

Assessment of the deuteron irradiation distribution in the LIPAc High-Power Beam Dump during Commissioning Phase B+

V. Lopez^{a,*}, K. Kumagai^b, D. Jimenez-Rey^c, Y. Qiu^d, K. Kondo^b, K. Ochiai^b, F. Ogando^a, A. Čufar^e

^a Universidad Nacional de Educación a Distancia (UNED), Madrid, Spain

^b National Institutes for Quantum Science and Technology (QST), Aomori, Japan

^c CIEMAT, Madrid, Spain

^d Karlsruhe Institute of Technology, (KIT), Karlsruhe, Federal Republic of Germany

^e Reactor Physics Department, Jožef Stefan Institute (JSI), Jamova Cesta 39, Ljubljana, SI-1000, Slovenia

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ABSTRACT

The Linear IFMIF Prototype Accelerator (LIPAc) aims to demonstrate the feasibility of operating a 125 mA deuteron beam up to continuous wave (CW), a key milestone for the development of future fusion-relevant neutron sources such as IFMIF-DONES and A-FNS.

In this work, the deuteron irradiation distribution in the High-Power Beam Dump (HPBD) was evaluated during the LIPAc Commissioning Phase B+, when a deuteron beam of approximately 120 mA and 5 MeV (with a maximum pulse duty of 8.75%) was achieved. The irradiation profile was inferred indirectly by comparing neutron flux measurements obtained from activation foils with Monte Carlo radiation transport simulations.

Results seem to indicate a more spatially distributed deuteron footprint than previously assumed. Although variations in irradiation distribution can influence thermomechanical stresses in the beam dump, the observed profile leads to a lower maximum power density and is therefore not expected to pose operational concerns. The findings also demonstrate the effectiveness of activation foils as a complementary diagnostic for beam irradiation, providing valuable data for neutron flux characterization and informing safe operation during subsequent LIPAc phases.

1. Introduction

The deuterium-tritium (D-T) reactions in future nuclear fusion reactors will give rise to very intense neutron fields. The 14.1 MeV neutrons emitted in the D-T reactions can escape the plasma confinement and irradiate the structural and shielding components. Material irradiation causes atomic displacements within the material. But in fusion environments, irradiation also causes the production of gas atoms due to reactions including a neutron capture followed by a proton or an α -particle emission (Gilbert et al., 2012). Safe licensing and operation therefore require demonstrating material performance after the irradiation under these extreme conditions. This needs to be demonstrated through material irradiation in a suitable neutron source facility under fusion-relevant conditions.

Fusion relevant neutron sources such as IFMIF-DONES (Ibarra et al., 2018) or A-FNS (Sato et al., 2021), both based on the IFMIF concept, will

allow these studies. The IFMIF/EVEDA Project has the goal of producing a detailed, complete and fully integrated engineering design of the IFMIF, and it has been carried out by Japan and EURATOM under the Broader Approach agreement since February 2007. As part of the IFMIF/EVEDA Project, the Linear IFMIF Prototype Accelerator (LIPAc) aims to demonstrate the feasibility of the operation of a 125 mA deuteron beam up to continuous wave (CW). This will be achieved by the manufacturing, installation, commissioning and testing activities of a 1:1-scale prototype accelerator until the first cryomodule (Dzitko et al., 2021).

The LIPAc “Phase-B+” commissioning configuration achieved a peak deuteron beam current of approximately 120 mA, with acceleration up to 5 MeV and a maximum pulse duty of 8.75%, using the radiofrequency quadrupole (RFQ). A comprehensive description of the beam characterization can be found in (Hyun et al., 2025). In previous works (Kumagai et al.) different types of measures were used to quantitatively

* Corresponding author.

E-mail address: vlopez@ind.uned.es (V. Lopez).

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evaluate the beam losses at different accelerator locations. Those measures included shutdown doses obtained with a NaI(Tl) survey meter, and decay photon spectrum using a portable High-Purity Germanium (HPGe) detector.

