ENGINEERING DESIGN OF THE EURISOL MULTI-MW SPALLATION TARGET

Adonai Herrera-Martínez*[,a], Yacine Kadi[a], Morteza Ashrafi-Nik[b],
Karel Samec[b], Janis Freibergs[c], Ernests Platacis[c]
[a] European Laboratory for Nuclear Research (CERN), Geneva, Switzerland
[b] Paul Scherrer Institute (PSI), Villingen, Switzerland
[c] Institute of Physics at the University of Latvia (IPUL), Riga, Latvia
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Abstract

The European Isotope Separation On-Line Radioactive Ion Beam project (EURISOL) is set to design the 'next-generation' European Isotope Separation On-Line (ISOL) Radioactive Ion Beam (RIB) facility. It will extend and amplify current research on nuclear physics, nuclear astrophysics and fundamental interactions beyond the year 2010.

In EURISOL, four target stations are foreseen, three direct targets of approximately 100 kW of beam power and one multi-MW target assembly, all driven by a high-power particle accelerator. In this high power target station, high-intensity RIBs of neutron-rich isotopes will be obtained by inducing fission in several actinide targets surrounding a liquid metal spallation neutron source.

This article summarises the work carried out within Task 2 of the EURISOL Design Study, with special attention to the coupled neutronics of the mercury proton-to-neutron converter and the fission targets. The overall performance of the facility, which will sustain fast neutron fluxes of the order of 10^{14} n/cm^2/s, is evaluated, together with the production of radionuclides in the actinide targets, showing that the targeted 10^{15} fissions/s can be achieved.

Some of the greatest challenges in the design of high power spallation sources are the high power densities, entailing large structural stresses, and the heat removal, requiring detailed thermo-hydraulic calculations. The use of a thin martensitic steel beam-window and a well-controlled mercury flow has been shown to reduce the von-Misses stress in the former below the 200 MPa limit, with reasonable maximum flow rates of ~6 m/s.

Alternatively, a windowless target configuration has been proposed, based on a liquid mercury transverse film. With this design, higher power densities and fission rates may be achieved, avoiding the technical difficulties related to the beam window. Experimentally, several tests have been performed at IPUL (Riga, Latvia) in order to study the stability of the liquid metal flow and validate the mercury loop design.

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[*] Corresponding author. *E-mail address*: adonai.herrera.martinez@cern.ch

Introduction

The EURISOL DS project [1] aims at a design study of the ‘next-generation’ European Isotope Separation On-Line (ISOL) Radioactive Ion Beam (RIB) facility, which will extend and amplify, beyond the year 2010, the work presently being carried out at the first generation RIB facilities in Europe and other parts of the World, in the fields of nuclear physics, nuclear astrophysics and fundamental interactions.

The scientific case for high-intensity RIBs using the ISOL method includes (a) the study of atomic nuclei under extreme and so-far unexplored conditions of composition (i.e. as a function of number of protons and neutrons, or the so-called isospin), rotational angular velocity (or spin), density and temperature; (b) the investigation of the nucleosynthesis of heavy elements in the Universe, an important part of nuclear astrophysics; (c) study the properties of the fundamental interactions governing the Universe, and in particular of the violation of some of their symmetries; (d) potential applications of RIBs in solid-state physics and in nuclear medicine. These cases require a ‘next generation’ infrastructure such as the proposed EURISOL facility, with intensities several orders of magnitude higher than those presently available or planned, allowing the study of hitherto completely unexplored regions of the Chart of the Nuclei.

