DRIVER BEAM-LED EURISOL TARGET DESIGN CONSTRAINTS*

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Abstract

The EURISOL (European Isotope Separation Online) Design Study is addressing new high power target design challenges. A three-step method [1] was proposed to split the high power linac proton driver beam into one H^- branch for the 4 MW_b [2] mercury target that produces radioactive ion beams (RIB) via spallation neutron-induced fission in a secondary actinide target and three 100 kW_b H^+ branches for the direct targets producing RIBs via fragmentation and spallation reactions. This scheme minimises transient thermo-mechanical stresses on targets and preserves the cw nature of the driver beam in the four branches. The heat load for oxides, carbides, refractory metal foils and liquid metals is driven by the incident proton driver beam while for actinides, exothermic fission reactions are an additional contribution. This paper discusses the constraints that are specific to each class of material and the target design strategies.

INTRODUCTION

High power targets are at the heart of facilities that deliver RIBs, spallation neutrons and neutrinos through one or multiple stages that all first involve the interaction of a high intensity beam of high energy projectiles with the target material. EURISOL [3] will deliver up to three orders of magnitude higher yields of radioactive isotope beams (RIBs) compared with existing facilities worldwide. The production of 1000 RIBs of 70 different chemical species will be enabled by a combination of fission reactions in a multi-MW converter-target unit and fragmentation and spallation reactions in three 100 kW_b target stations [4].

RIB intensities available to the experimental stands are governed by in-target production cross-sections for isotopes of interest, diffusion out of the target material, chemically selective effusion from the target to the ion source, ionisation in the ion source and beam transport. Moreover, these intensities must be provided in a stable, reliable manner over the lifetime of the targets. Target design consists in optimising different properties with conflicting requirements.

An understanding of the temperature profile throughout the target is one of the most important requirements for target design. The gain in RIB yield at EURISOL is principally due to the increased incident proton beam intensity which inevitably leads to higher in-target heat deposition and more stringent requirements for heat dissipation.

Although pulsed driver beams offer some advantages such as better signal to noise ratio at the experimental stands, a cw driver beam is the preferred option to supply the four target stations and maintain an acceptable target lifetime by minimising target fatigue. At EURISOL, the cw nature of the primary 4 MW_b H^- beam is preserved up to all target station front-ends by the adoption of a beam splitting technique [1]. For each of the three 100 kW_b target stations, 100 µA of beam is separated by magnetic neutralisation and then transformed into a proton beam by foil stripping. Most targets coupled to the 100 kW_b target stations will need to be segmented into sub-units to manage heat dissipation leading to further splitting of the beam. The thermal management and thermo-mechanical response of EURISOL targets are presented in this paper.

EURISOL multi-MW TARGET

In the EURISOL fission target assembly, neutrons are generated via the interaction of the primary beam with a neutron spallation source – the neutron converter. Fission RIBs are then produced in fissile material targets positioned close to the neutron converter. This arrangement leads to the convenient decoupling of primary beam deposited energy from the fissile target. The fission rate is limited by the fissile target arrangement and fission heat dissipation.

An important role to be fulfilled by the neutron converter is the transport of the heat deposited by the primary beam from its interaction region to dedicated heat exchangers, which is carried out by liquid metals (SNS, Oak Ridge, USA, and J-SNS, JPARC, Japan). EURISOL has adopted Hg since it is an excellent spallation target, has a high heat capacity and is liquid at room temperature. Two designs are under study for the neutron converter, one with a beam window, and the other without.

Liquid metal converter with beam window

In the baseline design which follows the Coaxial Guided Stream (CGS) principle, the Hg is confined to a double walled tube. It flows towards the proton beam in the outer part of the tube and along the p-beam in the inner part, making a u-turn at the beam window (T91 stainless steel). Energy deposition in Hg peaks 2 cm from the beam window, reaching 1.9 $kW/cm^3/MW_b$ whilst it is 900 $W/cm^3/MW_b$ in the beam window, Fig. 1 [5].

Optimization of the flow pattern was carried out using an iterative process to keep the temperature and thermal stress in the beam window below stress limits given for irradiated materials whilst minimizing pressure losses and preventing vaporization and cavitation in the back-swept surfaces. With a bulk pressure of 7.5 bar, the beam window peak temperature is 200°C, the maximum von-Misses stress is 135 MPa (cw beam), the Hg peak temperature is 180°C and the peak velocity is 6 m/s in the

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channels formed by the specially designed flow-guides and walls, at the u-turn.