In this work we study the irradiation of the High-Power Beam Dump (HPBD) (Branas, 2018). Fig. 1 shows the HPBD neutronic model and the main components referenced in this study. The HPBD is opened to the end of the accelerator line and stops the deuteron in a copper cone inside a cartridge. The copper cone is water-cooled in order to dissipate the power delivered by the beam.

LIPAc is equipped with both interceptive and non-interceptive diagnostics to directly measure the beam profile. However, interceptive devices can only be operated at very low duty cycles. And the signal produced in the non-interceptive diagnostics was too low because the duty cycle achieved during the operation was not sufficiently high. A detailed description of the available diagnostics, their measurements, and the limitations encountered during this operation is provided in (Kwon et al., 2024).

The exterior of the cartridge counts with several ionization chambers (IC) in order to detect deviations from the nominal beam power deposition. However, during Phase B+ the signal from the IC was also weak and their response was not calibrated yet. Consequently, it was not possible to collect useful information for the assessment of the irradiation distribution. Due to the difficult accessibility to the interior of the HPBD, it was not possible to directly measure the activation using the NaI(Tl) survey meter and the HPGe detector either. Thus, activation foils were inserted into the HPBD through the penetrations left for the support structure. After the irradiation, the foils were recovered and their activation was measured. Finally, the measures were compared against simulations in order to extract conclusion about the neutron flux, and consequently about the deuteron irradiation of the copper cone.

2. Method

2.1. Activation foils

An activation foil consists of a sample of a material with a known composition. When irradiated, the samples produce radioisotopes depending on the neutron fluence and spectrum. Once the machine operation is completed, the foils can be recovered, and the decay photons associated with the radioisotopes can be measured. From the information on the production of radioisotopes, it is possible to infer the information associated with the neutron flux during operation (International Atomic Energy Agency (IAEA and)).

In this study, we employed five types of activation foils. The

material, dimensions, reactions, energy threshold and the semi disintegration periods are shown Table 1. The Aluminum (Al), Nickel (Ni), Indium (In) foils have high threshold energies in MeV range, while the Gold (Au) is sensitive to thermal neutrons. In this work, we define the threshold energy as the energy of the incident neutron at which the reaction cross section is higher 1 mb, according to the activation nuclear data library used. The gold foil was also installed with a Cadmium (Cd) cover, because Cd absorption cross section is large for neutron energies below about 0.4 eV, where it drops abruptly and remains low for higher neutron energies. According to (Knoll, 2000), thicknesses of the order of 0.5 mm of cadmium act as a selective filter, blocking neutrons with energy below 0.4 eV but passing higher-energy neutrons with little attenuation. The uncovered foil will respond both to the thermal and resonance neutrons, whereas the covered foil will indicate only the resonance contribution.

The activation foils were inserted into the HPBD through the penetrations left for the support structure, as indicated in Fig. 1. The activation foils were at 50 cm from the opening of the beam dump copper cone, and 50 cm below beam level.

The foils were retrieved after one day of beam operation on June 18, 2024. Gamma rays emitted from each foil were measured using the HPGe detector with lead shielding to reduce background noise. The activity of each foil, A , was calculated using the equation below.

$$A = \frac{C\lambda}{(1 - \exp(-\lambda t))\epsilon_f I_\gamma}$$

In this equation, C is the net count, λ is the decay constant, t is the measurement time, ϵ_f is the HPGe detector efficiency, and I_γ is the decay intensity. Gamma self-absorption correction is not applied.

The reaction rates in the foils were derived from the activity using the irradiation and cooling times. To convert the activity into reaction rate estimation, the operation schedule of the accelerator needs to be

Table 1

Activation foils used for quantitative beam loss measurement.

