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OVERVIEW OF IFMIF-DONES LITHIUM TARGET SYSTEM DESIGN

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Abstract

At the core of IFMIF-DONES is placed the Target System. It generates a high-speed liquid lithium jet (15 m/s, 300°C) acting as the target for a 40 MeV, 125 mA deuterium-based linear accelerator, with the main aim of qualifying fusion-related materials. The design of the Target System has evolved during the last few years addressing key challenges. Managing the 5 MW of power deposited continuously in the target requires a reliable lithium loop supplying liquid lithium in well-defined conditions. The extreme operational conditions, exposed to high irradiation levels (~25 dpa/year), demand also careful selection of materials and regular replacement strategies for critical components, supported by dedicated Remote Handling systems. Current efforts focus on optimizing the design to meet the requirements for its upcoming construction phase. This includes advanced features to facilitate assembly, installation, and long-term operability. Additionally, attention is being paid to the integration of diagnostics. This contribution highlights the recent R&D and engineering solutions aimed at advancing the Target System toward successful construction, commissioning and subsequent operation.

INTRODUCTION

The successful development of fusion energy critically depends on the qualification of structural and functional materials under neutron irradiation conditions that closely replicate those in a fusion reactor first wall. In response, IFMIF-DONES is a facility to reproduce such conditions. Its primary function is to generate an intense neutron source with a broad peak of 14-15 MeV, similar to that expected in first wall of fusion power plants, to irradiate potential materials at a rate of 20 dpa/year.

This is achieved by directing a high-energy and intense deuteron beam (40MeV, 125 mA) produced by a linear accelerator onto a high-speed liquid lithium target. The interaction between the deuterons and lithium produces an intense neutron flux, of 1-5×10^{14} neutrons/cm^2s through a stripping reaction, delivering the neutron flux downstream towards the irradiation modules.

The Target System (TSY), located at the core of the facility within the Test Cell (Fig. 1), is designed to produce a stable liquid lithium jet that interacts with the accelerator beam. The lithium flows at a high speed of 15 m/s through a curved open channel 260 mm wide, producing a jet of 25 mm thick. As result of the beam interaction, 5 MW of continuous power is deposited into the flowing lithium. This heat is efficiently removed by the lithium flow and carried to the Quench Tank (QT), where the high-speed jet is slowed down, flow fluctuations are dampened, and both pressure and temperature are stabilized.

The TSY is supported by the Heat Removal Loops, which supply lithium at 300°C via a closed loop driven by an electromagnetic pump (97.5 l/s), and transfer the heat to the general heat rejection system of the plant systems through oil-cooled heat exchangers. Additionally, the Impurity Control System maintains lithium purity, mitigating corrosion/erosion of structural materials and trapping and confining radioactive impurities generated during operation.

During IFMIF/EVEDA phase, the stable operation of the lithium jet was successfully demonstrated (without beam) through a 1:2.6 scale Target prototype [1]. Nonetheless, there are several remaining challenges still. Those are for example related to: its thermo-mechanical performance, considering nominal and off-nominal conditions, where target is exposed to a peak power of ~85 kW/cm^3; assessment of lifetime of the components in such a harsh environment (over 25 dpa per full power year and in direct contact with lithium), this requiring a replacement strategy of the Target System by Remote Handling means; diagnostics, etc. This paper provides a brief overview of the most significant developments achieved during the last years.

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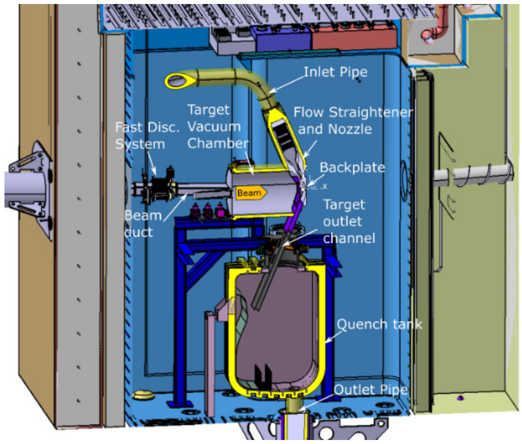

Figure 1: Illustration of the Target System allocated inside the Test Cell. TSY comprises: Inlet and Outlet Pipes route lithium to/from the Lithium loop; Flow Straightener and Nozzle forms the high-speed lithium jet; Backplate hosts the concave channel; Quench Tank converts the high-velocity free jet into a low-velocity confined flow; Vacuum Chamber maintains vacuum conditions for the D+ beam interaction; and Beam Ducts connect to the accelerator.

