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Advancements in the IFMIF-DONES target system for fusion materials irradiation

D. Oravecz [a,*], A. Zsákai [a], R.L. Csiszár [a], D. Ferenczy [a], T. Dézsi [b], F.S. Nitti [c], J. Maestre [d], D. Bernardi [c], A. Ibarra [d]

[a] HUN-REN Centre for Energy Research, Budapest, Hungary
[b] C3D Engineering Consultant Ltd, Budapest, Hungary
[c] ENEA-Brasimone Research Centre, Camugnano, Italy
[d] IFMIF-DONES España, Granada, Spain

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ABSTRACT

This paper provides an overview of the advancements in the Target System design of the IFMIF-DONES Project which simulates the effects of the extreme neutron irradiation conditions expected in the future fusion power reactors. The system's role in generating a high-intensity neutron source for testing candidate materials to be used in the reactor is highlighted. The discussion includes design innovations, recent developments, challenges, and future prospects, emphasizing critical aspects and validation needs for the Target System.

1. Introduction

The IFMIF-DONES project [1,2] aims to develop an accelerator-based Li(d,xn) [3] neutron source for the testing of materials intended for DEMO reactors and future fusion power plants, and also exploitable for various scientific experiments. This facility utilizes a high-speed liquid lithium jet, which is impacted by a 125 mA, 40 MeV deuteron beam, to achieve the desired levels of displacement damage (>10 displacement per atom/full power year (dpa/fpy) in > 0.3 l volume) and helium production rates in irradiated samples. The current design of the Target System (TSY) see Fig. 1, as part of the Lithium Systems, features a fully replaceable (by Remote Handling means) Eurofer 97 [4] section, known as the Target Assembly (TAA), which is scheduled for annual replacement due to material damage levels it faces.

Compared to previous studies [5], the current approach focuses on redesigning the TSY, including the Quench Tank, which is responsible for collecting discharged lithium from the Target Assembly, with an emphasis on improving manufacturability. This involves the implementation of advanced manufacturing features that consider possible production processes and optimize existing design elements to meet the specific requirements of the IFMIF-DONES target assembly. Key modifications include the adoption of advanced welding techniques to enhance joint reliability, precision machining to achieve the stringent dimensional tolerances required for optimal performance in high-radiation environments, and design enhancements that streamline manufacturing workflows.

This paper outlines the most recent updates to the DONES Target System, focusing on these design optimizations, the refinement of manufacturing processes, improvements in component replaceability, and enhancements to overall system performance and reliability.

2. DONES target system

The Target System is arranged inside of the Test Cell (TC), adjacent to the Target Interface Room (TIR) and accessible from the Access Cell (AC) [6]. above. It is designed to generate a stable liquid lithium jet for D-Li stripping reactions (as summarized in the Introduction). and achieve an adequate neutron flux for irradiating test modules downstream. The TSY's primary objectives include:

- Providing a stable neutron flux with the proper characteristics [7]
- Maintaining a stable lithium flow velocity of 15 m/s in the D-Li interaction area.
- Ensuring a consistent lithium flow thickness of 25 mm ± 1 mm in front of the deuteron beam.
- Providing a vacuum environment (10–2 Pa) to facilitate effective reactions.

* Corresponding author.
E-mail address: oravecz.denes@ek.hun-ren.hu (D. Oravecz).

