EURISOL Multi-MW Target Station – MAFF Configuration – Neutron Fluxes, Fission Rates, Dose Rates and Activation

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Abstract

The EURISOL (The EURopean Isotope Separation On-Line Radioactive Ion Beam) project aims at producing high intensity radioactive ion beams produced by neutron-induced fission on fissile targets (^{235}U) surrounding a liquid mercury converter. A proton beam of 1GeV and 4MW impinges on the converter, generating, by spallation reactions, high neutron fluxes that induce fission in the surrounding fissile targets.
In this work the state-of-the-art Monte Carlo codes MCNPX and FLUKA were used to assess the neutronics performance of the system, which geometry, inspired in the MAFF concept, allows a versatile manipulation of the fission targets. The first objective of the study was to optimize the geometry and the materials used in the fuel and reflector elements of the system, in order to achieve the highest possible fission rates. Indeed, it is shown that the appropriate combination of fission target material and surrounding reflector material leads to the aimed value of 10^{15} fissions/s per fission target. The second part of this work is related to safety parameters. Dose rate and activation calculations were carried out in order to identify the necessary shielding and access restrictions for each section of the entire facility, including maintenance, storage and remote control spaces.
The results presented in this work indicate that there are good prospects for the feasibility of the EURISOL fission target, in its new configuration, considered in this work. The safety analysis indicates that some points of the facility need special attention from the safety and radioprotection points of view.

Introduction

The EURISOL (European Isotope Separation On-Line Radioactive Ion Beam Facility) project aims to build in Europe, in a yet unspecified location, a nuclear facility for the production of radioactive ion beams (RIBs). The EURISOL facility will produce RIBs with intensities two to three orders of magnitude higher than those presently available, with applications in diverse research fields, like Nuclear Physics, Nuclear Astrophysics, Fundamental Interactions, Solid State Physics and Nuclear Medicine.

The proposed scheme for the EURISOL facility is represented in **Fig. 1**. A 4mA proton beam is accelerated to 1GeV in the driver-accelerator, the resulting power being 4MW. The proton beam hits a spallation target of liquid mercury, and the resulting neutron fluxes induce fission in fission targets that surround the spallation target. The assembly composed by the spallation target and the fission targets is called the *Multi-MW Target Station*.

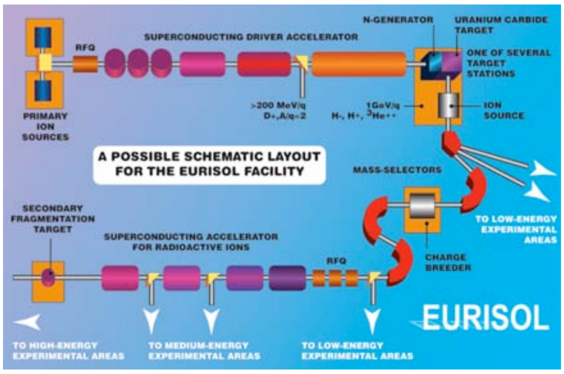

Fig. 1: The proposed scheme for the EURISOL facility.

The fission products that are formed in the fission targets are then ionized, extracted from the targets, mass separated and accelerated in the post-accelerator to the different energies required in the different experimental areas.

The objective of this work was to access the neutronics of the multi-MW target station of the EURISOL facility. This task was accomplished using the state-of-the-art Monte Carlo codes MCNPX [1] and FLUKA [2] [3].

The EURISOL multi-MW target station

The MAFF (*Munich Accelerator for Fission Fragments*) inspired configuration proposed for the multi-MW target station of the EURISOL facility is shown in **Fig. 2** [4] [5]. This was one of the main regions studied in this work.

The spallation target is composed by liquid mercury, which circulates in a loop. The fission targets (red) are located close to the spallation target, inside 7m long tubes, which are called *Extraction Tubes*, because the fission products are extracted through them. There are six extraction tubes in total.

