WINDOW TARGET UNIT FOR THE XADS LEAD-BISMUTH COOLED PRIMARY SYSTEM *

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A window target unit in a lead-bismuth cooled primary system is one of the three options for a target unit in the centre of the XADS core being investigated in the frame of the XADS study (PDS-XADS). This paper presents the current status of the mechanical design, the calculations on heat deposition and the corresponding thermal hydraulic analyses.

1. Description of Target Unit

1.1. *General Description*

The target unit is located in the centre of the core. It has a vertical orientation, penetrates the reactor vessel cover plate and the core from above and is supported on the reactor vessel top.

The proton beam enters the beam tube at the upper end, penetrates the beam tube window at the lower end and impinges on the upward flowing target material (Lead-Bismuth Eutectic, LBE) below the window (spallation zone). The heated target LBE is cooled in a heat exchanger at the upper end inside the target unit and is driven by natural convection forces. As secondary coolant a diathermic coolant has been chosen.

1.2. *Mechanical Design*

The general design of the target unit is shown in Figure 1. The target unit is composed of an evacuated central beam tube inside a circular flow guide and a main shell forming the pressure resistant boundary to the surrounding core assemblies and the primary coolant. The main shell takes the pressure difference

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between the primary system and the target unit, its upper end is flanged on the rotating plug, its lower end is guided in the core grid plate by aid of the primary coolant guide shell. The diameter of the main shell varies with the axial position. In the core region the primary coolant guide shell adapts the geometry of the target unit to the hexagonal core geometry.

The upper region of the main shell at the level of the upper plenum of the reactor vessel houses the heat exchanger and the piping for the externally arranged system components. The lower part of the main shell contains a hemispherical closure as an integral part at the lower end.

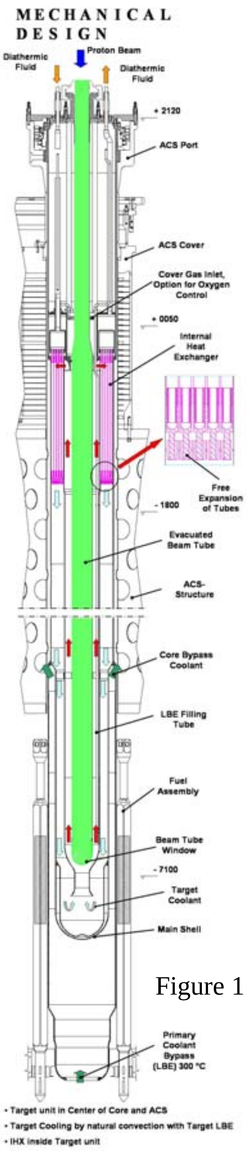

Figure 1

The circular skirt between the main shell and the beam tube serves as flow guide for the target coolant flow. The cold flow from the heat exchanger is guided downward in the annulus between beam tube and circular skirt, is reversed at the lower end and is directed upward towards the window and further to the internal heat exchanger.

The heat exchanger in the upper part of the target unit has been optimised with respect to the partly contradictory requirements for a large heat exchange surface and a low irreversible pressure drop. The heat exchanger is of a bayonet type, it is arranged in the annulus between beam tube and main target unit shell. It consists of the inner and outer shell, the head plate with inlet and outlet pipes, the upper plena for cold and hot secondary coolant and a bundle with about 550 double tubes (see detail in Figure 1).

The LBE is cooled by a diathermic fluid as secondary coolant entering the heat exchanger through the inlet pipe and the upper cold plenum before entering the tube bundle. The secondary coolant flows downward in the inner tubes to their open end where it is re-directed to the annulus between the inner and the outer tubes. Flowing upward the heat is taken from the target LBE coolant. The hot secondary coolant leaves the heat exchanger upward via the hot plenum into the outlet pipe.

All flange connections on top of the target unit are designed for remote handling. The beam tube inside the target unit can be removed and exchanged separately in a shielded flask or together with the target unit if required.