Foil	Dimensions	Reaction	Threshold	Half-life
Aluminum	10x10 × 1 mm	Al27 (n,α) Na24	5.8 MeV	15.0 h
Nickel	Φ15 × 1 mm	Ni58 (n,p) Co58	1.1 MeV	71.6 d
Indium	10x10 × 1 mm	In115 (n,n') In115 m	0.4 MeV	4.5 h
Gold (bare and w/Cd cover)	10x10 × 0.05 mm (Cd cover 0.5 mm)	Au197 (n,g) Au198	-	2.7 d

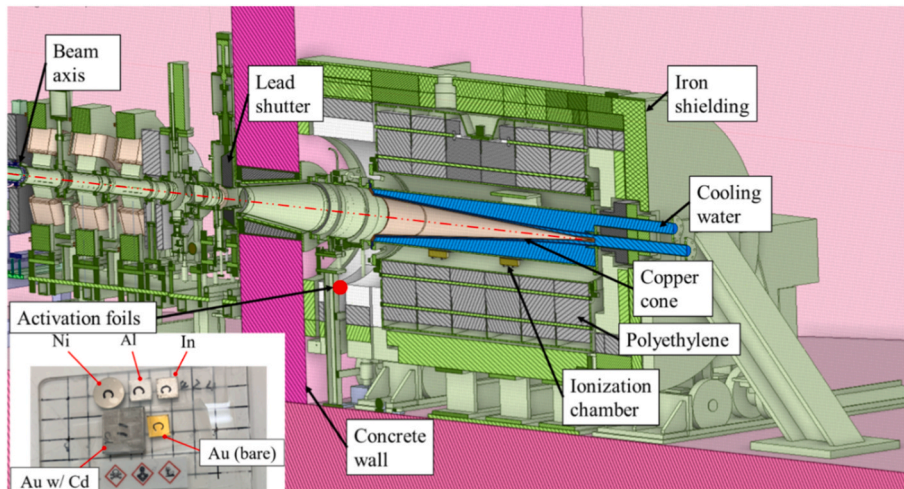


Fig. 1. LIPAc High Energy Beam Transport line neutronic model and location of the activation foils.

taken into account. The activity after a certain period is calculated with the equation below.

$$A_{i+1} = \delta_i (1 - \exp(-\lambda t_i)) \bar{R} + A_i \exp(-\lambda t_i)$$

A_i is the initial activity and A_{i+1} is the final activity of period i , t_i is the duration of that period, $\bar{R}$ is the reaction rate, and δ_i indicates whether it was a beam-on or beam-off period. The equation can be expressed recursively to account for the beam operation. The reaction rate is then isolated, thereby allowing the calculation of the reaction rate from the activity. This reaction rate can be compared with the Monte Carlo simulation. This methodology has been used in previous studies (Kumagai et al.), where the details of the measurements, the accelerator operating scheme during this day, and the method used to account for the pulsed nature of the beam during beam-on periods are described.

2.2. Simulations

Neutronic simulations aim to reproduce the experimental conditions, to estimate the neutron flux and the activation of the foils. Therefore, as first step of the analysis, we developed a detailed neutronic model of LIPAc. The models employed in previous analyses were based on highly simplified geometrical and material representations (Iglesias et al., 2011) (Kondo et al., 2016). While such simplified models proved adequate for dose calculations, they lack the level of detail required to accurately describe neutron transport and interactions. Therefore, they cannot be reliably used for experimental benchmarking or activation analysis. On the other hand, very accurate engineering models cannot be employed in neutronic simulations either, because they usually include all kinds of details about bolts and cables that have no influence on the radiation fields but that slow down the simulation, increase memory consumption, or even cause errors in the simulation.

We carried out intense work in order to produce a model adapted to the needs of the particle transport simulations while preserving all the details that are important for the accurate assessment of radiation fields. This detailed model considers an accurate representation of the full LIPAc accelerator line in its commissioning Phase B+ configuration. Fig. 1 shows CAD model of the HPBD and the High Energy Beam Transport line (HEBT) adapted for the neutronics needs, which is representative of the level of detail achieved. In addition, the model has been built with a modular and easy to modify approach. The spaces for each of the main accelerator components have been reserved. Then, the reserved space is filled with the model of the adequate component. Consequently, the detailed model can be easily adapted for future phases once the superconducting RF linac is installed. Finally, we included the activation foils in the neutronic model, preserving the real volume and material. Preserving the small volume of the foils increases the computational cost of the simulation, but it allows improving the accuracy by eliminating artificial modification of the reaction rates when the volume or material are changed. Finally, the CAD model was converted to Constructive Solid Geometry (CSG) representation used by the radiation transport code using the GEOUNED code (Catalan).