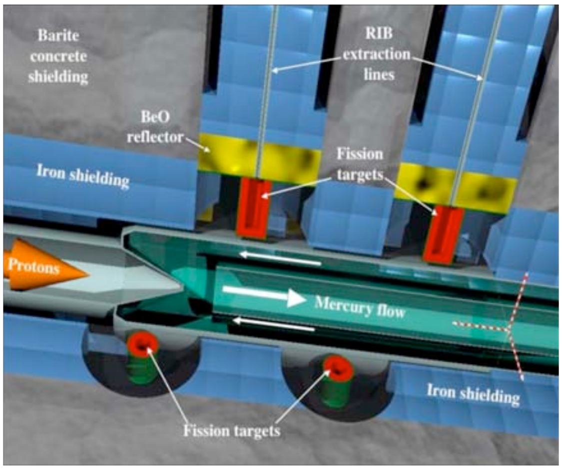

Fig. 2: Schematic view of the multi-MW target station of the EURISOL facility.

The implementation in FLUKA of the multi-MW target station is shown in **Fig. 3**. Two different cuts can be seen (planes x=0 and z=0). On the image on the right the proton beam direction is perpendicular to the plane of this page, and three of the six extraction tubes are shown (the missing row is behind the plane of this page).

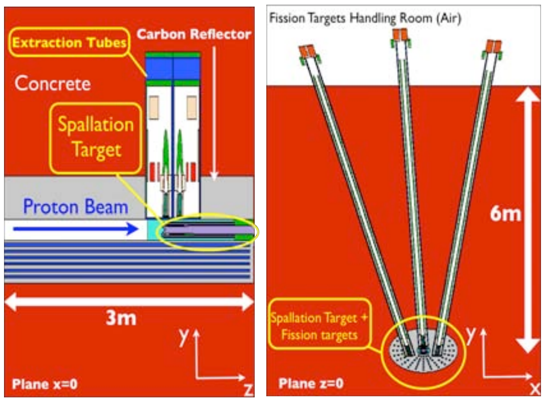

Fig. 3: FLUKA implementation of the multi-MW target station.

Results

In **Fig. 4** the neutron fluxes in the spallation and fission targets region are shown, for the planes represented in **Fig. 3**.

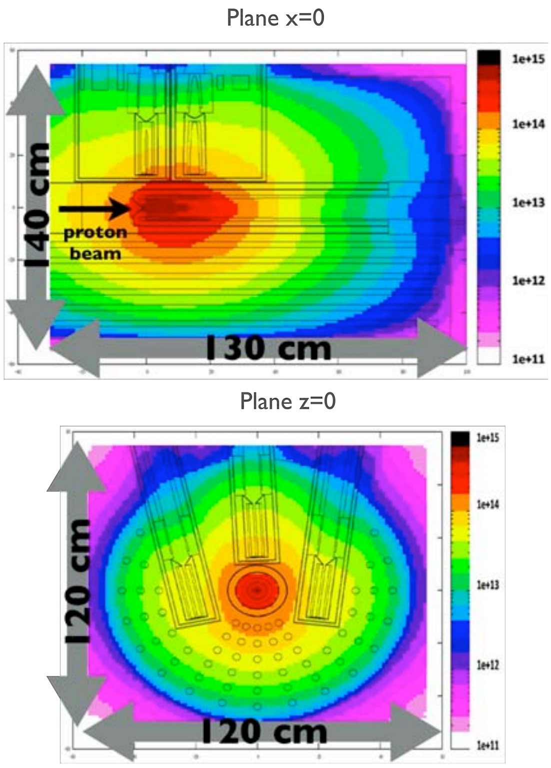

Fig. 4: Neutron fluxes (neutrons/cm^2/mA) in the spallation and fission targets region.

The neutron fluxes are very intense, with peak values of the order of 10^{15} neutrons/cm^2 for the 4MW beam (note that the presented results are normalized per 1mA of the incident proton beam, and therefore have to be multiplied by 4 for the 4mA beam). The neutron fluxes are more intense in the impact point of the proton beam in the spallation target, and decrease almost constantly with the distance to this point. The fission targets are located close to the spallation target to get the highest neutron fluxes possible.

