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Beam-facing material selection for mitigation of residual doses in the HEBT of IFMIF-DONES

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ABSTRACT

IFMIF-DONES will be an irradiation facility based on a 40 MeV deuteron accelerator. Unavoidable beam losses along the accelerator result in deuterium interactions with the beam facing materials of the vacuum beam pipe, some of them leading to material activation. The initial design of the beam pipe was based on stainless steel, but an evaluation of the residual doses from the pipe showed high values after operation of the accelerator. The accelerator beam line must be periodically maintained, and excessive cooling times for reaching acceptable dose levels may result in poorer availability of the facility. A deeper study of the High Energy Beam Transport line (HEBT) showed that a direct reaction between deuterons and iron in steel resulted in the production of Co-56, with a half-life of 77 days. This radioisotope is the main source of the radiation and makes it impractical to wait for a proper attenuation of the radiation field. A redesign of beam line elements has been performed to avoid the presence of stainless steel as a beam facing material and to replace it with aluminum where possible, resulting in faster decay of residual doses. This work contains a summary of the nuclear analysis performed for the computation of residual doses with stainless steel beam pipe, stressing the uncertainties of the calculations, based on the limited availability of nuclear data for the relevant nuclear reaction Fe56 (d,2n). The proposed replacement of element materials is also described, and an updated nuclear analysis shows the reduction of residual radiation, and its impact on possible maintenance operations.

1. Introduction

IFMIF-DONES [1] (International Fusion Materials Irradiation Facility — DEMO oriented Neutron Source) is currently under development as part of the EUROfusion Early Neutron Source work package (WPENS). It is designed to serve as a fusion material testing installation, generating a neutron flux with a broad energy distribution that covers the typical neutron spectrum of a (D–T) fusion reactor. This is achieved through Li (d,xn) nuclear reactions occurring in a liquid Li target when bombarded by a deuteron beam with a rectangular footprint. The energy of the deuterons (40 MeV) and the accelerator's current (125 mA) have been optimized to maximize the neutron flux (up to $5\times10^{18}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$) and replicate irradiation conditions akin to those within the first wall of a fusion power reactor.

In the IFMIF-DONES accelerator most of the deuteron interactions, although not all, occur in the lithium target. There are other, less intense interactions between deuterons and matter, which may be intentional and concentrated in scrapers, or unintentional due to beam losses colliding with the composing material of the vacuum pipe. These interactions outside the target, may also induce nuclear reactions and result in the production of secondary neutrons and gammas, as well as the generation of radioactive inventory. While this radiation is much less intense than the radiation produced in the target, it emerges in places where human intervention is expected, and mitigating its effects is crucial for the licensing of the facility. The intentional particle interactions are usually more intense that the unintentional ones and are located in specific places (collimators and scrapers), which can be shielded to mitigate the radiation fields. The latter interactions are less intense, but they cannot be easily shielded, since they occur along the entire length of the accelerator, especially in the high-energy region, where reaction cross sections and particle ranges in matter are larger.

During the initial analysis of IFMIF-DONES it was discovered that the Stainless Steel (SS) beam pipe became activated from interactions with deuterons, resulting in strong residual radiation persisting for extended periods, and preventing manual maintenance of the beam

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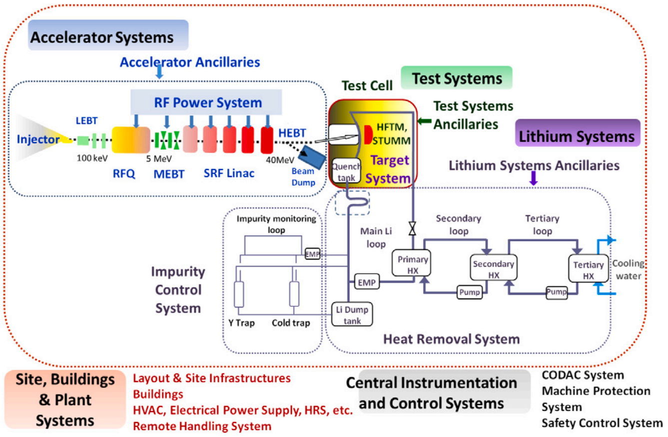

Fig. 1. IFMIF-DONES facility schematic plant configuration [1].

line elements. This study describes the phenomenology of the problem, the alternative solution devised following the ALARA principle with a focus on maintenance operations, and the implications for mechanical design. Not all the beam line elements could be replaced, leading to considerations for mitigation of residual doses. Finally, the conclusions are drawn and the future work is explained.