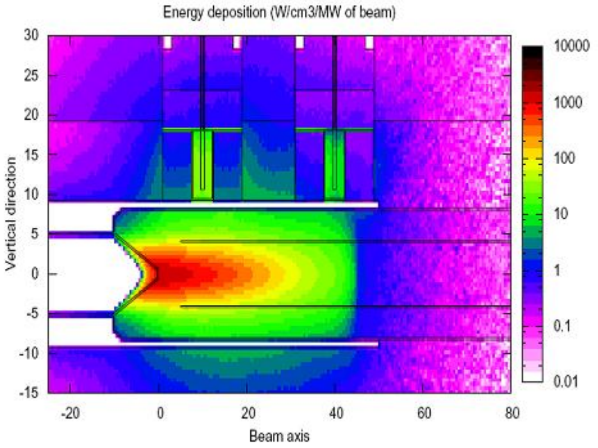

Figure 1: Energy deposition simulations of the Hg-CGS converter and fissile target with FLUKA [6]. Two fissile targets can be seen (Vertical position: from 10 to 20cm, beam axis location 10 and 40 cm).

Windowless liquid metal converter

An alternative to the CGS-based design, the so-called Windowless [7] Transverse Film (WTF) target, was proposed for EURISOL. A transverse Hg film is injected vertically downwards, interacts with the proton beam and efficiently removes the deposited heat. It is recovered below the interaction point where it is then pumped to the auxiliary circuit some 10 m away, where the volatile separator, magnetic pump and Hg reservoir are located. Because the Hg is not in direct contact with a beam window, it is possible to achieve one order of magnitude higher power density by reducing the beam sigma. For a Hg flow rate of 12 l/s, the Hg temperature increase is 117.5°C for a heat deposition density on the beam center line of 25 kW/cm^3/MW$_b$ and a total heat deposition of 2.3 MW. The obvious advantage of this design is its compactness: the harder neutron spectrum due to the reduced film thickness permits the positioning of actinide fission targets closer to the interaction point.

Fission target

The fission targets design is derived from the concept proposed by PIAFE and MAFF [8]. Six vertical pipes each containing a UC$_x$ production system are oriented perpendicular to the neutron converter tube and positioned in order to exploit the most intense neutron flux. Depending on the isotope of interest, the fissile material can either be non-military grade enriched ^{235}U, ^{238}U or ^{232}Th. The neutron spectrum is engineered to maximise the fission rate, thermal for ^{235}U, hard for ^{238}U and ^{232}Th via the adoption of suitable moderator and reflector materials between converter and fissile target. Up to 10^{15} fissions per second will occur for a ^{235}U target, releasing 30 kW of power, more or less uniformly throughout the target volume, Fig. 1. Dissipation of this power away from the target is achieved by thermal radiation on the outer surface of the target container from fins designed to increase its effective emissivity. The active target volume remains at around 2000°C. An order of magnitude less fission rate is expected for other actinide targets used with hard neutrons.

EURISOL 100 kW DIRECT TARGETS

Target materials typically used at ISOL facilities for direct targets are refractory metal foils (Ta, Ti, Nb), carbides (Si, U, Th), oxides (Ca, Mg, Zr, Ce) and molten metals (La, Pb, Sn). At CERN-ISOLDE, these target materials are exposed to primary proton beams of 1 or 1.4 GeV with typical average beam powers in the range of 1 to 4 kW$_b$ from the PSB. At TRIUMF-ISAC, the 0.5 GeV H$^-$ beam is incident on refractory metal foils or composite carbide targets that can withstand incident beams of up to 35 kW$_b$ [9], with short periods at the nominal 50 kW$_b$ beam power. The challenge for the EURISOL direct target stations is to operate all four classes of target materials with an incident beam power of 100 kW$_b$.

Thermal management

High temperature operation is required to minimise diffusion and effusion time constants and is also sought to improve radiative heat transfer from the container, the main heat transfer mechanism with a T^4 temperature dependence. Fast extraction required for short-lived isotopes is favoured by the adoption of compact target geometries to reduce effusion times, incompatible with sufficient radiative heat transfer where larger container surface areas are required to dissipate the high heat loads.

Increasing effective emissivity to improve radiation heat transfer can be achieved with fins mounted onto the outer surface of the target container, similarly to the MW fissile targets. For the direct targets, the hadronic cascade deposits some additional power in the fins.

The simulation codes FLUKA and ANSYS are used to simulate energy deposition and heat transfer respectively. Measurements of parameters such as heat conductivities, contact conductances, emissivities and their temperature dependence and evolution under irradiation are ongoing.