We modeled the radiation source as an anisotropic deuteron point source. The last HEBT triplet is used to defocus the beam and distribute the irradiation over the beam dump copper cone. Since the particle beam has a small radius when passing through the last quadrupole, we assume that all deuterons originate from the center of the beamline at this location. The source is considered monoenergetic (5 MeV), as the small variations in particle energy are expected to have a negligible impact on the results. The source exhibits a dependence on the polar angle and azimuthal symmetry about the beam axis. This deuteron source representation is reasonable because it allows taking into account core particles and halo particles. Smaller polar angles correspond to higher particle densities and represent the beam core, whereas larger polar angles correspond to the beam halo and are associated with progressively lower particle densities. The relative intensity assigned to

each polar angle is adjusted to reproduce the desired beam footprint at the entrance of the beam dump. The footprint is the projection of the beam onto a plane perpendicular to the beam axis at the entrance of the copper cone.

This deuteron source representation can consider small displacements of the beam in the X or Y directions. However, it does not consider differences in the X and Y distributions, describing circles instead of ellipsis. Fig. 2 shows the footprint at the entrance of the copper cone. This footprint is from (Garcia et al), and it currently is considered the reference in the project. It features the power density profile from (Brañas, 2009) obtained from beam dynamics simulations (Oliver et al). Other studies in LIPAc such as (Kumagai et al., 2025) used deuteron distributions in the HPBD close to Fig. 2, even though the approach was different.

Once the deuteron source was defined, we ran the simulations using the MCUNED-Plus code (Lopez et al., 2024), an extension of MCNP6 (Goorley et al., 2016) which implements a variance reduction technique to bias the neutron production during deuteron irradiation. This allows reducing the computational load. The reaction rates of interest in the foils were computed using a tally multiplier that results in the product of the neutron flux by the pointwise cross section. The statistical errors from the simulation and the main errors from the input data were taken into account when processing the results, as will be explained in the result section. Deuteron-induced interactions were modeled with the JENDL-5 library (Iwamoto et al., 2023) for the available elements. TENDL-2023 (Koning et al., 2019) was used to complement the JENDL-5 evaluations for the elements for which suitable deuteron data were not available. FENDL-3.2c (Schnabel et al., 2024) was used for neutron transport and TENDL-2017 for the activation calculation. TENDL-2017 is commonly used in the fusion neutronics community for the activation calculations, following the IAEA Nuclear Data Services recommendation in (Schnabel et al., 2024). IRDFF-II (Trkov et al., 2020) is not used as a comprehensive activation library due to the lack of many activation reactions. However, reactions included in the IRDFF-II library may contain better quality evaluations than those listed in TENDL-2017. Thus, TENDL-2017 was compared with IRDFF-II and experimental data. The comparison showed good agreement and thus good quality of the TENDL-2017 library for neutron activation in this analysis.

When the reaction rates calculated through the simulations didn't match the measures, we investigated the source of the discrepancy. A source contribution map was used. When a neutron is emitted from a deuteron induced reaction, its location and energy are stored. When that neutron reaches a foil, its contribution to the activation is tallied according to those location and energy. The neutrons that don't contribute to foil activation are simply disregarded. This feature allows improving

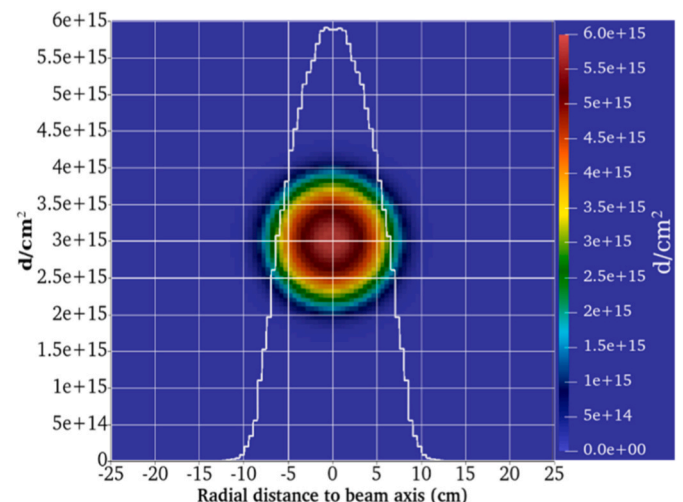


Fig. 2. Footprint at the entrance of the copper cone, color scale in d/cm^2 .