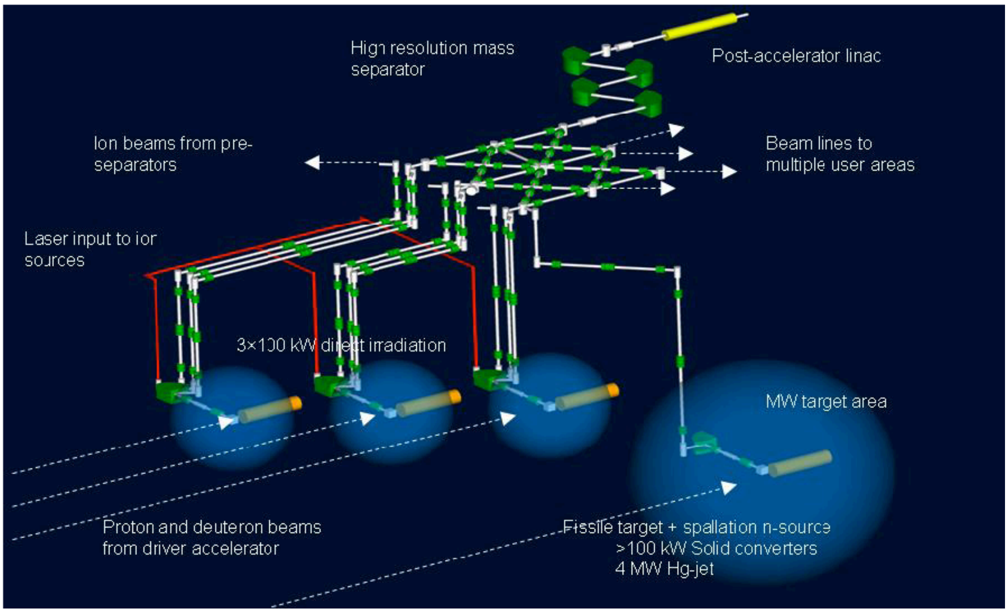


Figure 1. EURISOL DS schematic layout, presenting the three direct targets and the multi-MW target station.

The main components of the proposed facility are: a driver accelerator, a target/ion-source assembly and a mass-selection system [2]. As shown in Figure 1, the proposed ISOL facility would use (a) three 100 kW proton beams on a thick solid target to produce RIBs directly, and (b) a liquid metal 1 – 5 MW proton-to-neutron converter, similar to intense spallation neutron sources such as ESS [3], SINQ [4] and SNS [5], to generate high neutron fluxes, which would then produce RIBs by fission in secondary actinide targets. An alternative windowless liquid mercury-jet ‘converter’ target to generate the neutrons was also proposed for this multi-MW target station [2].

Since the purpose of the facility is to produce certain radioisotopes, maximising the yield of such isotopes (e.g. ^{74}Ni, ^{81}Ga, ^{90}Kr or ^{132}Sn) is the main objective in the design. In the case of the proton-to-neutron converter this implies increasing the neutron yield and reducing the parasitic absorptions in the spallation target. The compactness and efficiency of the assembly is mandatory in order to minimise the total inventory of material in the facility and attain the specified neutron flux and fission density. Moreover, to increase the fission rate in a non-enriched target, the neutron energy spectrum should lie in the fast region, since fission cross-sections for non-fissile isotopes are higher at these energies. This harder neutron spectrum may be achieved by decreasing the moderation of the spallation neutrons in the target.

Finally, minimising the power densities is a requirement to allow for the evacuation of the heat from the converter, in particular from the liquid mercury target and the beam window interface. This is one of the most complex issues when dealing with high power spallation targets. Consequently, a sensitivity analysis, covering a broad range of parameters, was performed [6] in order to propose some alternatives for the design.

Neutronic design of the multi-MW target

Following the results from the aforementioned study, performed using the Monte Carlo particle transport code FLUKA [7], a baseline design was defined [8, 9]. In order to maximise the neutron production, favour a fast-neutron spectrum and confine the charged particles inside the assembly, a 8 cm radius 40 cm long mercury proton-to-neutron converter was proposed, surrounded by fission targets and, possibly, by a neutron reflector (Figure 2). For the latter, beryllium-oxide (BeO) was proposed due to the high albedo of this material and to produce ^{6}He (via n,α reactions in ^{9}Be) for neutrino physics (β-beams) [10].

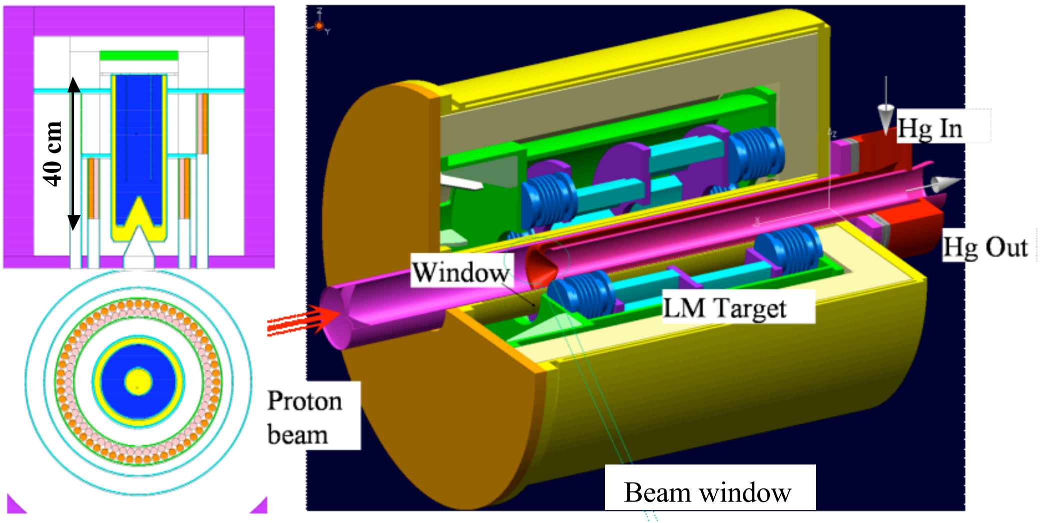


Figure 2. Schematic representations of the baseline design, where several components of the facility have been integrated.