2. IFMIF-DONES facility description

IFMIF-DONES facility is divided into five primary group of systems, as shown in Fig. 1.

The systems devoted to produce the high power beam are grouped under the Accelerator Systems (AS); the systems related to the Lithium Target management constitute the Lithium Systems (LS); the systems in charge of the irradiation test module(s), the Test Cell and their support systems compose the Test Systems (TS); the systems in charge of performing the global control of the Plant are grouped under the Central Instrumentation and Control Systems (CI&CS) and finally the Site, Building and Plant Systems (PS) include the buildings and the systems providing power, cooling, ventilation, remote handling of components and services to the other systems.

The AS is composed by several systems [2]. The Injector supplies the deuteron beam, giving the beam an initial energy of 100 keV DC HV. The Radiofrequency Quadupole (RFQ) transforms the beam from 100 keV to 2.5 MeV. The Medium Energy Beam Transport line (MEBT) transports the beam to the next section of the AS. The Superconducting Radiofrequency (SRF) LINAC is responsible to accelerate the beam from 2.5 MeV to 40 MeV. The HEBT is placed at the exit of the SRF LINAC and interfaces with the Target system. The main goal of the HEBT is to shape and guide the beam to the beam dynamics footprint requirements in the Target System (TS). The second goal of the HEBT is to provide an alternative beam exit for commissioning and beam tuning, facilitated by the Beam Dump Transmission Line (BDTL).

3. Radiological criteria

Particle accelerators typically emit secondary ionizing radiation, as accelerated particles may induce nuclear reactions, resulting in the generation of neutrons or gamma radiation. Not all accelerated particles travel unperturbed from the ion source to the final beam target, some escape magnetic confinement and collide with the vacuum beam pipe, or are intentionally removed in collimators or scrapers to preserve specific spatial distributions. In the HEBT of IFMIF-DONES, deuterons have already reached full energy, capable of inducing numerous exo- and endoenergetic reactions. These reactions lead to the emission of secondary radiation and the creation of various nuclear species, some of which are radioactive, releasing ionizing radiation even in a shutdown scenario. While the accelerator is operational, both prompt radiation from nuclear reactions and residual radiation from produced radioactive materials are present. However, the former is significantly more intense, resulting in radiation levels that prohibit human access to the accelerator vault. During accelerator shutdown however, only the less intense residual radiation remains, which is produced by the previously generated radioactive inventory.

The accelerator of IFMIF-DONES is a very complex equipment, which will require maintenance procedures during the commissioning and even the operation phase of the facility. The existing residual radiation during maintenance operations results in a radiological challenge, and to contributions to the collective dose, impacting the Operation Radiation Exposure (ORE) of the facility. One of the main safety requirements is to lower or mitigate the residual doses to able humans to entry inside the Accelerator vault where the elements are placed.

Most usual structural materials for vacuum pipes (steel, aluminum and other metals) produce a similar yield of neutrons [3] when irradiated with deuterons. This is why prompt neutron production is not a deciding criterion for the material. However the resulting radioisotopes from deuteron-induced activation may indeed have quite diverse features, mainly the emission of gamma radiation and the half-life, which determines the required cooling times in order to reduce the activity values to safe levels. The characteristics of the residual radiation is indeed an important radiological criterion to design the beam line, especially in the areas where human intervention is expected. The effect of the deuteron interaction on the prompt production of neutrons, and its radiological effects, has already been covered in previous studies [4,5] In this work the study is only focused on the unintentional beam losses, and their radiological effect when interacting with the surrounding vacuum pipe.