the information about the neutrons that contribute to a certain foil activation. Finally, new footprints, and their subsequent irradiation distribution, which produce neutron fields compatible with the measurements from the foils were investigated.

3. Results

The first simulation reproduced the deuteron footprint shown in Fig. 2. This distribution causes a very low irradiation of the first part of the cone while it reaches maximum values close to its center, at around 125 cm from its opening. The reaction rates and the Calculated over Experimental (C/E) values obtained in the first simulation are shown in the first column of Table 2.

This first comparison shows big discrepancies, especially in the nickel and indium foils. The discrepancies in the Au foils are not as large as those in the Ni and In foils, but they are sensitive to thermal neutrons and that implies higher uncertainties as we discuss later. Thus, we initially placed greater emphasis on the Ni and In foils.

Using the source contribution map methodology, we obtained the location of the emission of the neutrons that contributed to the activation of each foil, which is shown in Fig. 3. Curves in Fig. 3 are normalized such that their integral over the plotted domain is equal to 1. There is a clear shift in the distributions. Neutrons emitted near the cone opening are also closer to the foils and therefore were expected to contribute more to the activation in relative terms. However, it was observed that while the deuterons impacting the first 75 cm of the cone accounted for around 10% of the total, the neutrons emitted in this section caused between 60% and 70% of the activation of the foils. The conclusion is that during the operation, the beam was probably less focused, causing an increased irradiation of the first part of the cone.

Horizontal and vertical displacements of the point source of up to 5 mm were considered in the simulations. No significant effect on the calculated activation levels was observed, supporting the assumption that the measured irradiation pattern is primarily associated with beam broadening rather than source displacement.

We investigated new beam distributions, featuring lower particle densities in the beam core, and larger halos, developed with support of private communications with the team at LIPAc. The new distributions were obtained varying the relative intensities at different polar angles in the source definition. We found that this less peaked distribution resulted in better agreement with the measurements. Fig. 4 shows the new footprint at the entrance of the beam dump. The reaction rates and the C/E values are shown in the second column of Table 2.

On the one hand, the new footprint results in a very tight agreement with the measurements of the nickel and indium foils. On the other hand, the simulations seem to overestimate the activation of the gold foils. Simulations of Au foils imply higher uncertainties. However, we did not expect such discrepancies. So, in the next paragraph we

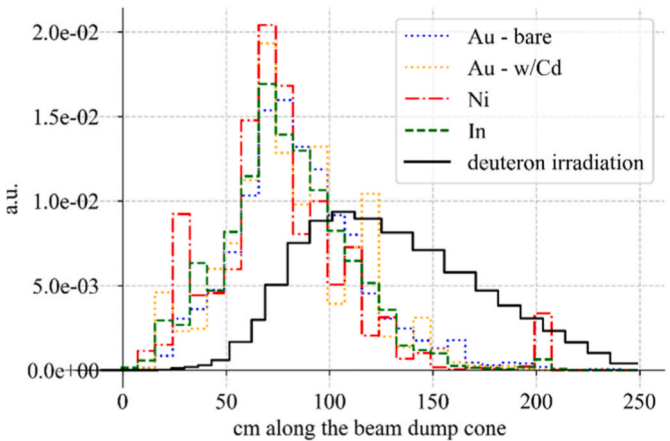


Fig. 3. Location of the emission of the neutrons that contributed to the activation of each foil compared to the location of the deuteron incidence.