The neutron flux distribution in the baseline design is rather isotropic a few cm away from the centre of maximum production (from 0 to 10 cm from the impact point), as elaborated in [8]. The flux in the fission target is ~10^{14} n/cm^{2}/s per MW of beam, similar to those of conventional nuclear reactors. As elaborated below, these flux levels are more than sufficient to produce the aimed ~10^{15} fissions per second [8] with reasonable fission target volumes (5 litres) and using an acceptable beam power.

Multiple calculations were carried out to assess the performance of fission target materials for the baseline design, taking advantage of the new developments implemented in FLUKA [11]. The use of natural uranium-carbide was analysed and compared to thorium-oxide, for the same target densities, the latter producing one order of magnitude lower fission rates.

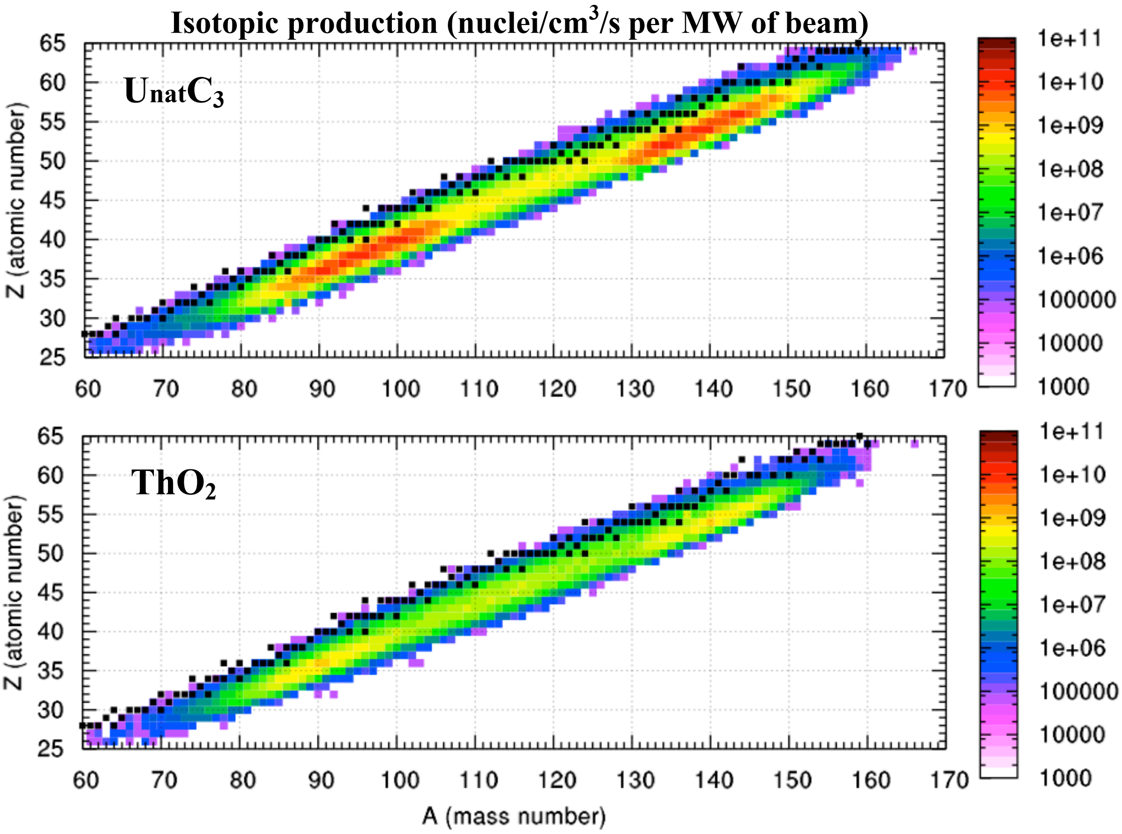


Figure 3. Fission fragment distribution (nuclei/cm^3/s per MW of beam) as a function of atomic number (Z) and mass number (A), for two actinide targets. Stable isotopes are represented by black squares.

The detailed isotopic distribution of the fission fragments may be observed in Figure 3, allowing the prediction of RIB intensities for specific isotopes. These distributions show the nature of the isotopes produced by fission: these lie on the unstable, neutron-rich area of the chart of nuclides (β^- emitters), ranging from manganese to terbium. The use of depleted uranium carbide or thorium oxide entails a reduction in the production of asymmetric fission fragments ($32<Z<42$ and $50<Z<58$); thus, the presence of ^{235}U is advantageous for the production of elements such as krypton or tin, major references in the physics case for EURISOL [2].