2. Heat Deposition

2.1. *Calculation Tool*

The heat deposition in the target unit caused by beam protons was calculated with help of the MCNPX 2.4.0 code [1]. The Bertini intra nuclear cascade model has been applied for hadron-nucleus interaction simulation; the data based on ENDF/B-VI library have been used for the transport of neutrons with energies below 150 MeV. Transport of protons, photons, neutrons, charged pions and light ions (deuterons, tritons, He-3, a-particles) was modelled in the present calculations.

For the comparison with the available experimental data [2, 3], the heat deposition has been calculated for the thick targets made of lead, bismuth, iron. It was found that the experimental data are well reproduced with the MCNPX 2.4.0 code, except for the iron target [4].

2.2. *Calculation Model*

The target model based on the mechanical design described above was realized as input file for MCNPX. In order to investigate the influence of the neutrons and photons born in the core on the heat deposition in the target, 3 cases were considered: bare target and target with the core for two criticality levels keff = 0.971±0.001 and keff = 0.943±0.001:

- Bare target: the MCNPX model is limited to the target module only, therefore no irradiation outside the target module goes back;
- Target + core with Keff = 0.971: all XADS parts relevant for the neutronics calculations are presented in this model. The core is represented by the hollow homogeneous cylinder;
- Target + core with keff = 0.943: the same MCNPX model as previous, except the fuel composition changed to decrease the criticality.

The initial proton energy is 600 MeV. The proton beam intensity obeys an elliptical radial distribution:

$$\Phi(r) = \frac{3I_0}{2\pi r_0^{\;2}} \left(1 - \left(\frac{r}{r_0} \right)^2 \right)^{1/2} \tag{1}$$

where I_0 – the total proton beam current, $r_0 = 8.0\ cm$ – the radius of the beam spot.

2.3. *Results*

Main part of initial proton energy is released in LBE volume below the window, in the cylinder region with radius about 8 cm and height – about 30 cm. The maximal heat deposition density, 0.15 kW/cm3/mA, is reached 2 cm below the lowest window point at the beam axis.

The maximum heat deposition density in the window reaches 0.14 kW/cm3/mA on the outer window surface on the beam axis. The heat spatial distribution in the window is defined mainly by the shape of the proton beam.

The core influence is negligible in the central target region (close to the beam axis) and becomes more important in the target periphery. The core impact to the total heat deposition in the target depends on the criticality level (see Table 1). For the constant beam current the core influence is larger for the higher keff. Nevertheless, during the XADS operation the core criticality will change and the current should be adjusted in order to maintain the nominal core power level. According to the present calculations the proton current is 2.49 mA for keff=0.971, and 5.10 mA for keff=0.943 for the nominal core power level 80 MWt. The total heat deposition in the target module correspondent to both values of keff is presented in table 1. As one can see, for the constant core power level, the core influence on the heat deposition in the target is larger for the lower keff.

Parameter↓ Model→	Bare target	Keff=0.971	Keff=0.943
Heat deposition in the target per proton current (kW/mA)	447,5	483,1	466,9
Proton current to maintain 80 MWth in the core (mA)	--	2,49	5,10
Heat deposition in the target corresponding to 80 MWth in the core (kW)	--	1202	2383

Table 1. Total heat deposition in the target unit for different core criticality levels.

3. Thermal Hydraulic Analysis

For the purpose of thermal hydraulic analyses, two different types of codes are used, i.e. the one-dimensional system code HERETA [5] and the CFD code CFX4 [6]. With the HERETA code, the heat removal system and its components are optimized to achieve optimum heat removal performance and transient behavior of the target loop is investigated. The calculated global flow conditions by HERETA are used for boundary conditions of CFX analysis. Using CFX, the detailed thermal hydraulic behavior in the lower part of the target is investigated with emphasis on the assessment of the cooling capability of the window. For spallation heat depositions, results of the MCNPX calculation are adopted. The maximum proton beam intensity is defined as 6 mA in the XADS design specification [7]. Therefore 6 mA of the beam current is adopted for the present thermal hydraulic calculations.