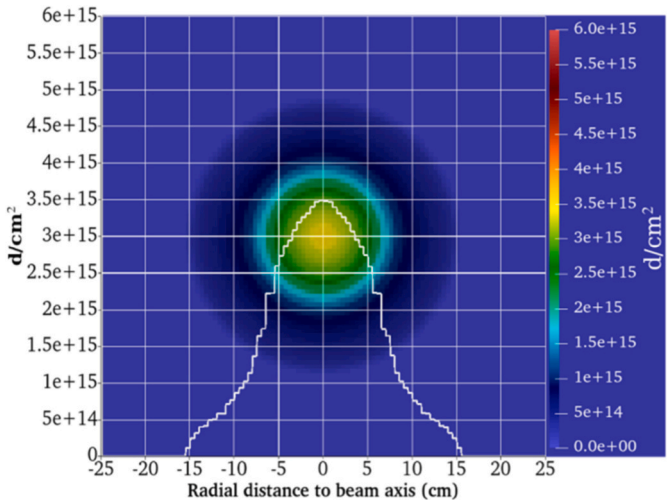


Fig. 4. Final iteration of the footprint at the entrance of the copper cone, color scale in d/cm².

investigate the source of the overestimation. The Al foil did not produce experimental data because the number of counts was below a certain detection threshold. The simulations give reaction rates consistent with the observation. However, no C/E or other analysis can be carried out.

In this case, we investigated the energy of the neutrons that

Table 2
Comparison of the measurement of the reaction rates in the activation foils and simulations with different deuteron distributions. Results are in reactions per second (s⁻¹).

Measurement (experimental error in brackets)	Original assumption about the irradiation distribution.		New assumption about the irradiation distribution.		New assumption about the irradiation distribution. Corrected by neutron emission uncertainties.		
	Simulation (MC statistical error in brackets)	C/E	Simulation (MC statistical error in brackets)	C/E	Simulation (total error in brackets)	C/E	
Al	N. D. ($<1.8 \times 10^2$)	$(2.2 \pm 1.0) \times 10^0$	-	$(6.62 \pm 0.75) \times 10^1$	-	$(6.6 \pm 1.4) \times 10^1$	-
Ni	$(4.70 \pm 0.20) \times 10^4$	$(2.38 \pm 0.16) \times 10^3$	0.06	$(4.322 \pm 0.090) \times 10^4$	0.91	$(4.32 \pm 0.78) \times 10^4$	0.91
In	$(3.20 \pm 0.10) \times 10^4$	$(2.27 \pm 0.10) \times 10^3$	0.07	$(3.416 \pm 0.049) \times 10^4$	1.06	$(3.42 \pm 0.61) \times 10^4$	1.06
Au (bare)	$(1.900 \pm 0.010) \times 10^6$	$(1.275 \pm 0.038) \times 10^6$	0.63	$(9.568 \pm 0.095) \times 10^6$	5.0	$(3.8 \pm 1.3) \times 10^6$	2.0
Au (w/Cd)	$(4.700 \pm 0.020) \times 10^5$	$(2.52 \pm 0.19) \times 10^5$	0.53	$(1.785 \pm 0.060) \times 10^6$	3.8	$(7.2 \pm 2.4) \times 10^5$	1.5

contributed to the activation of the gold foils at the moment of their emission, which is shown in Fig. 5. More than 75% of the neutrons that contribute to activation are emitted with energies lower than 2 MeV. We compared the spectrum of the neutrons produced during the irradiation of copper obtained with JENDL-5 against the available experimental data from N. Shigyo (Shigyo et al., 2011) in Fig. 6. JENDL-5 fits the spectrum within the experimental errors, except in the low energy part.

There is no experimental data for neutrons emitted with energies lower than 1.15 MeV. We compared the experimental neutron-emission data below 2 MeV available in the EXFOR database for the experiment of N. Shigyo, with the simulations of the same experiment using the JENDL-5 deuteron library. From Fig. 5 we know that these neutrons dominate the foil activation response. We found that the simulated values were approximately 2.5 times higher than the experimental values, indicating a systematic bias in the simulated neutron production below 2 MeV. Since this systematic error could be quantified, the factor of 2.5 was applied as a correction factor to the simulated gold-foil reaction rates, rather than being treated as an additional uncertainty. However, this is a rough estimation, given the scarcity of experimental data in the range of interest. We also considered random errors of 30% obtained from the experimental error provided in (Shigyo et al., 2011). For the Ni, In and Al foils, the nuclear data library shows better agreement with the experiment. We assumed a random error of 10% from the experimental measurements with no systematic error.