Moreover, a relevant benefit of the large fission densities in uranium-carbides is the possibility to investigate the lower end of the so-called *terra incognita*, neutron-rich isotopes of neodymium and above (e.g ^{157}Nd, ^{159}Pm, ^{162}Sm, ^{163}Eu, ^{166}Gd, ^{167}Tb etc.), hitherto unexplored. A study of the neutronic design of the facility and its RIB production potential was published in [12].

An estimation of the actinide inventory produced after 3,000 hours of operation is presented in [13]. Between 40 and 70 g of ^{239}Pu would be produced in a diluted manner within 30 kg of fissile material surrounded by a neutron reflector and by up to 10 m of concrete shielding. The shielding of the assembly was designed to maintain the effective contact dose below 1 μSv/h at its outer surface.

Thermo-hydraulics and beam window design

A key parameter in the design of the experiment is the power distribution, since it will determine the maximum beam intensity that the system may withstand, which in turn is correlated with the fission rates. As elaborated in [8], the energy deposition peaks at ~2 cm after the interaction point, reaching 1.9 kW/cm^3 per MW of beam, and decreases rapidly, along the beam axis. The beam window is enduring lower heat deposition (~900 W/cm^3/MW of beam). These power densities demand an innovative liquid mercury flow design and a careful choice of beam window material.

An iterative design process was necessary to limit the large thermal stresses in the beam window, which were higher than the 200 MPa limit for martensitic steel T91 (below 2 dpa of radiation damage), and the temperature gradient. Finally, these stresses were reduced to ~150 MPa for a beam of 4 MW [14]. Nevertheless, a wider beam profile was considered, 25 mm standard deviation (σ) for the Gaussian beam distribution instead of 15 mm, to further reduce stresses in the window. Figure 4 shows a comparison of power densities for both cases. There is a 2.6 reduction factor brought about by the beam enlargement, and a decrease in temperature gradients, proven by the more homogenous power distribution for a 25 mm σ beam.

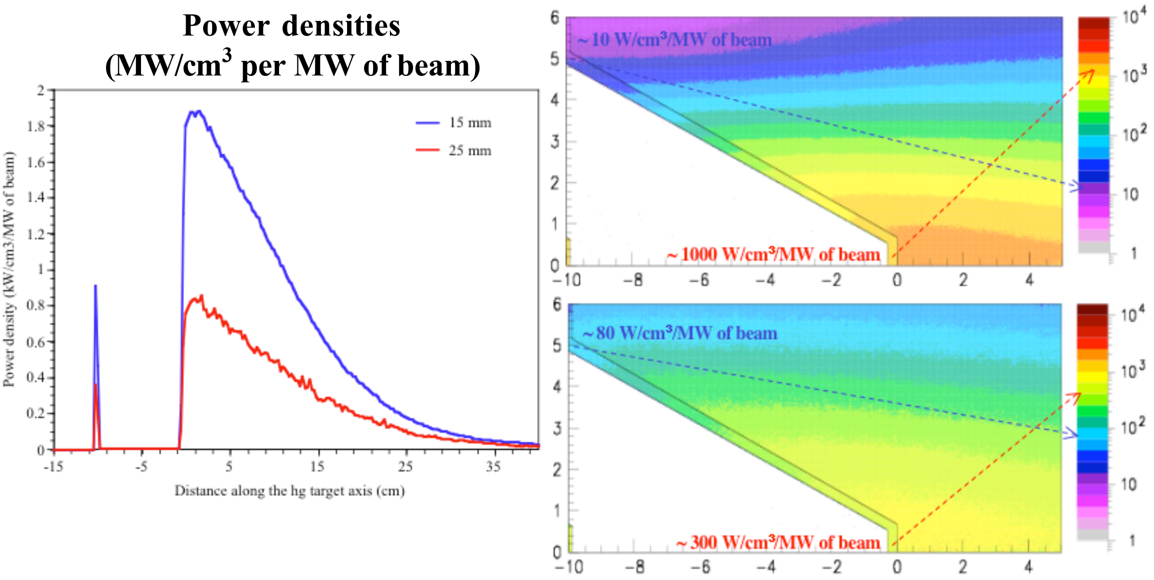


Figure 4. Power density distribution for different beam widths, along the beam axis and around the window.

Once the beam window was optimised, the liquid mercury flow inside the target container was recalculated to minimise pressure losses while ensuring adequate cooling and preventing boiling and cavitation in the back-swept surfaces. Several design changes were performed to improve the flow, such as the use of annular blades along the beam window to accelerate the flow, increase the local cooling and reduce the pressure drop at the 180-degrees turn. Holes through the guide tube were also foreseen to avoid recirculation.

With this design and a bulk pressure of 7.5 bar, the maximum temperature in the beam window is ~200 °C and the maximum von-Misses stress ~135 MPa. Concerning the mercury flow, the peak temperature is 180 °C (at the beam axis, 2 cm away from the interaction point) and 6 m/s is the maximum velocity (in the channels formed by the flow-guides and the walls, at the 180-degrees turn).