3.1. Beam losses interactions with the vacuum pipe

When an accelerated particle has some phase space coordinates outside certain parameters, there is a certain probability of escaping the confinement and this becoming a *beam loss*, normally impacting with the beam pipe. Beam dynamics studies of IFMIF-DONES [6] showed the expected beam profiles along the accelerator, and shown in perpendicular plane cuts containing the beam axis. From this study two conclusions are extracted: the beam losses along the HEBT are conservatively estimated in a linear density of $1\,\mathrm{W\,m^{-1}}$ and also, the external isodensity lines of the beam mostly keep a angle with the axis around 3°. It is assumed that beam losses travel approximately following the same direction as the isodensity lines of the particle beam and therefore will impact the beam pipe in a shallow angle and be completely contained inside it.

When a stray deuteron collides with the pipe wall, it undergoes multiple electrostatic interactions, experiencing a continual loss of kinetic energy and a slight change in direction. Given that accelerated particles have the potential to initiate nuclear reactions throughout their trajectory, assuming complete containment within the duct wall is a conservative estimate regarding the total number of reactions they might induce.

4. Calculation methodology

The calculation of residual dose fields originated by charged particles required both transport and activation calculations. The MCNP6 is one of the most widely used radiation transport codes, includes slowing-down modules for computing the trajectory and loss of energy and final range of charges particles in matter, but only a simple activation module. The D1SUNED code [7] used for this study, created by some of the authors, is an extension of the MCNP code, and includes advanced algorithms for computing the production of radioisotopes due to neutrons and/or charged particles, as well as the resulting radiation

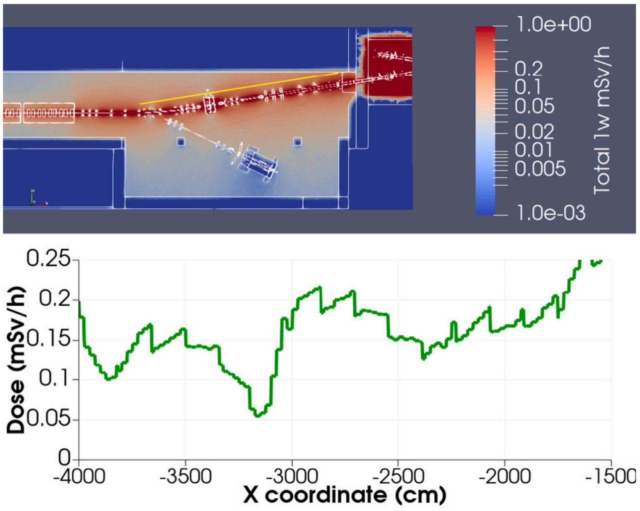

Fig. 2. Residual doses (mSv/h) at 1 week cooling with the Steel pipe. 1D plot computed over yellow line at 1.5 m from the beam line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fields. The geometrical determination of the radioisotope generation and subsequent source emission is directly computed with the transport algorithm without spatial averaging, which is specially important when computing activation from charged particles, which may be located in thin layers due to the limited range of the ions. D1SUNED has been thoroughly verified, and has been extensively used for residual dose calculations for the design of the most complex neutronic facility in the world: the ITER fusion reactor.

The nuclear data for deuteron transport calculation was taken from the TENDL19 library [8] and the older EAF2007 [9], but only for comparing with pure activation calculations using the ACAB code [10] for isotopic inventory computation.

5. Radiological design

Initially, the wall of the beam duct of the HEBT of IFMIF-DONES was designed to be made of steel with a thickness of 1 mm, as it has been previously used for the accelerator LIPAc [11]. The chosen steel composition was SS316L with a standard composition of 0.2% cobalt. In order to evaluate the production of secondary radiation in this pipe, a source of deuterons was modeled into the transport code, pointing into the pipe wall. A quick evaluation of the deuteron transport in this metal sheet using MCNP showed that deuterons traveling with angle with respect to the beam line lower than 30° have negligible probability of crossing it. Considering the small angle of beam losses with respect to the beam line, as discussed in Section 3.1, it is safe to consider that the pipe wall behaves as a thick target.