An accurate estimation of all sources of uncertainty in the nuclear analysis would require a workload beyond the scope of this study. However, it is expected that the uncertainty associated with the neutron source is expected to dominate over other factors, especially for the gold foils. Consequently, we assumed a combined 15% error due to geometry definition, material composition and densities, and nuclear data for neutron transport and neutron activation. We combined in quadrature the previous errors with the statistical error from the Monte Carlo simulation. The reaction rates and the C/E with the correction factor applied for the gold foils, as well as the final error estimations, are shown in the third column of Table 2.

Considering these errors, we performed a statistical analysis where the null hypothesis is that the experiment and simulation results belong to populations with the same mean value. Considering a typical significance level $\alpha = 5\%$, the null hypothesis cannot be rejected for any of the foils. This suggests that there is no compelling evidence that the newly inferred footprint differs from that during operation. Nevertheless, there is strong evidence that the original assumption was not accurate.

Finally, comparing the C/E obtained for the two gold foils, it is clear how the Cd cover was useful to absorb the thermal neutrons. The simulation shows better agreement when this low energy part of the spectrum is removed. This indicates uncertainties in the simulation of neutrons that undergo multiple scattering before reaching the foil. Thus, the error in the simulation of the bare gold foil may be even larger than

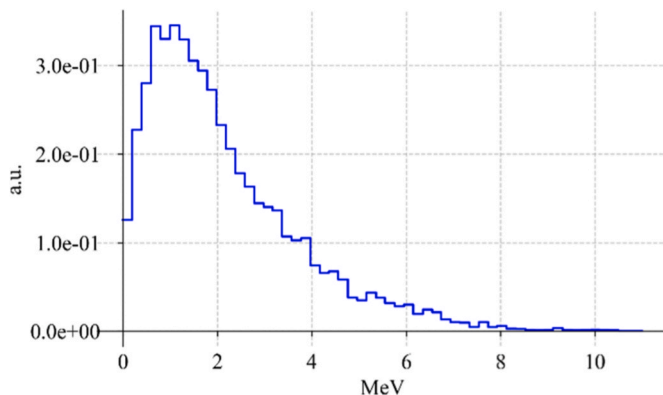


Fig. 5. Energy distribution of the neutrons that contributed to the activation of the foils at the moment of their emission.

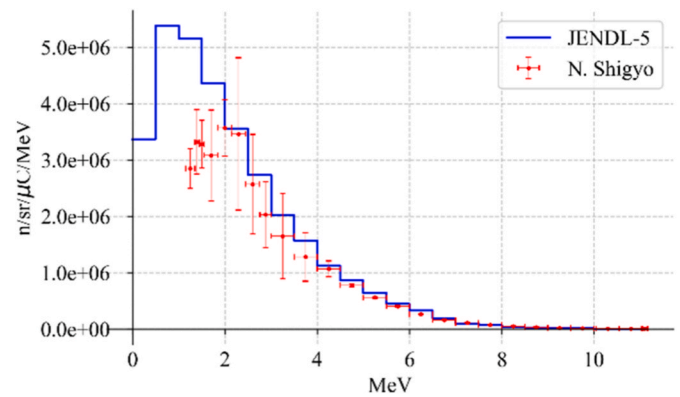


Fig. 6. Spectrum of the neutrons emitted at 140° during 5 MeV deuteron irradiation of copper.

the estimate given in the previous paragraphs.

4. Conclusions

4.1. Deuteron irradiation distribution

This work concludes that the activation foils installed during commissioning Phase B+ in the LIPAc HPBD seem to indicate a deuteron irradiation distribution on the copper cone that differs from that commonly assumed in previous studies. The deuteron footprint consistent with the observed foil activation is less concentrated, resulting in a more spatially distributed irradiation, particularly within the first meter of the cone.

