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Evolution of IFMIF-DONES' heart: System overview of the Test Cell

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ABSTRACT

The IFMIF-DONES Facility is built with the purpose of irradiating materials under DEMO Tokamak-like conditions and is a first-of-a-kind project that is foreseen to be built in Granada, Spain. A systematic top-down approach is used to design its Systems and to aid the harmonization and interaction between them. One of these main systems is the Test Systems which serves as the meeting point for other major systems such as the Lithium System (LS) and Accelerator Systems (AS), while also providing a connection to the Facilities for Complementary Experiments (FCE) for additional irradiation campaigns to take place. The Test Cell is a confined space for the experiments to take place, with critical functions for operation and safety. The TC is a subsystem serving as a convergent space for other systems, therefore the design of the TC has to fulfil the needs and requirements of the connecting systems also. In this paper, the design evolution of the Test Cell is discussed in detail from the early concept to the last more mature design, while also describing the connecting systems and the challenges these provide.

1. Introduction

An irradiation environment in the future Fusion Power Plants is characterized by the presence of 14 MeV fusion neutrons in the first wall area. Understanding the degradation of the materials and components' properties throughout the reactor's operational life is a key issue to allow the design and subsequent facility licensing by the corresponding safety authorities.

A design called IFMIF (International Fusion Materials Irradiation Facility) [1] has been in development since 1990, but later it was agreed to first design DONES (Demo-Oriented Early NEutron Source) [2] [3], which is the first step towards IFMIF. The advantage of DONES is that it can yield specimens and experimental results earlier as it is a smaller design containing only one accelerator instead of two. Thus, the earlier provided results can be used for the design of DEMO [4] and possibly ITER fusion devices [5].

The DONES facility is defined to provide an accelerator-based D-Li neutron source to produce high-energy neutrons at sufficient intensity and irradiation volume to simulate as closely as possible the first wall neutron spectrum of future nuclear fusion reactions. The first wall is the area of a fusion reactor which has to withstand most of the plasma radiation inside the vacuum chamber [6].

In its starting working configuration (IFMIF-DONES case), the Plant will produce a 125 mA deuteron beam, that is accelerated up to 40 MeV and shaped to have a nominal cross-section in the range from 100 mm x 50 mm to 200 mm x 50 mm and impinges on a liquid lithium curtain of 25 mm thickness that is cross-flowing at about 15 m/s with an inlet temperature of 300 °C. The stripping reactions generate a large number of neutrons that interact with the material samples located immediately behind the Lithium Target [7], on the Test Modules [8].

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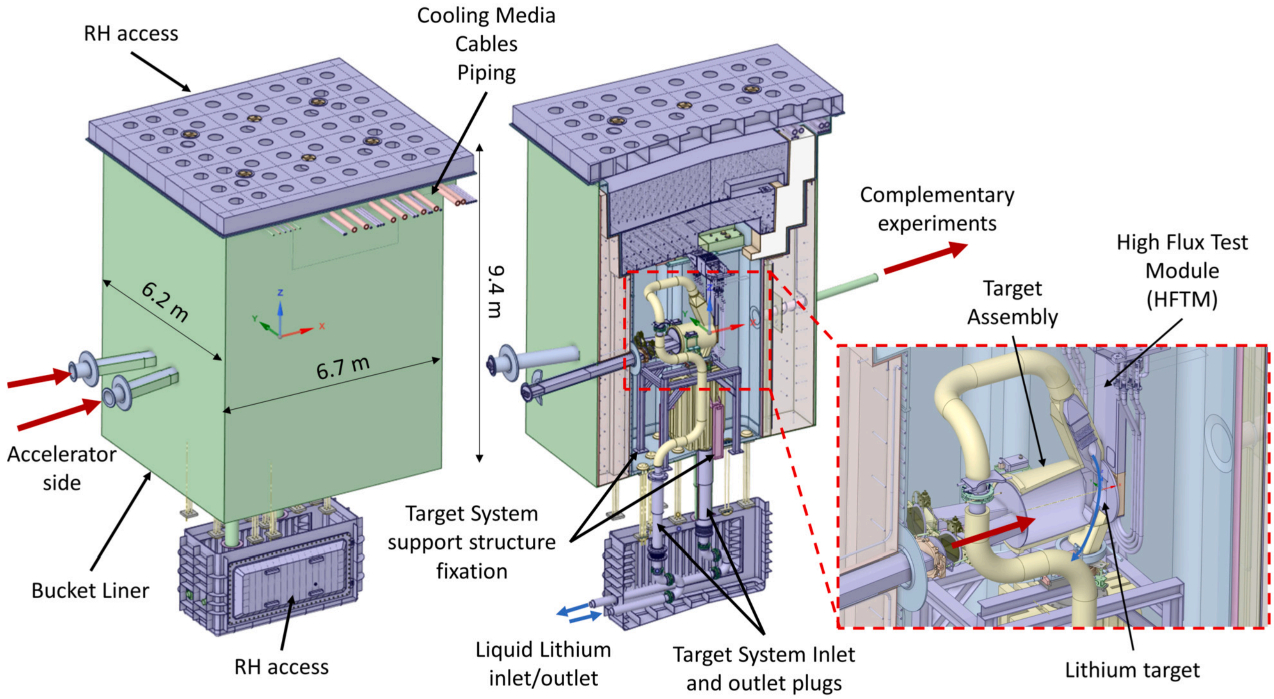