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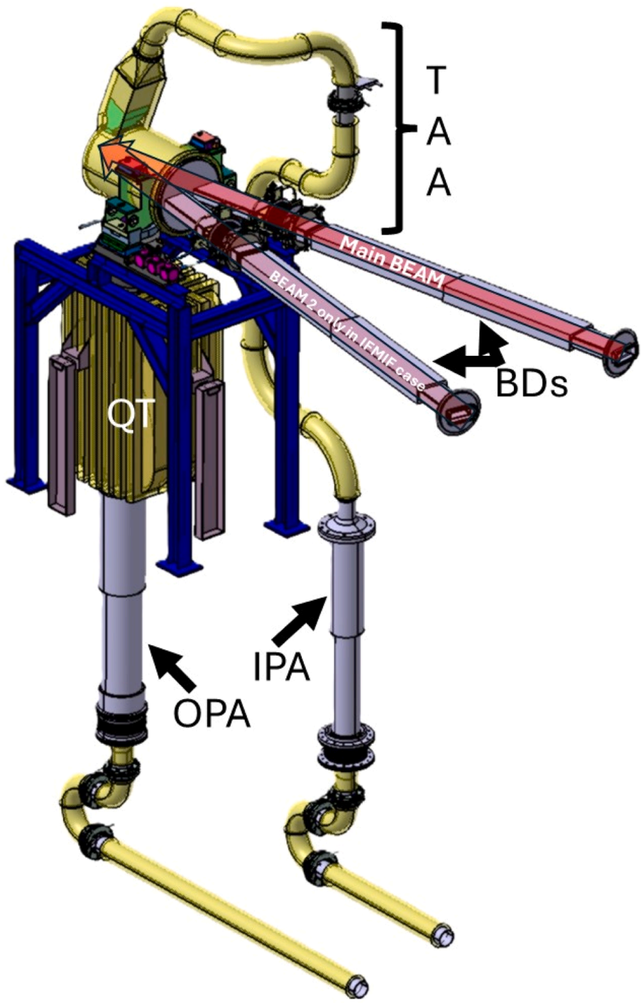

Fig. 1. Target systems 3D official CAD model.

- Possibly supporting the qualification of Eurofer 97 as main candidate for fusion structural material, by using portions of the TAA itself as irradiated sample [8]

To achieve these aims, the TSY comprises several key components. The whole system can be seen in Fig. 1, including the removable TAA part, which can be seen in Fig. 2 in detail. The TSY's parts are:

- Target Assembly (TAA): the summary name of the removable section that allows easier RH maintenance and replacement due to material damage levels [8], components of this part:
  - Flow Straightener: suppresses secondary flow and reduces turbulence in the Li jet
  - Reducer Nozzle: accelerates and shapes the lithium flow towards the interaction area
  - Target Vacuum Chamber (TVC): maintains the necessary vacuum conditions (10–2 −10–3 Pa in the TVC increased by Ar injection) for D-Li reactions.
  - Backplate (BPL): hosts the concave-shaped lithium flow channel with reduced thickness (1.8 mm in the thinner part) to mitigate the loss of neutron streaming towards the irradiated specimens placed behind the BP.
  - Beam Ducts (BDCs): transport and guide the deuteron beams to the target (in the future IFMIF configuration with 2 beams). In the DONES baseline (only 1 beam), one BD is used to host the diagnostics of the Li jet.

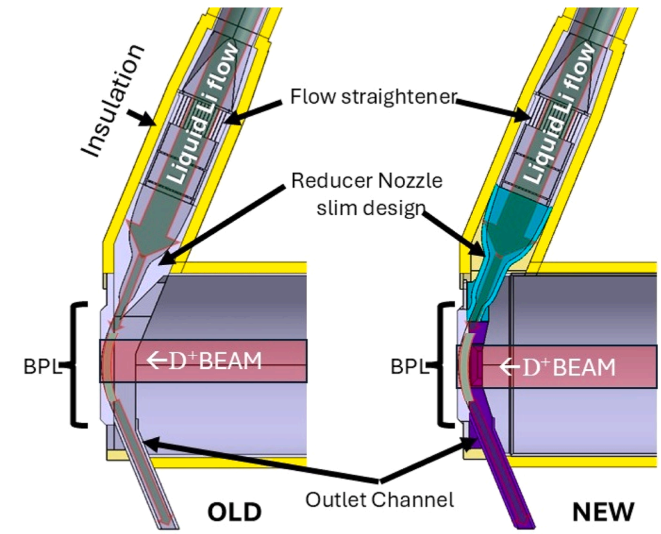

Fig. 2. Target systems 3D official CAD model(left)-and new proposal (right).

- Quench Tank (QTA): collects the discharged lithium and is supported by a dedicated frame.
- Lithium Inlet-Outlet Pipes Assemblies (IPA-OPA): ensure the continuous flow of lithium into- and out of the TSY trough the concrete Test Cell shielding floor.
- Target Assembly Support Frame (TAS): provides physical support and ensures overall structural integrity of the system.