Thermocouples installed on the beam pipe upstream of the copper cone showed an increase in the temperature during this operation, indicating losses before reaching the copper target due to the change in the quadrupole electromagnets current. The deuteron footprint that resulted from this study also produces the irradiation of the pipe. The results agree with the thermocouples measurements. However, it has been observed that the activation caused by these beam losses does not contribute significantly to the activation of the foils.

Fig. 7 shows the comparison of the irradiation profiles. The peak on the left side of the distribution compatible with the activation foils is due to the chamfer at the opening of the cone, which presents a surface more perpendicular to the direction of the beam. This surface is partially

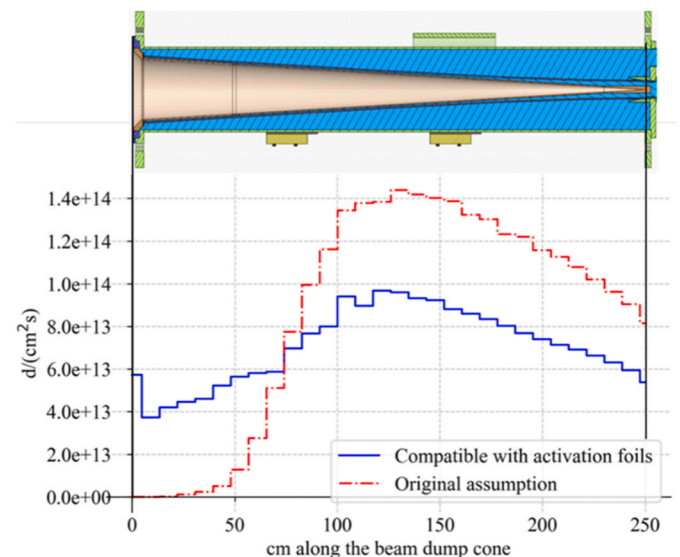


Fig. 7. Comparison of the irradiation profiles.

shielded by a scraper near the lead shutter. However, with the new footprint, the irradiation in this area is also higher. The difference in the irradiation profiles implies differences in power deposition and, consequently, in thermomechanical stresses. A detailed analysis of these stresses is beyond the scope of the present study. Nevertheless, the resulting maximum power density is lower than that assumed in (Brañas, 2009), and is therefore not expected to be problematic.

4.2. Application of activation foil measurement in future phases

In addition to enabling conclusions to be drawn regarding the irradiation distribution during commissioning Phase B+, this study also demonstrates the usefulness of installing activation foils as a complementary diagnostic system. Although these foils constitute an offline technique and therefore do not provide real-time measurements, which is a limitation, they offer a simple and robust measurement approach.

In the subsequent phases of LIPAc commissioning, the cryomodule will be installed to accelerate deuterons up to 9 MeV. During the initial campaigns, operation at low duty cycle will be required to prevent potential damage to the accelerator. Under these conditions, the ionization chambers (ICs) surrounding the cartridge may not yet provide reliable measurements. Moreover, at this stage the activation level of the HPBD will still be low, allowing the installation and retrieval of additional activation foils. Due to the increase of the beam energy, and consequently of the emitted neutrons, it is expected that the aluminum foils will produce meaningful results. In addition, zinc and hafnium foils could be included, as they enable the $\text{Zn}64(n,p)\text{Cu}64$ reaction, with an energy threshold of 1.5 MeV, and the $\text{Hf}180(n,n')\text{Hf}180\text{m}$ reaction, with a threshold of approximately 2 MeV, respectively. This would allow more detailed conclusions to be drawn regarding the neutron energy spectrum.

CRediT authorship contribution statement

V. Lopez: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **K. Kumagai:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. Jimenez-Rey:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Y. Qiu:** Writing – review & editing, Supervision, Conceptualization. **K. Kondo:** Writing – review & editing, Supervision, Resources, Conceptualization. **K. Ochiai:** Writing – review & editing, Supervision. **F. Ogando:** Writing – original draft, Conceptualization. **A. Čufar:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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Data availability

Data will be made available on request.

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