Figure 5 represents the temperature distributions within the structural materials (a), and in the flowing mercury (b). Note the sharp temperature gradient in the beam window, main source of difficulties in the design of this element.

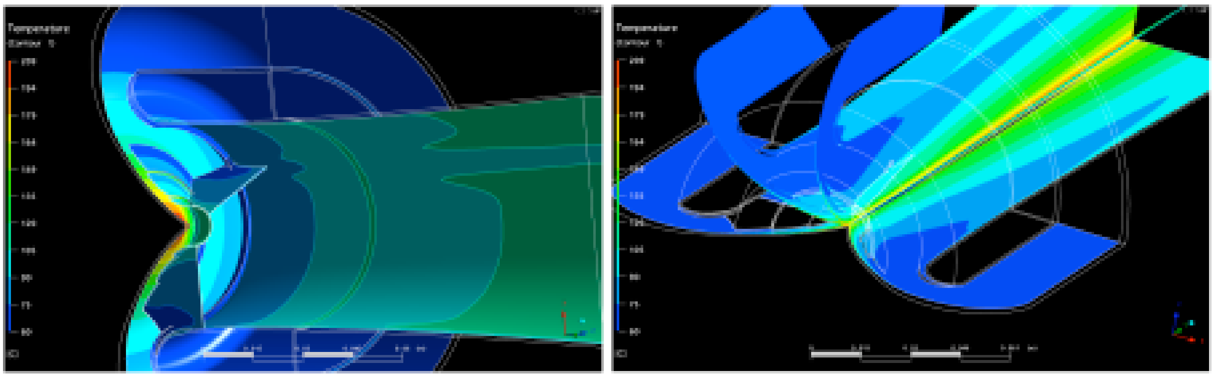


Figure 5. Temperature distribution in the structures of the container (a), and within the mercury flow (b).

Alternative transverse mercury film spallation target

An alternative and innovative windowless design was also developed to avoid the technical difficulties related to the beam window, also presenting several advantages in terms of neutronics. The transverse windowless mercury film would fall by gravitation, interacting with the proton beam to produce spallation neutrons and efficiently removing the heat deposited at reasonable flow rates. The most relevant benefit of such design is the brief exposition of the liquid metal to the proton beam, thus permitting an accurate control of the temperature increase in the molten metal. This is also achieved setting the local velocity by varying the pitch between flow-guides depending on the beam cooling requirements.