Fig. 1. Test Cell and its interfaces.

IFMIF-DONES consists of five main systems: Site, Buildings and Plant Systems (S&BP), Test Systems (TS), Lithium Systems (LS) [9], Accelerator Systems [10] (AS), and Central Instrumentation and Control Systems (CICS) [11]. The Test Cell (TC) is part of the Test Systems, and its main purpose is to contain and confine the irradiation modules with their material specimens and to shield, using thick concrete blocks, the high-energy neutrons produced inside the TC by the deuteron-lithium interaction; in this sense, the TC system can be considered the heart of the IFMIF-DONES facility.

In the following chapters, the Test Cell will be detailed alongside its component design and its connections and interaction to other systems.

2. Functions, interfaces and requirements for the Test Cell

The purpose of the Test Cell is to provide a convergent space for the testing of the material specimens housed in the Test Modules. The Test Cell is situated inside the main building, at its core [2] [3]. It is surrounded by an outer layer of permanent concrete and then a layer of removable concrete blocks. Together these provide the main neutron shielding of the Test Cell. The TC serves as a vacuum vessel (Helium atmosphere at 100 mbar, 50 °C during operation) and therefore provides a vacuum boundary which also serves as the primary nuclear safety boundary of the facility. It houses the components of the Lithium Target System (TSY) and the Test modules (TM). The TSY comprises of the liquid lithium loop and its accessory components, which are the inlet and outlet lithium piping, the target assembly (housing the liquid lithium target curtain), the lithium Quench Tank (which is slowing down the lithium jet), the Through Wall Beam Ducts (TWBDs, protruding to the Accelerator Room) and the supporting structures of these components (Fig. 1, [7]). In case of the TMs, only the High Flux Test Module (HFTM) is developed in detail and included in the model currently (Fig. 1), which is the first module after the lithium target and is designed to withstand an irradiation higher than 10 dpa/fpy in approximately 0.5 litre volume. Other modules (e.g. Medium and Low Flux Test Modules, MFTM and LFTM) are under development [8]. The two deuterium beams are coming in through the Through Wall Beam Ducts (TWBD) that have a 9° inclination with respect to the orientation of the Test Modules and impact into the Lithium Target. Then material specimens inside the TMs are irradiated. In the case of DONES, only one beam is considered, the other TWBD is used for diagnostics, but the system still needs to be designed for the IFMIF case (two beams) to prepare it for an easy upgrade in a later stage. After the TMs, the beam goes through an opening to the room for Facilities for Complementary Experiments (FCE) to be able to harness the remaining neutrons [12].

Inside components of the TC can only be maintained by Remote Handling (RH) means [13] due to the high neutron radiation. RH is an integral part of the design as any component within the bucket liner (which is fixed to the permanent concrete) must be maintainable either in case of failure or planned regularly [13]. Therefore, access to the inside components from the top of the TC needs to be ensured. Two cranes are available in the Access Cell for component handling, the Heavy Rope Overhead Crane (HROC) manages large components and has a payload of 140 t with an accuracy of ±5 mm and ±1°, while the Access Cell Mast Crane (ACMC) has a payload capacity of 2 t and installs and aligns smaller components and also carries out cleaning and inspection operations inside the TC. Recent updates of these components are reported in [14].