The resulting residual dose field in the HEBT after one week cooling time is represented in Fig. 2. A 1D plot is included for better readability of values, and is placed at 150 cm from the beam line, so it does not intersect radiation shields. The dose distribution approximately follows the 1/R law of linear sources with the distance to the beam line. One week has been considered as a upper limit of the possible cooling time for maintenance operations. Longer cooling times would are deemed unacceptable, for the impact it would have on the availability of the facility. The 1D plot in the bottom shows radiation doses along the yellow line of the colormap, computed at 2 m distance from the beam line, and with peak values up to 200 μSv/h in the region dominated by beam losses, in the coordinate range between −4000 and −2000 cm. The main responsible radioisotope of these doses was identified as Co-56, which is produced by a (d,2n) reaction with Fe-56. The doses from activation of the steel pipe by neutrons are vary along the beam line, depending on the proximity to neutron sources, but are between one and two orders of magnitude lower than the doses from activation by deuterons. This radioisotope has a half-life of around 77 d, resulting in residual doses with little attenuation during acceptable cooling times. The next step of the analysis was assessing the quality of the nuclear data used for the calculation. Experimental data was found only in EXFOR up to 20 MeV [12], showing in that range a good match between TENDL2019 and EAF2007, but a significant mismatch between these two libraries was found beyond that energy, as shown in Fig. 3, with differences by a factor over three. These analyses were computed with the most conservative data source. A deeper analysis of the nuclear data is required, but it was found that, even with the most optimistic data, the radiological situation had a very large impact on the maintenance procedures of the accelerator. The production of Co-56, directly originating from iron, a primary component of steel, cannot be mitigated with impurity controls. Therefore, it is necessary to explore alternative materials that are not iron-based when considering a replacement.

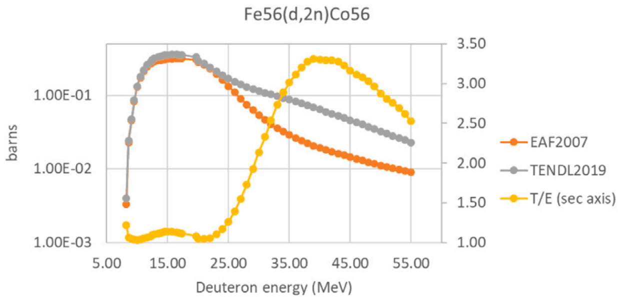

Fig. 3. Comparison of relevant nuclear data between EAF and TENDL, including their ratio.

5.1. Solution proposed

Previous studies showed the use of aluminum alloys for beam pipes at other accelerators [13,14] with promising results. As late shown in Table 1 the chosen aluminum alloy for the replacement was Al-6061 for its good compromise between density, yield, and ultimate tensile strength. An evaluation of the activation of this alloy resulted mainly in the production of short-lived radioisotopes like Na-24 (12.4 h) and Mg-27 (9.5 min) which rapidly decay after the first days of cooling time. An activation analysis shows, that Na-22 and Co-56 are also produced by deuterons from the aluminum and iron contents, but resulting in 10 times lower residual doses during maintenance operations. The residual dose field shown in Fig. 4 shows a much lower residual dose level, with values near the pipe around 30 μSv/h in the coordinate range between −4000 and −2000 cm. The region on the right hand side keeps the former values, since the beam line elements could not be replaced to aluminum, as explained in following sections.

The irradiation of aluminum with deuterons an neutrons results also in longer-lived radioisotopes, which may result in hazardous waste. Al-26 dominates the shallow burial (SBI) index of aluminum after some decades, but with values as low as 1×10^{-4}, while a steel pipe would results in 1×10^{-5} SBI value due to Tc-99. Any of those options is not challenging from the waste perspective.

6. Mechanical design

The change from stainless steel to aluminum is not trivial, as it results in a significant alteration of mechanical properties, as indicated in Table 1. Extensive research was conducted on the design of new beam duct sizes, elements integration, and preparing a flange connection between ducts and elements.

Table 1
Mechanical characteristics comparison for aluminum grades and stainless steel [15].

	AW 6061-T6* [AlMg1SiCu]	AW 5083-H116* [AlMg4.5Mn0.7]	AW 6082-T6 [AlSi1MgMn]	Stainless Steel 316L
Ultimate tensile strength (MPa)	310	317	300	580
Yield tensile strength (MPa)	276	228	255	290
Elongation at break (%)	17	16	10	50
Modulus of elasticity (GPa)	69	71	70	193
Density (kg/m^3)	2700	2660	2700	8070