Fig. 5 presents the fission rates achieved with different fissile materials, listed in **Table 1**. The highest fission rate is of 6.4×10^{15} fissions/s, which is above the aimed value of 1×10^{15} fissions/s. In this case, the material in the fission target is ^{235}U dispersed in a matrix of grafite. The analysis of the results shows that the system is well optimized for fission in ^{235}U.

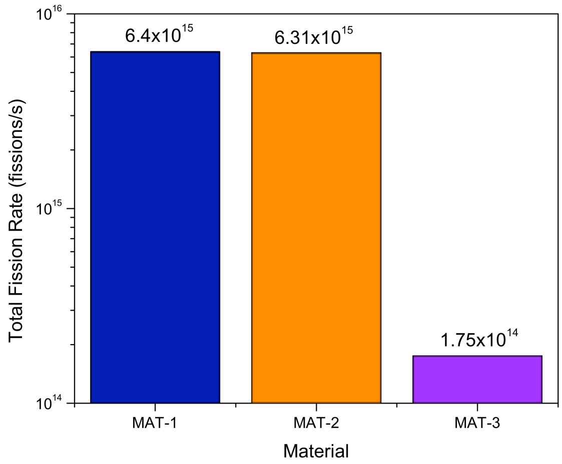

Fig. 5: Total fission rates (six targets) with different materials in the fission targets.

Material ID	Density (g/cm^3)	Composition
MAT-1	1.883	Carbon (95.58%) ^{235}U (4.42%)
MAT-2	4.4	^{238}U (93.4%) Carbon (4.7%) ^{235}U (1.9%)
MAT-3	9.86	ThO_2

Table 1: Materials tested in the fission targets.

Fig. 6 shows the dose maps in the same planes shown before, during the operation of the facility. The dose in the impact point of the proton beam in the spallation target is of the order of 10^{10} Sv/h/cm^3, and decreases with the distance to this point.

Fig. 7 shows the dose maps in the same planes one day after the stoppage of the proton beam. These doses are only due to the decay of the radioactive products that are formed in the different materials. The peak value is of about

10^6 Sv/h/cm^3, about four orders of magnitude lower than during operation. It is also important to notice that the distribution pattern of the doses is now different. The highest values for the dose are not only in the impact point of the proton beam but also in the fission targets. This is due to the variety of radioactive fission products that are formed in the fission targets.

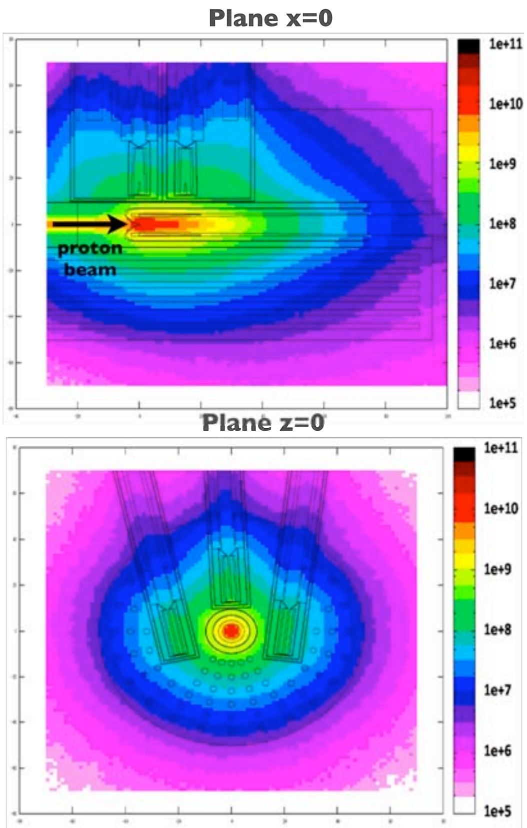

Fig. 6: Doses (Sv/h/cm^3) in the spallation and fission target regions, during operation.