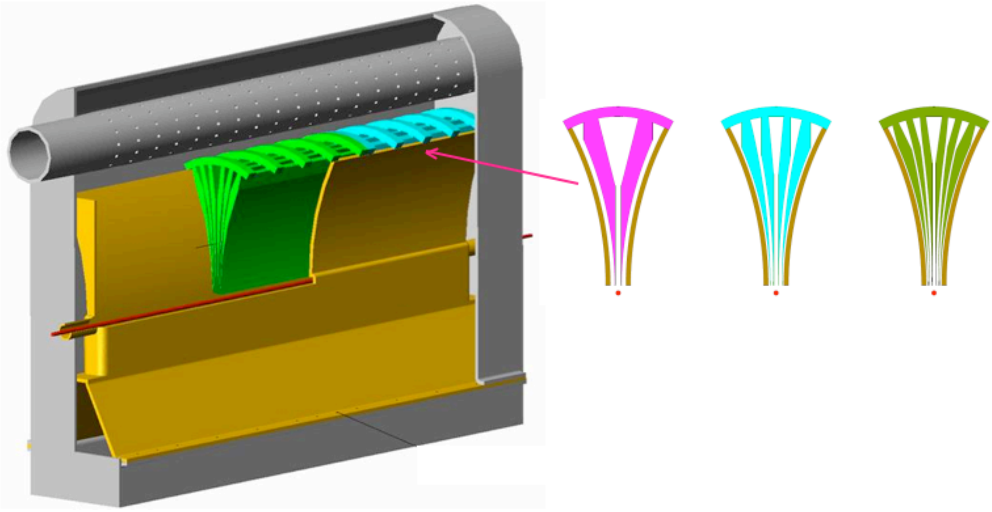


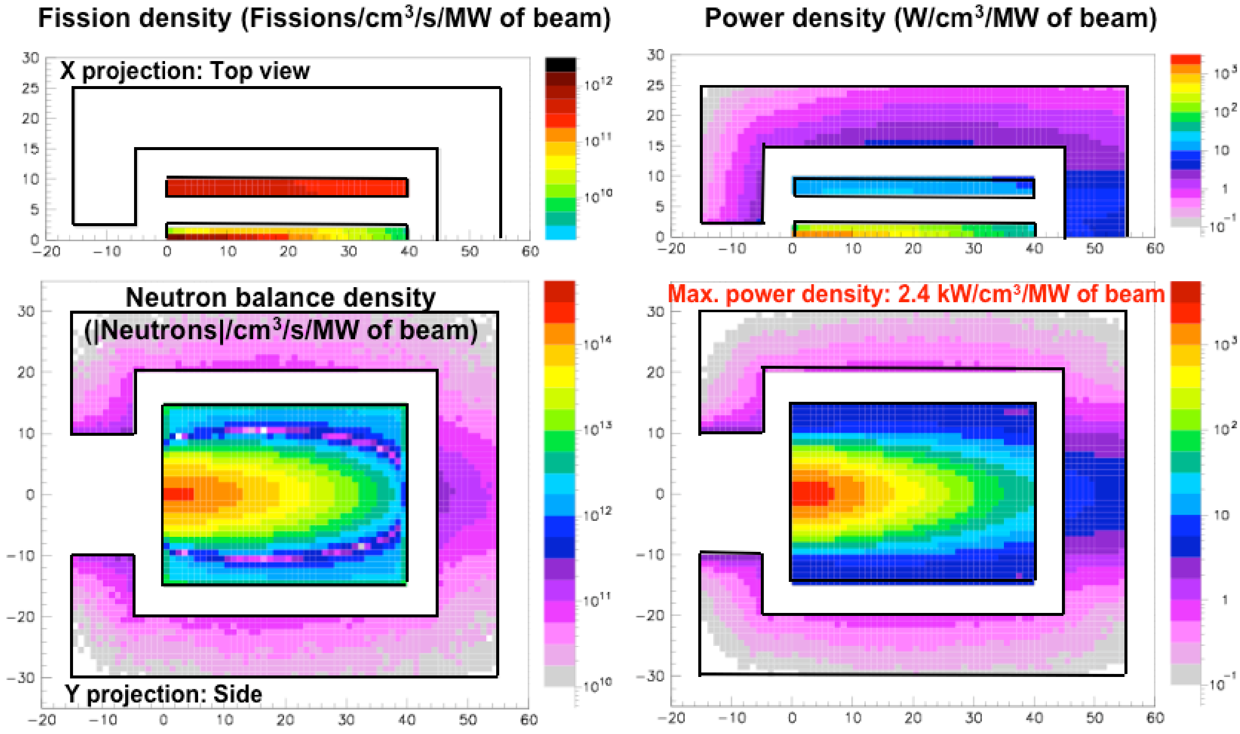
Figure 6. Schematic view of the liquid metal transverse flow target, including the variable pitch flow-guide segments to regulate the flow rate for different power densities.

Figure 6 shows the basic layout of such design, where the proton beam path is represented by a red line. The liquid metal flows through the upper tube and the fins guide the falling mercury.

Below the interaction point, the mercury is recovered and driven to the auxiliary circuit some 10 m away, where the volatile separator, the magnetic pump and the mercury reservoir are placed.

The technical simplicity of the system, in particular of the beam-target interaction as a free surface, facilitates its operation for extended periods of time by eliminating the need to exchange targets every few months due to beam window radiation damage and aging [5]. Moreover, the reduced thickness of the film produces a harder neutron spectrum and permits the positioning of flat actinide fission targets closer to the interaction point. This fact increases the fission density rates and reduces the higher actinide production, by favouring fission reactions rather than capture. The film is decoupled in two regions, a central one (~1 cm thick), receiving the direct impact of the beam and flowing at greater speed, and an external one, (~1.5 cm thick on each side), confining the former, to reduce the high-energy escapes and maximise the production of spallation neutrons.

The proton beam is mostly contained within the proton-to-neutron converter, as opposed to the mercury jet design previously proposed in [2]. The neutron flux in the fission targets reaches 2×10^{14} n/cm^2/s per MW of beam and the proton and neutron distributions are similar to that of the mercury jet option [2, 9]. High fission densities (~5×10^{11} fissions/cm^3/s per MW of beam, Figure 7) are achieved, allowing for the aimed RIB yields with reduced fission target volumes (1 – 5 litres). The neutron balance shows that the neutron-producing region extents to ~40 cm along the beam axis.


Fission density (Fissions/cm^3/s/MW of beam)

Power density (W/cm^3/MW of beam)

Figure 7. Neutronic parameters for the transverse film configuration, showing high and homogeneous fission densities in the UC_3 target and the power density distribution.

The maximum power density for a wide beam (σ_x ~4 mm, σ_y ~30 mm) is 2.4 KW/cm^3 per MW of beam. Even for more concentrated proton beams, i.e. $\sigma_{x,y}$ ~2 mm and 20 KW/cm^3 per MW of beam, this design would remove the energy deposited with moderate flow rates (~4 m/s), keeping temperatures well below the boiling point of mercury (ΔT ~100 K) [15].

