 3 mm perpendicular to the LBE flow.

3.2. Visual inspection

An optical camera was positioned both nearly perpendicular and parallel to the LBE surface, focussing on the beam interaction point. Visual images were recorded for beam currents of 100 μA up to 5 mA. No obvious distortion of the LBE surface was detected for any of the beam currents.

3.3. Infrared inspection

The infrared camera was positioned perpendicular to the LBE surface, focussing on the LBE surface just downstream of the beam interaction point (see Fig. 6). The camera was used to measure the surface heating of the LBE for beam currents of 100 μA up to 7.5 mA. Temperature increase at the LBE surface of several hundred K was observed. However, due to the high reflectivity of the liquid metal surface, precise quantitative interpretation of the infrared data is not straightforward. Analysis of the results of calibration experiments as well as the actual irradiation data is still in progress.

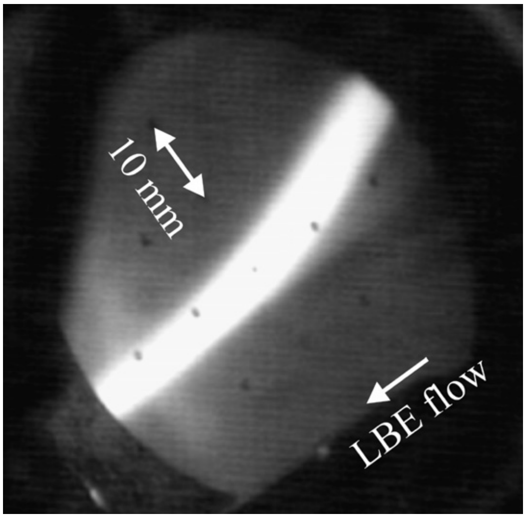

Fig. 5. Beam spot on Al_2O_3.

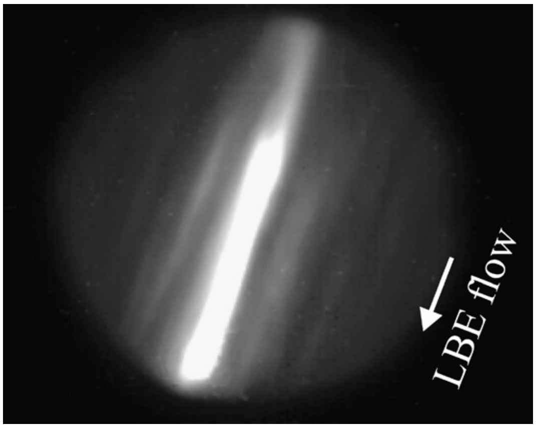

Fig. 6. Infrared image of beam spot on LBE at a beam current of 1.5 mA.

3.4. Enhanced evaporation

The enhanced evaporation of the LBE as a result of surface heating by the electron beam was measured with a shieldless Bayard-Alpert vacuum gauge positioned close to the beam interaction point. The increase in pressure was monitored for beam currents of 100 μA up to 10 mA. Even at 10 mA, the pressure in the interaction chamber stayed well below 10^{-4} mbar which is the vacuum pressure level required in the MYRRHA/XT-ADS spallation target design. At currents above 5 mA, pressure spikes are observed which can possibly be attributed to the evaporation of LBE droplets that are hit by the electron beam.

Surface samples were taken at a number of cold positions in the interaction chamber for off-line determination of amount of LBE condensation. A chemical analysis of this material is still ongoing.

4. Conclusions

The aim of the WEBEXPIR experiment was to check for any LBE surface distortion or enhanced evaporation as a result of surface heating with a 7 MeV electron beam in conditions representative of the MYRRHA/XT-ADS spallation target. Various tests have been carried out at electron beam currents of up to 10 mA, which corresponds to 40 times the nominal beam current necessary to reproduce surface heating in conditions.

No significant shockwave effects or enhanced LBE evaporation were detected. As a first preliminary conclusion it can be stated that the WEBEXPIR free surface flow was not disturbed by the interaction with the electron beam and that the vacuum conditions stay well within design specifications of the MYRRHA/XT-ADS.

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