As the construction of the DONES facility has started in 2023 at the Escuzar site in Granada (Spain), its component systems also need to be levelled to a manufacturability state.

To ensure adherence to the tender launch deadline, a comprehensive manufacturability study is required for the TSY, followed by a detailed re-evaluation of the components within the TAA.

Key modifications include design enhancements that streamline manufacturing workflows based on material availability studies. Eurofer97 is being tendered as a relatively new material-compared to stainless steels like AISI 316 L, which is commonly used worldwide and great practice has been set to manufacture it- Eurofer97 presents unique challenges due to its limited availability in diverse forms, requiring meticulous planning and innovative approaches to its application.) Also the adoption of advanced welding techniques is needed to enhance joint reliability and precise machining to achieve the stringent dimensional tolerances required for optimal performance in high-radiation environments.

In the following Sections, a brief overview of the TSY updates identified on the basis of the performed manufacturability study and/or other specific needs is given.

3. Target assembly (removable section)

The design has been optimized and tailored to the manufacturing technique and the specific material requirements. The baseline material of the TAA is Eurofer 97. Based on these constraints coming from the recent studies, the Reducer Nozzle needed to be modified. Within this inevitable update, the manufacturability study has been focused on the most complicated part of the Target Assembly, namely the Nozzle-Backplate- Outlet Channel-Vacuum chamber fully welded assembly, can be seen in Fig. 2. This complicated section represents the core of the TSY removable section. This assembly has to withstand the highest temperatures, the effects of the liquid lithium circulating at high speed (erosion and corrosion phenomena), and the high neutron and gamma fluxes generated by the collision of the beam with the lithium curtain [9]. In this phase, particular attention was paid to this assembly, and all the above mentioned components have been updated to different extent.

3.1. Reducer nozzle updates

The Reducer Nozzle is a critical component of the Target Assembly featuring a proven double-stage SHIMA geometry [10], engineered to optimize flow characteristics and minimize turbulence within the lithium flow. By enhancing flow uniformity and reducing pressure losses, the SHIMA geometry enables precise control over flow patterns and velocities, ensuring optimal system performance and reliability.

The aims of the study are as follows:

- Reducing raw material sizes: studies on material availability highlight the need to reduce raw material sizes to streamline production and ensure accessibility.
- Investigating thickness reduction possibilities: the study explores potential thickness reductions for the nozzle to optimize its design and minimize material usage.
- Implementing possible manufacturing features in the design.

The proposed manufacturing process for the reducer nozzle employs advanced techniques alongside rigorous quality control measures, ensuring components meet stringent standards for compatibility, durability, and operational efficiency in the DONES lithium loop.

To simplify manufacturability and optimize raw material usage, the nozzle wall thicknesses have been unified (see Fig. 3). Assembly features have been incorporated, and a proposed assembly and welding sequence has been outlined. In the current proposal the Nozzle is made of four uniformly 15 mm thick pre-shaped plates with corner welds, and EDM is proposed for final shaping process to achieve desired tolerances. The Outlet Channel is foreseen to have the same thickness, with overlapping connection to the Nozzle, to guarantee efficient alignment and base for welding. Vacuum and nuclear standards [11] have been used as guidelines, serving as a foundation for good engineering practices to achieve the highest quality products.