In terms of RIB production, there is a clear advantage in using this design, particularly for the symmetric neutron-rich fission fragments. In fact, the transverse film design equals, and for some isotopes exceeds, the mercury jet estimated performance, as presented in Figure 8. As an example since krypton and tin are two of the most relevant elements in the EURISOL DS physics case [2], this system could produce up to 5×10^{13} isotopes/s of ^{90}Kr and ^{132}Sn for a 4 MW proton beam and a total UC_3-target volume of 5 litres.

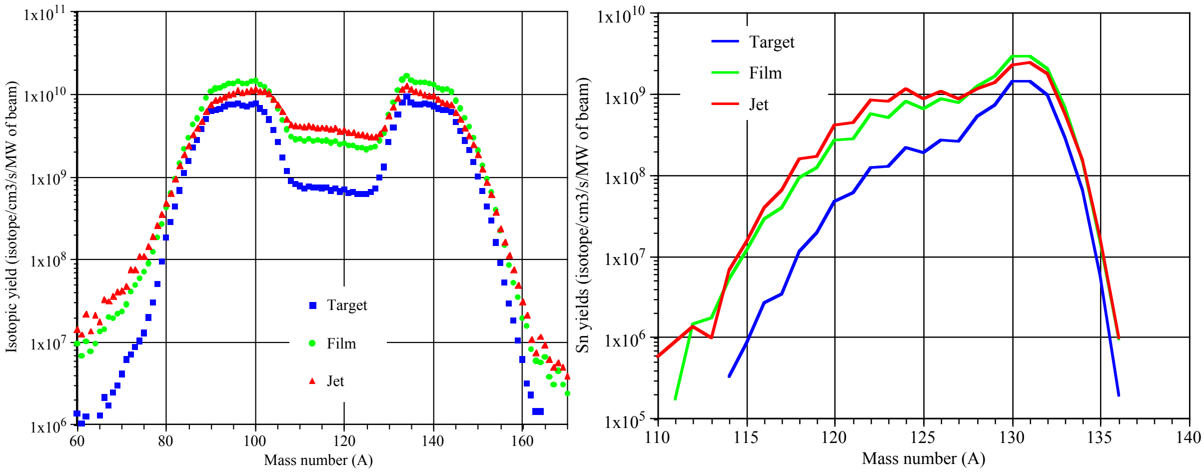


Figure 8. Fission fragment distribution (a), and Sn isotopic distribution (b), in UC_3 targets for different three different target designs (nuclei/cm^3/s per MW of beam).

Liquid metal loop experimental tests

The experimental validation of the liquid metal loop has been carried out by the Institute of Physics at the University of Latvia (IPUL), where a prototype mercury loop and transverse film have been studied. The film behaviour and flow stability seems compatible with the EURISOL design requirements, although further tests, involving larger mass flows and the addition of heat deposition, should be performed. As previously mentioned, in order to test the feasibility of the proposed design, a mock-up of the transverse film target was developed and constructed, with a length of 100 mm and a width of 10 mm (Figure 9).

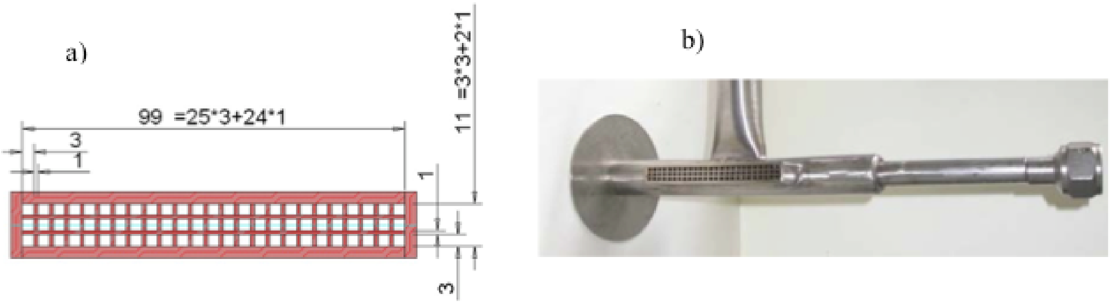


Figure 9. Schematic representation of the transverse film target honeycomb (a), and injector prototype (b).

The model was installed in an adapted indium-gallium-tin loop, presented in Figure 10. The film observed was rather stable, with a few droplets detaching from the main body [15]. Nevertheless, further studies shall be carried out, improving the visualisation of the film and increasing the flow rates and dimensions to progressively approach the real configuration.

Figure 10. View of the liquid metal experimental loop (a), including the magnetic pump (to the left, in blue). Front view of the liquid metal transverse film (b).