THERMO-HYDRODYNAMIC AND MECHANIC PERFORMANCE OF THE TARGET SYSTEM

Pre-heating of the TSY

The TSY is equipped with a thermal-insulation and heating system sectorized by elements, whose main function is to reduce thermal losses and preheat the TSY prior circulation of the liquid lithium through the target to avoid potential lithium solidification and thermal shock.

Several thermo-mechanical analysis and experiments has been conducted to define the heating procedure and configuration [2]. One of the main challenges is related to the backplate (BP), which does not include dedicated heaters due its strong irradiation exposition and space constrains. Those analyses have demonstrated the BP can reach the steady above 200ºC (above melting point of lithium) after ~ 17h by heat conduction from heater placed strategically at adjacent elements around the TSY and thermal stress are acceptable, according to RCC-MRx design criteria [3]. Failure analyses of the heaters have also been conducted, leading to an independent sectorization of the heater configuration by elements. Those analyses allow to optimize the sectorization strategy, trying to compensate for the loss of a failed unit by providing the remaining ones additional heat.

Nominal Operation

Beam-on-target requirements have recently been revised with the aim of optimizing both neutron production and machine operation [4]. The reference beam profile features a nominal 20x5 cm² footprint; an alternative 10x5 cm² halved beam is also specified to enhance neutron flux. Furthermore, the nominal lithium flow temperature has been increased from 250 to 300°C for purposes of Beryllium-7 management (reducing risk of saturation and deposition).

Updated thermo-hydrodynamic and thermo-mechanical analyses have been conducted to assess the target performance for such conditions. The improved model has been indirectly coupled with McDeLicious software [5] to compute nuclear heating (considering both neutron and photon contributions). Those models provide the temperature distribution in the lithium and the target system structure during nominal beam operation and transient lithium mixing in the QT. As main results, the maximum lithium temperature remains below its saturation point, and the target structures generally exhibit an acceptable stress field for both beam types (Fig. 2).

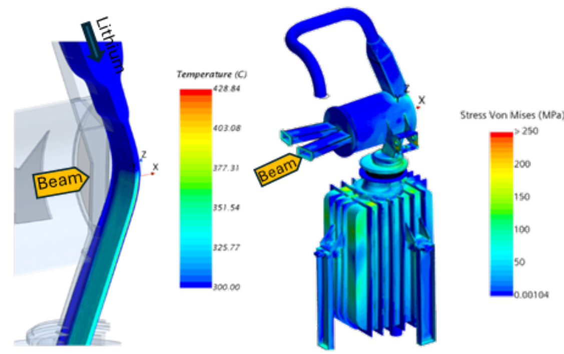

Figure 2: Thermo-hydrodynamic and mechanical performance of the TSY under nominal beam 20x5 cm².

Special attention has recently been focused on the Li channel discharge into the QT (see Fig. 3). The QT is partially filled with lithium, whereas the cover is under vacuum (10^{-2}-10^{-3} Pa). Target outlet channel is partially immersed inside the QT to reduce free-surface fluctuations. The QT incorporates a deflector to smooth the high-speed lithium discharge and internal mesh conditioning the liquid lithium. Advance Fluid-Structure Interaction simulations, with biphasic fluids have been developed to analyse the complex lithium discharge dynamics [6]. Those analyses preliminary show a vibration behaviour of the outlet channel as result of the fluid interaction with the QT wall and on pressure fluctuations on the channel. This has led to stiffening of the channel, reducing the vibrations (~1 mm amplitude), though it may deserve further numerical and experimental analysis.

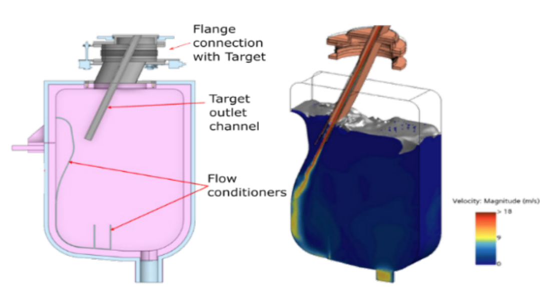

Figure 3: Fluid-structure simulation of the quench tank under nominal operation.

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Off-nominal Operation

Different off-nominal operation scenarios have been analysed to understand its behaviour and potential consequence.