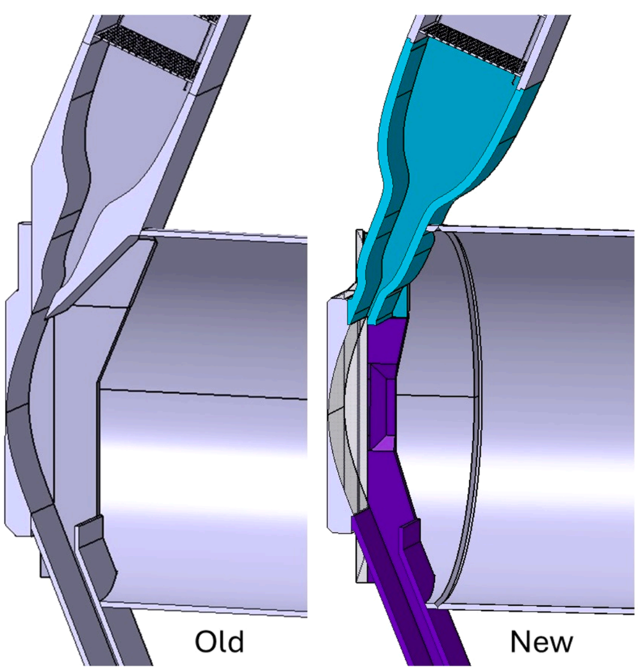

Fig. 3. Target Assembly (Nozzle-Backplate-Outlet Channel assembly) 3D official CAD model(left)-and new proposal (right)- section view.

3.2. Outlet channel updates

The motivation behind updating the outlet channel is primarily driven by the need to enhance the overall performance and safe operation of the TSY [7]. Key objectives for this update include:

- Preventing interaction of beam tail with lithium channel wall. It is crucial to ensure that the beam tail does not interact with the lithium channel wall, as such interactions could lead to the damage of the component.
- Avoiding collision due to beam deviations: the design must accommodate potential beam deviations of up to ± 5 mm with respect to the nominal position. By addressing this concern, the updated outlet channel (see 3. Fig.) the “slim design”(right side) incorporates a smaller protruding vertical Outlet Channel wall from the BP, with a purposefully narrowed section, optimized so it will minimize the risk of collisions between the channel and the beam, thereby maintaining system integrity.

As the Reducer Nozzle, Backplate, and Outlet Channel parts are highly interdependent on each other, they need to be treated as a single unit (see Fig. 3) and any approach towards further updating one of them will inevitably affect the others. For this reason, manufacturability study of the components and the whole assembly together need to be carried out- which is the next step of our currently ongoing study.

4. Quench tank

The Quench Tank (QTA) is responsible for managing the lithium discharged from the TAA at a velocity of 15 m/s. Its primary function is to provide the safe transition of the high-velocity free lithium jet into a controlled low-velocity pipe flow, facilitating its return to the main lithium loop. The QTA incorporates structural and functional components, including a vessel for flow conversion, thermal expansion supports, and connection units, ensuring seamless integration and operational reliability.

The design is currently being updated to address recently identified remote handling (RH) needs, enabling effective management of heating blankets and thermal insulation through RH methods. Additionally, seismic evaluations and thermal studies have been conducted to validate the updated QTA design [12].

The recent studies seen on Fig. 4 include, among others:

- A fully welded QTA approach (except for the legs)
- Stiffening ribs simplified
- QTA Support (legs) modified (location and height)
- TAA-QTA top connection relocated, size and orientation have been changed
- Heat shield (to be updated)
- Manufacturability study (ongoing)

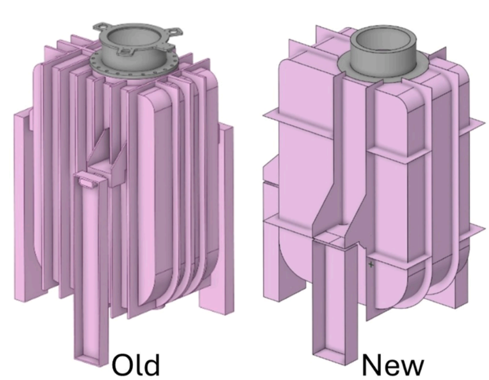

Fig. 4. Quenc Tank 3D official CAD model(left)-and new proposal (right).