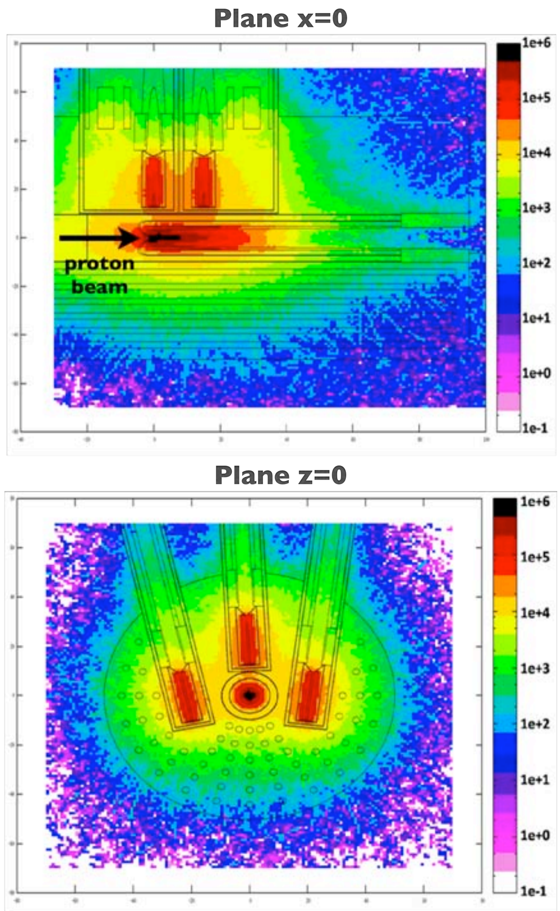

Fig. 7: Doses (Sv/h/cm^3) in the spallation and fission target regions, 1 day after shutdown.

Fig. 8 represents the dose rates 10 years after the shutdown of the facility. In the most activated regions, like the spallation target and the fission targets, the activities are still of the order of 100 Sv/h/cm^3.

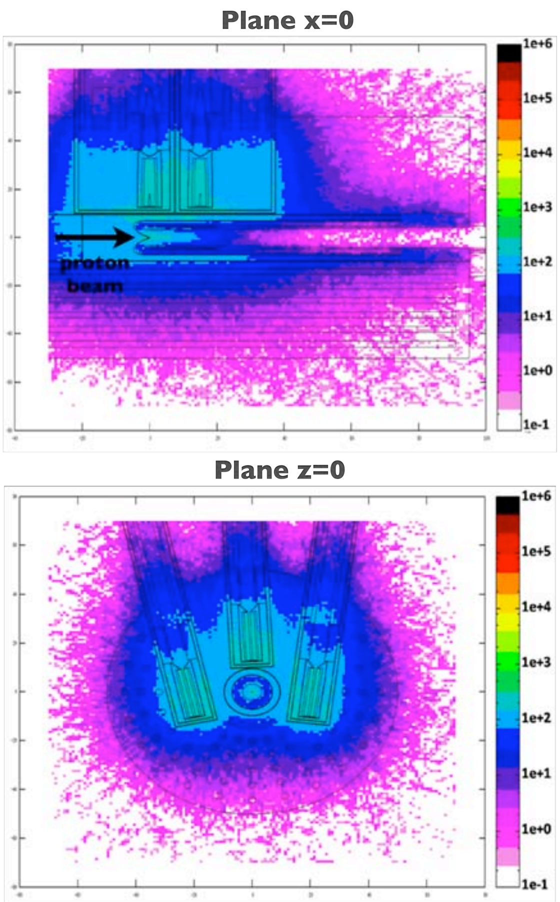

Fig. 8: Doses (Sv/h/cm^3) in the spallation and fission target regions, 10 years after shutdown.

The bottom of an extraction tube is represented in detail in **Fig. 9**. The extraction tubes need to be exchanged from time to time, due to the burnup of the fission targets, and so the conditions in which they are going to be handled must be known. It is very important to know the activities in all the regions of the extraction tubes, to estimate the dose a worker would be subject to if in contact with the extraction tubes. For this reason, the activities in each of the regions shown in **Fig. 9** were calculated, as well as the nuclides responsible for those activities.

Fig. 10 shows the evolution of the activity with the cooling time in the fission target container, the small volume region that surrounds the fission target. Two materials were tested for this region: tantalum and molybdenum.