The deuteron beam is supposed to be a continues wave, nonetheless, sudden beam trips (beam off - beam on) may happen during operation due to the proper nature of the accelerator. This phenomenon may induce fast transition and affect to the structural integrity. Dedicated CFD analyses have been carried out analysing parametrically the fluid dynamic transient of the lithium jet for different beam trip (ranging from 1 µs-30 µs). Those numerical models show the generation of a pressure wave travelling along lithium jet, this inducing a static pressure peak up to 0.3 MPa in the BP in the worst case. Simulations do not detect occurrence of cavitation in the zone of low pressure after the beam-off. Fatigue analysis has been also conducted by dedicated Finite Element Analyses. The total strain variation in the Backplate is found to be relatively small (~0.0014), this being below the fatigue limit for EUROFER (baseline material for the target), corresponding with more than 10^6 cycles to failure [7].

An extreme off-nominal scenario concerns with the lithium jet reduction without sufficient time to shut down the beam (due for example a failure of the electromagnetic pump). The lithium jet has a thickness of 25 mm, sufficient to fully stop the deuteron beam within it. The Bragg peak occurs at a depth of approximately 20 mm, about 5 mm from the backplate. According to the numerical simulations the backplate may melt in a range of 20-150 ms if the beam penetrates towards it [8]. To mitigate this scenario, the electromagnetic pump is equipped with a flywheel, and in case of failure the inertia continues suppling lithium during several seconds.

Beam misalignments may also occur during the installation phase of the target inside the Test Cell or as a result of thermo-mechanical deformation of the target or test cell during start-up or operation phases. This scenario has been preliminary analysed by dedicated thermo-mechanical simulations (accepting lateral deviation lower than 30 mm), although further analyses are being carried out considering the beam error due to the proper accelerator, beam tails and beam collimation before the TSY.

OPTIMIZATION DESING

Material Analysis

The currently baseline selected material for the Target is EUROFER97, a Reduced Activation Ferritic/Martensitic (RAFM) steel. RAFM steels exhibit a well-balanced combination of thermophysical and mechanical properties, low susceptibility to radiation-induced swelling and helium embrittlement under neutron irradiation, and good compatibility with primary cooling and breeding materials [9,10].

Material compatibility with flowing liquid lithium has been experimentally studied for EUROFER and AISI 316L at Lifus-6 under representative DONES conditions [11]. Results show that EUROFER has a corrosion rate approximately one order of magnitude lower than that of AISI 316L. Ongoing experiments are extending this investigation to other conditions, whilst other are being focused on welded joints and gasket under static lithium.

On the contrary RAFM materials are typically susceptible to Ductile-to-Brittle Transition Temperature (DBTT), which drives to a periodic replacement of the target (yearly basis). This issue is absent in austenitic steels like AISI 316 or 321 [12]. A comprehensively comparison of EUROFER97 and other austenitic alloys under various conditions (irradiated/non-irradiated, room temperature/300°C) is being carried out to assess their suitability for the Target for DONES specific conditions (to be published in dedicated paper).

Manufacturing & Remote Handling Installation

To ensure reliability, availability, and performance, the TSY has stringent manufacturing requirements. Even minor imperfections on the nozzle and backplate can create free surface waves, compromising the target integrity. A comprehensive manufacturing assessment, focused on vacuum-compliant welds has been preliminary performed. The sub-assembly breakdown has been also evaluated, considering the manufacturing techniques for specific element and the overall assembly procedure.

Due to irradiation degradation, the target has to be replaced annually. Given the high levels of activation, Remote Handling (RH) considerations have been incorporated into the TSY design [13]. Features like a Fast Disconnection System (FDS) and alignment systems have been implemented to facilitate the replacement and maintenance. Penetrations have been also further optimized, including additional flexibility via RM means (see Fig. 4).

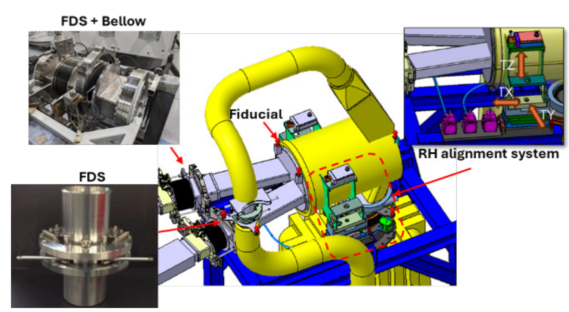

Figure 4: Remote Handling implementations of the TSY.

CONCLUSIONS

The paper highlights the recent advancements in the IFMIF-DONES Target System during last years. Key analyses confirm the thermo-mechanical and fluid-dynamic resilience of the system under nominal operation, as well as during transient conditions (e.g., beam trips, misalignment) and failure scenarios (e.g., pump failure), including an assessment of consequences and mitigation measures. Additionally, the design addresses some manufacturing and integration aspects, incorporating Remote Handling features that account for the full lifecycle of the Target System, those requiring further validation and qualification.

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