Part of the TC protrudes into the Lithium Room below, which is called the Test Cell Lithium Interface Cell (TLIC) and it serves as the entry point for the Liquid Lithium Inlet and Outlet Piping and also provides remote handling access to inside components.

Finally, the TC needs to ensure the routing of cables, cooling piping (both water and helium), instrumentation and atmosphere regulation piping with remote handling compatible feedthroughs.

The TC needs to fulfil a set of strict safety requirements against a set of identified Design Basis Accident Scenarios to be able to fully commission the components [15] as the TC serves as the primary safety boundary of the DONES facility.

3. Test Cell evolution

The Test Cell went over a huge design evolution throughout the years (see Fig. 2). The 2013 design [16] exhibits components in an early stage without any features and a monolithic shielding concrete approach. The lithium quench tank is situated outside of the Test Cell. The 2017 design [17] has matured, but efforts are still more towards

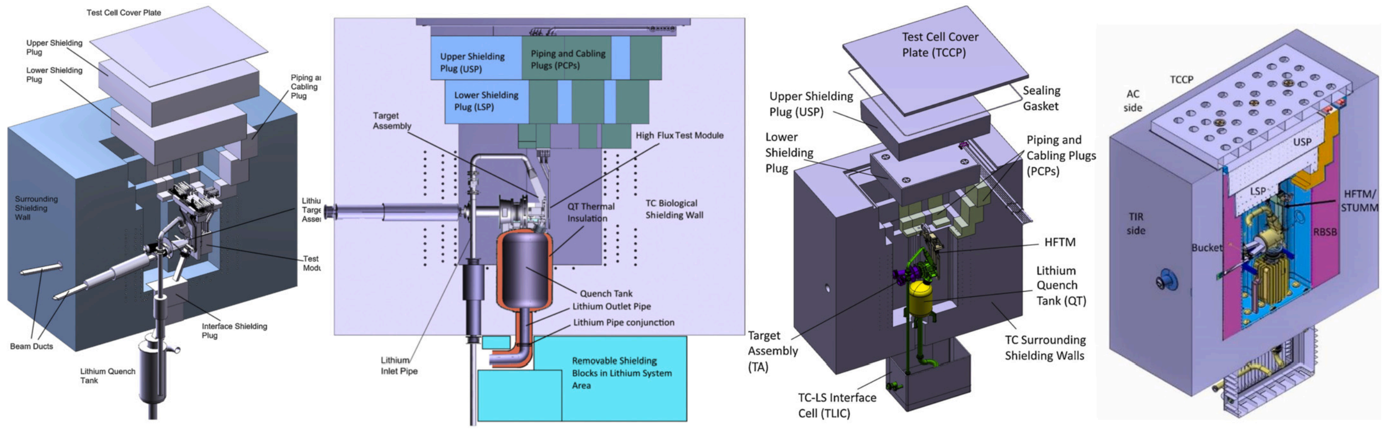

Fig. 2. Test Cell Evolution: 2013 (first, [16]), 2017 (second, [17]), 2019 (third, [18]), and the latest design (last).

the design of the Lithium system and the Test Modules, however, the design of PCP piping and the cooling of the permanent concrete have been added. The Lithium Quench Tank is partly situated in the Test Cell. The 2019 design [18] incorporates even more updates starting with a detailed design of the Lower Shielding Plug (LSP), sealing of the Test Cell Cover Plate (TCCP), full inclusion of the quench tank in the TC and the addition of an early design of the TLIC. The latest version has components that are already in the detailed design phase and almost ready to be commissioned for manufacturing (see Fig. 1 and Fig. 2), but there are investigations ongoing to see if tolerance errors are in the acceptable range. The main change is that removable biological shielding blocks (RBSBs) have been introduced into the design because the concrete-embedded cooling pipes exhibited a high risk in case of failure, therefore the need for maintenance arose. Early design of RBSBs is reported in [19]. In the following sections, the TC components are described.