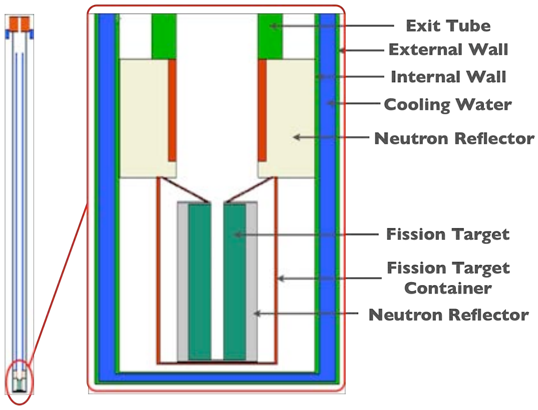

Fig. 9: Extraction tubes geometry.

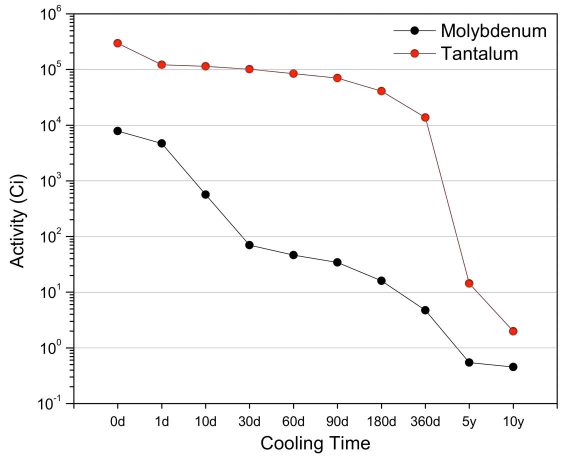

Fig. 10: Fission target container activity evolution: tantalum *vs* molybdenum.

Tantalum proved to be much more activated than molybdenum. As an example, the activity in the tantalum container two months after shutdown is of the order of 10^5 Ci, which is huge for such a small volume. Therefore molybdenum is a much better choice than tantalum, from the radioprotection point of view.

Fig. 11 shows the activity evolution with the cooling time in the structural components, which are the external wall of the extraction tube, the internal wall, and the exit tube. Two materials were also compared in this case:

aluminum and L316 stainless steel. The chart shows that aluminum was much less activated than stainless steel. The fact that stainless steel is better from the structural point of view makes the decision more difficult in this case.

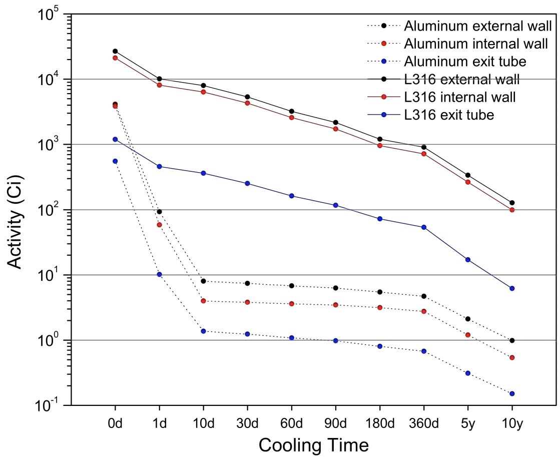

Fig. 11: Structural components activity evolution: aluminum *vs* L316 stainless steel.

Cooling Water			
Time after shutdown	Total Activity (Ci)	Main nuclides responsible for the activity	
0d	$5.39x10^2$	^{11}C (72.7%)	^{7}Be (20.9%)
1d	$1.93x10^1$	^{7}Be (76.1%)	^{3}H (23.6%)
10d	$1.74x10^1$	^{7}Be (74.0%)	^{3}H (25.7%)
30d	$1.40x10^1$	^{7}Be (68.7%)	^{3}H (30.9%)
60d	$1.03x10^1$	^{7}Be (59.9%)	^{3}H (39.6%)
90d	$7.79x10^0$	^{7}Be (50.4%)	^{3}H (49.0%)
180d	$4.14x10^0$	^{3}H (74.8%)	^{7}Be (24.2%)
360d	$2.60x10^0$	^{3}H (95.7%)	^{7}Be (3.1%)
5y	$1.95x10^0$	^{3}H (98.4%)	^{14}C (1.6%)
10y	$1.48x10^0$	^{3}H (97.9%)	^{14}C (2.1%)

Table 2 – Activities in the cooling water.