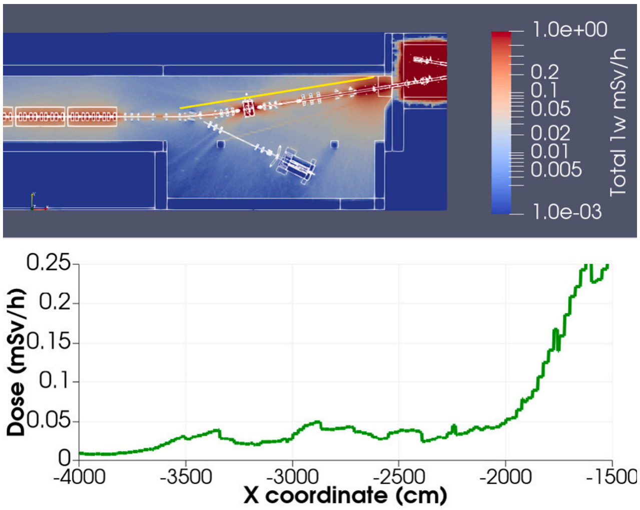

Fig. 4. Residual doses (mSv/h) at 1 week cooling with the Aluminum pipe. 1D plot computed over yellow line at 1.5 m from the beam line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.1. Beam duct design

Beam duct sizing for the HEBT is constrained by beam dynamics, spatial restrictions, and mechanical properties. Beam dynamics [16] requires beam duct Internal Diameters (ID) of 100 mm, 120 mm, 160 mm and 250 mm. Smaller diameters should be avoided, as they can unintentionally turn the drift into a collimator, leading to increased beam interaction and thus more activation of the duct. The Outer Diameter (OD) must be smaller than the surrounding magnetic elements gap to avoid interference. Quadrupole magnetic elements [17] have the most restrictive gap of 110 mm, 130 mm, 180 mm and 260 mm. As a consequence, a margin of at least 200 μm must be given for commissioning purposes. Mechanical properties must ensure that the new size (ID and OD) is sufficient to withstand the external differential pressure of 1 bar(a). Among the available standards for pressure vessel design, the nuclear ASME Boiler and Pressure Vessel Code (BPVC) standard was chosen for its combination of convenience and conservatism, as outlined in [18]. Specifically, BPVC Section VIII, division 2, part 4.4.5 [19], details a guideline for the design of cylindrical vacuum shells under external pressures. Iterative adjustments to thickness (t) are made, ensuring compliance with requirements until the desired Safety Factor is reached. Final HEBT beam duct dimensions are summarized in Table 2.

6.2. Elements integration

However, aluminum cannot replace all beam facing elements in the HEBT. Stainless steel is essential for the manufacture of critical diagnostic elements such as beam profile and position monitors, as well as AC, DC, and CW current transforms [20]. Figs. 5–8 show in red the remaining stainless steel elements for Sections 1, 2, 3 and the BDTL respectively.

Table 2
Dimensions of the newly designed aluminum 6061 duct.

Size (DN)	OD [mm]	ID [mm]	t [mm]	Safety factor
DN100	109.8	100	4.9	106
DN125	129.8	120	4.9	64
DN160	169.8	160	4.9	28
DN250	259.8	250	4.9	8

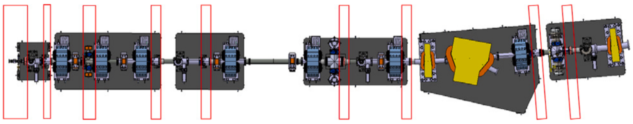

Fig. 5. In red: HEBT and BD components currently in stainless steel in Section 1 of the HEBT. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

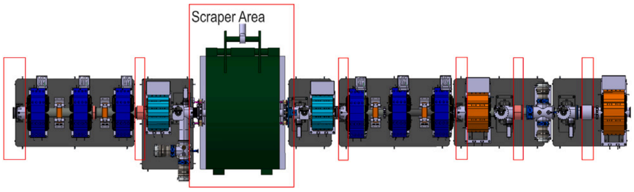

Fig. 6. In red: HEBT and BD components currently in stainless steel in Section 2 of the HEBT. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