- Remote Handling needs to be further studied

5. Beam ducts and trough-wall beam ducts

The Beam Ducts (BDC) are responsible to house the $D+$ beam and transport it in the last section of the accelerator, the so called High Energy Beam Transport (HEBT) line, to the Target Vacuum Chamber and finally to the Target itself. The BDCs are two rectangular cross section channels, made up of two sections. On the TSY removable side (TAA) they are made of Eurofer 97 and are welded to the TVC, on the other end of the BDCs, bellows made of AISI 316 L are connected with dissimilar welds between the two different materials. These removable sections are then connected by an integrated, customized system composed of a QDS (Quick Disconnecting System), purposely designed for RH operation [13] and an alignment system between the sections to help the engagement of the bellows in proper positon of TAA- to the fixed sections of the channels made of AISI 316 L steel, the so called Through-Wall Beam Ducts (TWBDs). which penetrate the TC wall towards the TIR side. Both of the two beams are identical and equipped with the same features even though, the second beam is foreseen to be implemented only in later stages (IFMIF phase- see Fig. 4), but the inner structure is already designed from the start in a way that it can receive the 2nd beam without major modifications. Based on the requirements coming from beam dynamics studies, the inner outdated dimensions 100 (H) x 260 (W) mm of both the BDCs, TWBDs and QDS had to be enlarged, which has now been implemented in the official 3D CAD model, as can be seen in Fig. 5. showing the new duct configuration and the BDC/TWBD connection with the updated dimensions 120 (H) x 270 (W) mm. The effect of these modifications on the related systems were examined and any necessary change has been implemented or scheduled for the next phase.

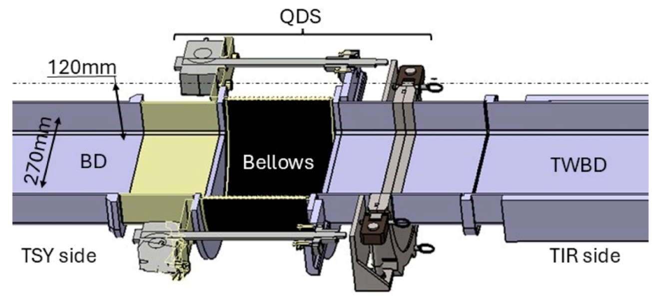

Fig. 5. BD-TWBD connection with updated inner dimensions section view (TSY 3D CAD model).

6. Summary and conclusions

The Target System (TSY) concept of the IFMIF-DONES project allows for the simulation of irradiation conditions that materials will face in a fusion environment, making it essential for the development of reliable and durable materials. A key feature of the TSY is its Target Assembly (TAA), which includes a fully replaceable section made of Eurofer 97. This design ensures that the target can be regularly refurbished, with annual replacements planned to maintain optimal performance and reliability. The TAA is complemented by several critical components, including the reducer nozzle, which utilizes an effective double-stage SHIMA geometry to optimize flow characteristics and reduce turbulence in the lithium flow. This design not only improves flow uniformity but also decreases pressure losses, allowing for precise control over flow patterns and velocities.

Recent modifications have been implemented on various components, such as the Target Assembly and the Quench Tank, to enhance overall system performance. The Quench Tank is designed to collect discharged lithium from the TAA, and updates are underway to improve its functionality and meet remote handling requirements. Additionally, the outlet channel is being updated to prevent interactions between the beam tail and the lithium channel wall, as well as to avoid collisions due to potential beam deviations of up to ± 5 mm. These updates are based on recent studies and aim to implement new geometries that optimize flow dynamics.

The reducer nozzle is also undergoing updates, motivated by the need to reduce raw material sizes based on Eurofer availability and to investigate possibilities for thickness reduction. These efforts represent the first steps toward optimizing the design for manufacturability, ensuring that the components can be produced efficiently and effectively.

Currently, the TSY is in the detailed design phase, with a strong focus on optimizing all components. This phase is a crucial milestone for the IFMIF-DONES project, whose design is expected to be completed within the next few years. Successful completion of this phase will enable the timely commencement of manufacturing processes, ensuring that the project meets its deadlines and advances the development of materials for future fusion applications.

CRediT authorship contribution statement

D. Oravecz: Writing – original draft. **A. Zsákai:** Writing – review & editing. **R.L. Csiszár:** . **D. Ferenczy:** Conceptualization. **T. Dézsi:** Writing – review & editing. **F.S. Nitti:** Writing – review & editing. **J. Maestre:** Writing – review & editing. **D. Bernardi:** Writing – review & editing. **A. Ibarra:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Denes Oravecz reports financial support was provided by Centre for Energy Research. Denes Oravecz reports a relationship with Centre for Energy Research that includes: funding grants. If there are other authors, they 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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Data availability

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

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