3.1. *System Heat Removal*

Figure 2 shows the predicted transient performance of the XADS target by HERETA during two starting up conditions (power jump and power ramp). At initial steady state conditions, i.e. proton beam is switched off and HEX is put into operation, LBE temperature and mass flow rate are about 200°C and 70 kg/s, respectively. In case the proton beam is suddenly increased to its full power at the time point t=100 s, LBE temperature at the upper end of the spallation zone increases sharply and reaches its maximum temperature of about 410°C. A strong increase in the LBE mass flow rate enhances the cooling and leads to a reduction in the LBE temperature. Flow parameters approach their steady state conditions in about 200 s. At steady state conditions, a LBE mass flow rate of about 185 kg/s is achieved and the maximum cross-sectional LBE temperature is 330°C.

According to the XADS design specification [7], a slow ramp of beam power was defined, i.e. at first a small beam power jump from zero to 45 kW, 1.5% of the full power, after then a linear increase to its full power in a few thousand seconds. To give an impression about the effect of the ramp time duration on the thermal-hydraulic behavior, a transient analysis was carried out with the following start-up procedure: at first a beam power jump to 45 kW and then a power ramp to full power in 200 s. As seen in Figure 2, no temperature peak is observed under this transient procedure.

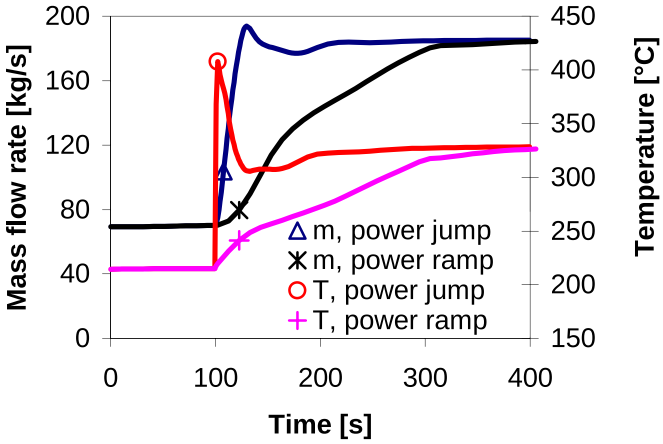

Figure 2. Transient performance of the target during two starting up condition

3.2. *Cooling Capability of Beam Window*

For analyzing the window cooling capability, the lower part of the target module is considered, i.e. from the bottom to an elevation 1 m above the spallation zone. Figure 3 and 4 show the results of calculations with CFX4. The maximum velocity, 1.37 m/s, is obtained in the funnel centre. No flow re-circulation zone is observed, except in the outer side of the funnel. Figure 4 illustrates the temperature profile in the spallation region. The maximum temperature in the beam window reaches 531°C, which is close to the design limit 525°C. Therefore optimization study is necessary to get better thermal performance. The maximum temperature in the funnel structural material is about 400°C, much lower than that in the beam window. Figure 5 shows the temperature distribution on the window inner surface (vacuum side) and on the window outer surface (LBE side). The maximum temperature drop across the window thickness is about 150°C. The temperature on the window outer surface is lower than 400°C. Therefore, oxygen control for this target module might not be necessary.

Figure 3. LBE velocity in the spallation region.