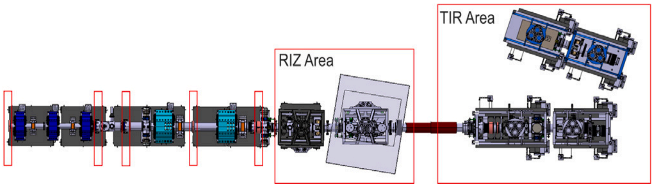

Fig. 7. In red: HEBT and BD components currently in stainless steel in Section 3 of the HEBT. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The elevated radiation doses in the Scraper area, the High Power Beam Dump (HPBD) interface with the BDTL area, Target Interface Room (TIR), and Radiation Isolation Zone (RIZ) oblige remote handling for commissioning and maintenance operations, with restricted access for staff personnel. Consequently, the activation of ducts and elements in these sections is not a concern, and the transition to aluminum is avoided to mitigate potential issues, as it can be seen in Fig. 6, and the last part of Figs. 7 and 8. The Accelerator Vault (AV) houses the remaining sections of the HEBT and BDTL, allowing personnel

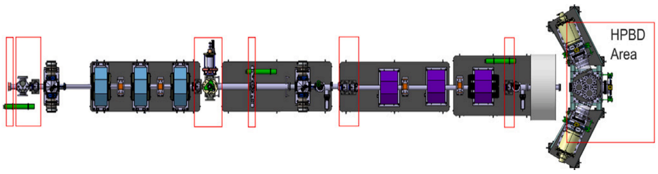

Fig. 8. In red: HEBT and BD components currently in stainless steel in the BDTL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Length, remaining beam facing elements in SS length, and ratio of aluminum over SS, inside the AV and total, for HEBT and BDTL.

	AV [m]	Total [m]	SS, AV [m]	SS, total [m]	% AV	% total
HEBT	35.95	48.81	8.19	17.39	77	64
BDTL	–	14	–	2.5	–	82

access during maintenance periods. Mitigating residual doses inside the AV is crucial. Table 3 displays the lengths, remaining stainless steel element lengths, and the aluminum-to-SS ratio for the new beam-facing material, both inside the AV and in total, for the HEBT and BDTL lines. The introduction of a 77% of aluminum-to-stainless steel ratio in the AV, has effectively reduced residual doses, as shown in Fig. 4.

6.3. Connection types

The shift from stainless steel to aluminum requires new connection flanges for beam ducts and elements. However, as stated in Section 6.2, not all elements will undergo a material change, as some stainless steel components will remain. Three alternatives are being considered to connect beam ducts and HEBT&BD line elements. The first explores using aluminum ConFlat (CF) flanges, akin to the previous stainless steel connections, but with a drawback of extended maintenance times. The second option is the KF–ISO flange, which eliminates the need for screws, improving maintenance efficiency. However, this approach may be limited by the presence of stainless steel elements that use CF flanges. The third alternative combines both with adaptors from CF to KF–ISO, but it requires additional longitudinal space.

The choice among these alternatives will depend on the specific integration needs of each element.

7. Conclusions

This work emphasizes the critical role of residual doses in the planning of maintenance periods. The use of stainless steel for beam pipes in the HEBT of IFMIF-DONES leads to the production of Co-56, resulting in prolonged residual doses. Despite significant uncertainties in the nuclear data for the reaction, even in the most optimistic case, the residual doses remain unacceptable. The mitigation of residual doses becomes feasible by employing low-activation materials for the beam-facing elements, such as aluminum 6061. The reduced half-life of the newly produced radioisotopes proves to be a good solution, significantly minimizing residual doses and consequently reducing the required cool-down periods.

The mechanical design has effectively incorporated the new requirements, with particular emphasis on:

- Safely altering the beam duct sizing design to aluminum, ensuring diameters and thickness that comply with beam dynamics, safety, and structural requirements, following the BPVC section VIII division 2 ASME standard.
- Ongoing study of new connection types for the beam ducts and elements, with each selection is based on specific criteria.
- The introduction of a 77% of aluminum-to-stainless steel ratio, has effectively reduced residual doses.

CRediT authorship contribution statement

Francisco Ogando: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Llorenç Macia:** Writing – review & editing, Writing – original draft, Data curation. **Victor Lopez:** Software, Methodology. **Ivan Podadera:** Validation, Supervision. **Daniel Sanchez-Herranz:** Validation, Supervision.

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.

Data availability

No data was used for the research described in the article.

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