Table 2 summarizes the results for the activities in the cooling water of the extraction tube. The cooling water circulates between the internal and the external walls, and it needs to be removed before the extraction tubes are exchanged. Therefore, the activity of the water must be known. There are total activities of about 500Ci at the moment of shutdown and about 15Ci ten years after shutdown. The nuclides responsible for these activities are also listed, and it can be seen that for most of the cooling periods ^{3}H and ^{7}Be are the main nuclides responsible for the activities registered in the cooling water.

Table 3 lists the activities and the main nuclides responsible for the activities in the fission target. The production of radioactive fission products makes the fission targets one of the most activated regions of the extraction tubes. Only a few nuclides are listed here, because the complete lists are very long.

Conclusions

The multi-MW target station of the EURISOL facility will be a very complex system from the radioprotection and waste management points of view. This work intended to give a contribution to a better knowledge of the system and to provide important information for future decisions regarding material choices, cooling times needed before accessing the different regions and access type to these regions.

A fission rate of $6.4x10^{15}$ fissions/s was obtained, with ^{235}U dispersed in a matrix of grafite as fissile material. This result is above the aimed value of $1x10^{15}$ fissions/s, and this means that the system is well optimized for fission in ^{235}U.

Fission Target					
Time after shutdown	**Total Activity (Ci)**	**Main nuclides responsible for the activity**			
0d	$1.56x10^5$	^{131}I (20.9%)	^{133}I (12.3%)	^{140}Ba (5.8%)	^{132}Te (5.6%)
1d	$2.82x10^4$	^{131}I (27%)	^{133}I (8%)	^{140}Ba (7.7%)	^{89}Y (6.7%)
10d	$1.37x10^4$	^{131}I (24.1%)	^{91}Y (11.4%)	^{144}Ce (9.7%)	^{89}Sr (9.5%)
30d	$8.10x10^3$	^{144}Ce (17.4%)	^{91}Y (16.9%)	^{89}Sr (13.5%)	^{131}I (81%)
60d	$5.10x10^3$	^{144}Ce (25.8%)	^{91}Y (18.9%)	^{89}Sr (14.3%)	^{95}Zr (8.7%)
90d	$3.60x10^3$	^{144}Ce (31.6%)	^{91}Y (17.5%)	^{89}Sr (12.5%)	^{95}Zr (8.3%)
180d	$1.61x10^3$	^{144}Ce (43.7%)	^{90}Sr (12.7%)	^{91}Y (10.3%)	^{137}Cs (6.3%)
360d	$6.11x10^2$	^{144}Ce (49.1%)	^{90}Sr (21.9%)	^{137}Cs (10.9%)	^{106}Ru (7.1%)
5y	$8.94x10^1$	^{90}Sr (60.1%)	^{137}Cs (30.1%)	^{144}Ce (4.2%)	^{90}Y (2.7%)
10y	$5.56x10^1$	^{90}Sr (64.3%)	^{137}Cs (32.4%)	^{90}Y (2.9%)	^{147}Pm (0.2%)

Table 3 – Activities in the fission target.

Very high doses were registered during operation, especially near the impact point of the proton beam, where the proton and neutron fluxes are the highest. The doses are still high after the stoppage of the beam, due to the decay on the radioactive nuclides that are formed in the different materials by activation. For this reason, the access to the multi-MW target station will have to be made by remote control, when maintenance is required. The most activated regions are the spallation target and the fission targets.

The analysis of the activities in the extraction tubes shows that molybdenum is a better choice than tantalum for the fission target container and that aluminum is a better option than L316 stainless steel in the structural components, from the radioprotection point view.

Acknowledgements

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