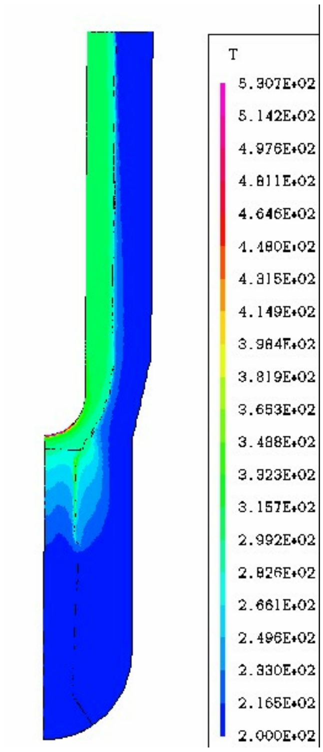

Figure 4. Temperature distribution in the spallation region.

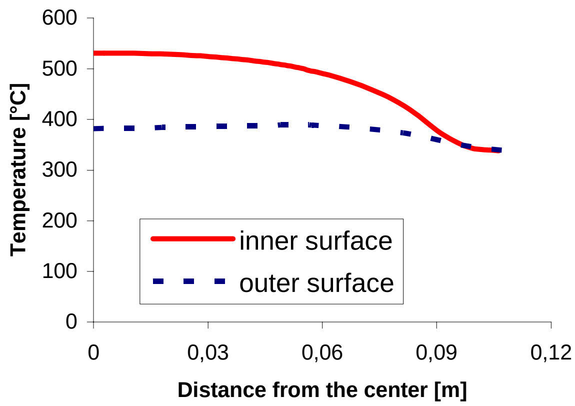

Figure 5. Temperature profile on the window surface.

3.3. *Beam Interrupt Transient*

The operating experience of existing accelerators shows that beam interrupts occur frequently. Beam interrupts produce thermal cycles and lead to additional stress, which would become one of the main issues of structural material failure. In the technical specification of accelerator for XADS, the frequency of beam interrupts with time duration larger than 1 s is kept below 5 interrupts per year. No special requirements are defined for shorter beam interrupts (< 1 s). In the present work, the effect of such short beam interrupts is investigated using the HERETA and CFX4 codes. The CFX4 code was used to predict the window temperature based on LBE results obtained by the HERETA code. Figure 6 shows the LBE temperature and the maximum window temperature in the case of a beam interrupt with a duration of 0.5 s. It was found out that the LBE mass flow rate hardly changes, whereas the LBE temperature drops strongly down from 330°C to 260°C. The maximum temperature on the window inner surface drops from 530°C down to about 380°C. A temperature change rate of 300°C/s is observed.

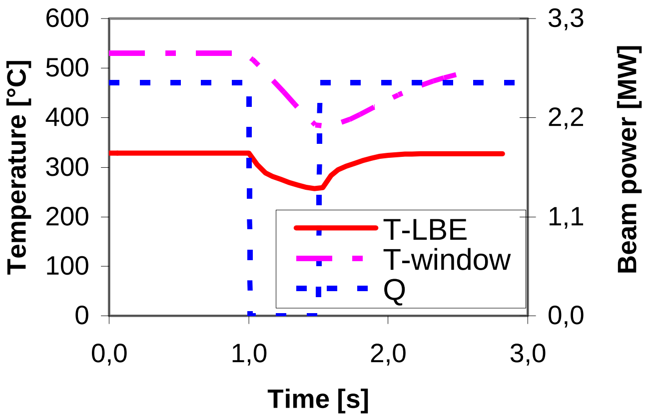

Figure 6. Temperature behavior under beam interrupt (0.5 s) conditions

4. Conclusions

The concept for a window target unit in a LBE cooled primary system is based on target cooling by natural convection. Therefore no pump is needed for the target LBE and the target LBE can be kept inside the target unit.

The very high energy protons and neutrons provide high damage rates of the window material thus limiting the residence time of the beam tube. Nevertheless, the results of the detailed analysis show that an optimization of the window thickness leads window temperatures below the design limit assuring an acceptable residence time of the beam tube in the reactor. This has still to be supported by a mechanical analysis based on the presented results.

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The design of this target unit is based on studies carried out by L. Cinotti, Ansaldo, Italy.

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