Solid 100 kW direct targets

The technical design of a majority of oxide and carbide targets is defined by their moderate operation temperatures (1700 K and 1900 K for Al_2O_3 and SiC) as compared to refractory metals (2500 K for Ta), required to limit target ageing through sintering of the target material and to minimise vapour pressure, Table 1. At these temperatures, thermal conduction is still the dominant heat transfer mechanism from the oxide or carbide pills to the target container. For good conduction heat transfer, both a good thermal contact between pill and container and a temperature gradient must be present between the center and edge of the target pill. The latter condition is incompatible with the requirement to have a uniformly high temperature to maximise effusion and diffusion whilst minimising cold spots where radioactive isotopes might condense. The intrinsically low thermal conductivities lead to the adoption of composite target pills, where the target material is coupled to a material with higher thermal conductivity, such as Al_2O_3 and SiC combined with Nb foils and graphite sheets respectively.

The container radius is set to $3\sigma_b$ where σ_b = 7 mm and its total length is set by the average density achievable at operation temperature for each target material.

Table 1: Thermal management parameters for benchmark solid targets. Container dissipation is taken for ε = 0.9 and and an area given by l = 20 cm and r = 2.1cm.

Parameters	Ta	SiC	Al_2O_3
Density @ RT [g/cm^3]	16.6	3.22	3.96
Operating temperature (OT) [K]	2500	1900	1700
Avg. density @ OT [g/cm^3]	5.17	1.2	0.8
Target length [cm]	50	115	50
Thermal conductivity [W/m.K]	75	15	5
Container dissipation @ OT [W/cm^2]	200	66	43
Container dissipation [kW]	54	18	12

Moderate operation temperatures also set a limit on the amount of heat that can be dissipated by radiation from the target container. A multi-body target system is therefore proposed of between 4 sub-units for oxides and 2 sub-units for carbides, which has the advantage of sharing the heat load between several target sub-units whilst keeping the target geometry compact for fast effusion.

Refractory metal foil targets can be accommodated within one target container, their operation temperatures and thermal conductivities being much higher than those of oxides and carbides, Table 1.

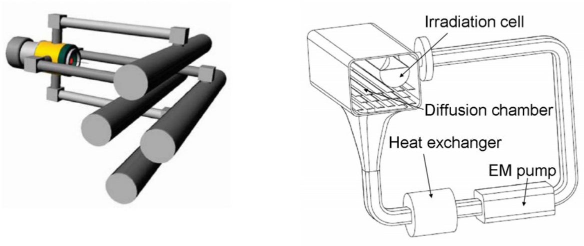

Figure 2: Multi-body target concept for 100 kW_b direct oxide and carbide targets (left) and liquid metal loop concept (right).

Liquid metal 100 kW direct targets

The 100 kW_b beam is a factor 20 higher than can be accommodated by a static confined liquid metal target. The multi-body target concept is no longer applicable and a liquid metal loop is required in order to transport the ~30 kW deposited in the target towards a heat exchanger. The operation temperature of a liquid Pb loop is 1100 K. For an average temperature increase due to the proton beam of ΔT = 100°C, the flow rate was calculated to be 0.2 l/s. A prototype is currently under construction to validate the design and ensure that a large fraction of radioactive isotopes can diffuse and effuse out of a custom diffusion chamber towards the ion source.

50 HZ OPERATION

A cw driver beam is the baseline for EURISOL but an alternative 50 Hz beam with a 1 ms pulse was proposed during the feasibility study. For multi-body direct targets, the 100 kW beam whether pulsed or cw must be further split. Under pulsed beam conditions, target lifetime is also affected by thermal cycling and shocks.

Although the average beam power is only 1-4 kW_b, the pulsed nature of the PSB beam leads to 11.7 GW peak powers within a bunch on ISOLDE targets. Moreover, if the bunch-to-bunch spacing matches the pressure wave period (~10 µs for Pb targets), constructive interference results in higher stresses on the container [10]. Operation of liquid metal targets is limited to 10^{13} protons per pulse, beyond which target failure has been observed to occur. ANSYS AUTODYN simulations show that peak powers at EURISOL are below the threshold required to induce shocks. However, target material fatigue through thermal cycling is an issue that must be addressed.

Table 1: EURISOL beam parameters.

	100 kW Targets		Multi-MW Target	
	cw	50 Hz	cw	50 Hz
Protons per pulse	-	1.248×10^{13}	-	5×10^{14}
Pulse length	-	1 ms	-	1 ms
Average power	100 kW	100 kW	4 MW	4 MW
Peak power	100 kW	2 MW	4 MW	80 MW

SUMMARY AND OUTLOOK

Prototyping work is currently ongoing for the multi-MW converter target and benchmark target-ion source units representative of the 100 kW_b direct targets. Several European laboratories are currently planning upgrades that will bridge the gap between existing facilities and EURISOL. Ongoing CERN injector upgrades call for careful investigations of their suitability for high power RIB targets.

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