Conclusions

The technical feasibility of such an innovative target assembly has been demonstrated by Monte Carlo and finite element calculations as well as by the experimental tests. The high-energy neutron-induced fission densities aimed for can be achieved with the proposed multi-MW target baseline design, by using moderate proton beam intensities and reasonable fission target volumes, independently of the actinide composition. A 1 GeV proton beam on a compact mercury proton-to-neutron converter seems favourable to obtain fluxes above 10^{14} n/cm^2/s/MW of beam, producing more than 10^{11} fissions/cm^3/s per MW of beam, and intense RIBs.

The beam-window and mercury flow design have been carefully addressed, producing a configuration which will keep stresses below rupture limits under radiation in the window and avoid cavitation within the liquid metal. Maximum flow rates of ~6 m/s under 7.5 bars of pressure seem aceptable, removing the 2.4 MW of beam power deposited within the system and maintaining stresses below 150 MPa in the beam window.

Nevertheless, an alternative windowless spallation neutron target design has been produced based on the transverse film concept, technically simple and showing improved neutronic performances. This innovative design, experimentally tested, would allow for higher power densities, avoiding the need to replace the beam window every few months.

Due to the intense neutron flux within the assembly, there are obvious potential synergies between EURISOL and other nuclear physics activities. For example, a neutron escape line could be foreseen for neutrino physics, time-of flight measurements and other neutron applications (e.g. material science), without hindering the performance of the ISOL facility.

Acknowledgements

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References

[1] *EURISOL DS; European Isotope Separation On-Line Radioactive Ion Beam Facility Design Study*, EC – FP6 Research Infrastructure Action- Structuring the European Research Area, Project Contract no. 515768 RIDS.

[2] J. Cornell (Ed.), *The EURISOL Report: A Feasibility Study for a European Isotope-Separation-On-Line Radioactive Ion Beam Facility*, GANIL, France, 2003.

[3] G. Bauer et al. (Eds.), *ESS: A Next Generation Neutron Source for Europe*, ISBN 090 237 6 500 and 090 237 6 659, ESS Council, March 1997.

[4] G. Bauer et al., *Target Options for SINQ – A Neutronic Assessment*, TM-36-97-04, Paul Scherrer Institute, Villingen PSI, Switzerland, 1998.

[5] The SNS Collaboration, *National Spallation Neutron Source Conceptual Design Report – Volume 1*, NSNS/CDR-2/V1, Oak Ridge National Laboratory, United States, May 1997.

[6] A. Herrera-Martínez, Y. Kadi, *EURISOL-DS Multi-MW Target: Preliminary Study of the Liquid Metal Proton-to-Neutron Converte*r, CERN-AB-Note-2006-013 and EURISOL-DS/TASK2/TN-2005-01.

[7] A. Fassò, A. Ferrari, J. Ranft, and P.R. Sala, *FLUKA: a multi-particle transport code*, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[8] A. Herrera-Martínez, Y. Kadi, *EURISOL-DS Multi-MW Target: Neutronic Calculations for the Baseline Configuration*, CERN-AB-Note-2006-035 and EURISOL-DS/TASK2/TN-2006-05.

[9] A. Herrera-Martínez, Y. Kadi, *EURISOL-DS Multi-MW Target: Comparative Neutronic Performance of the Baseline Configuration vs. the Hg-Jet Option*, CERN-AB-Note-2006-037 and EURISOL-DS/TASK2/TN-2006-07.

[10] M. Lindroos, *The Technical challenges of Beta-beams*, EURISOL-DS/TASK12/CONF-05-01.

[11] A. Ferrari et al., *Recent Developments in the FLUKA Nuclear Reaction Models*, in the proceedings of the 11th International Conference on Nuclear Reaction Mechanisms, Varenna, Italy, June 12-16, 2006.

[12] A. Herrera-Martínez, Y. Kadi, *Radioactive Ion Beam Production by Fast-Neutron-Induced Fission on Actinide Targets at EURISOL*, in Proceedings of Science (POS), International Workshop on Fast Neutron Detectors and Applications (FNDA 2006), Cape Town, South Africa, 3-6 April 2006 and EURISOL-DS/TASK2/CONF-2006-08.

[13] M. Felcini, A. Herrera-Martínez, Y. Kadi, T. Otto, L. Tecchio, *Design of the Multi-MW Target Assembly: Radiation and Safety Issues*, in Proceedings of the OECD-organised 8th International Meeting on Shielding Aspects of Accelerators, Targets and Irradiation Facilities, (SATIF-8), Pohang, Republic of Korea, 22-24 May 2006.

[14] M. Ashrafi-Nik, *Thermo hydraulic optimisation of the EURISOL DS target*, TM-34-06-0, Paul Scherrer Institute, Villingen PSI, Switzerland, 2006.

[15] J. Freibergs, E. Platacis, *Engineering design and construction of a function Hg-loop*, EURISOL DS Task 2 Internal Note, Institute of Physics at the University of Latvia (IPUL), 2007.