4. Component design

The components of the TC are the following (see Fig. 3):

- Test Cell Cover Plate (TCCP): Removable vacuum boundary at top
- Upper and Lower Shielding Plugs (USP and LSP): Heavy concrete components providing neutron shielding on top
- Piping and Cabling Plugs (PCPs): Providing neutron shielding while routing instrumentation and gas supply cables into the TC
- Test Cell Liner (TC Liner): Main vacuum boundary
- Removable Biological Shielding Blocks (RBSBs): Providing neutron shielding on sides
- Bucket Liner: Providing separation between permanent and removable concrete
- Test Cell Lithium Interface Cell (TLIC): Vacuum boundary extension to Lithium Room accommodating the Lithium inlet/outlet piping

In the following subsections, these components and their purpose are discussed in detail.

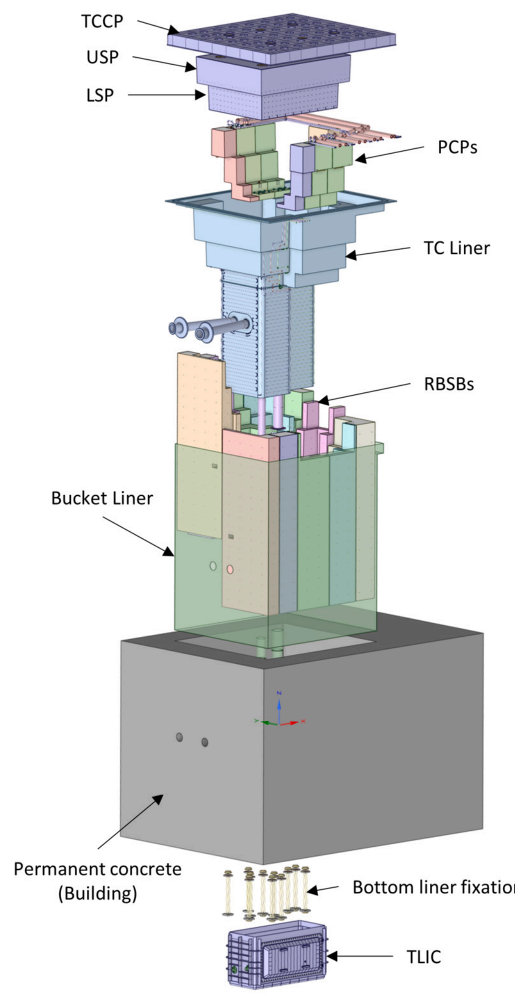

Fig. 3. Test Cell Overview.

4.1. Test Cell Cover Plate - TCCP

The TCCP is a 7.95×7.1×0.6 m component which can still fit inside the main building through the maintenance hatch on the top of the Access Cell (in case of commissioning or component change due to failure), which is a 7.7×7.1 m opening. The TCCP provides the vacuum and safety boundary on the top of the TC and maintains vacuum by a removable O-ring seal. It has a stainless steel (SS 316L) rigid welded structure to maintain low deformation (Fig. 4) and to be able to lift during maintenance by the HROC using the RH connectors. The O-ring seal is positioned on the perimeter of the TC liner, further away from the TC cavity, to maintain low exposure to neutron streaming so that it can be removed by hand (Fig. 4). Moreover, the TCCP is filled with polyethylene (PE) to mitigate neutron streaming to the Access Cell (which is above the TC cavity, Fig. 6).

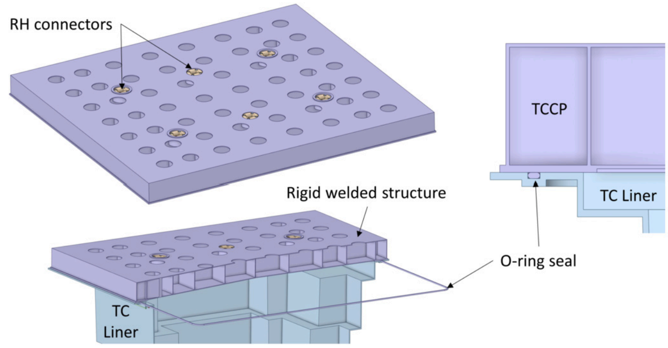

Fig. 4. TCCP detailed design.

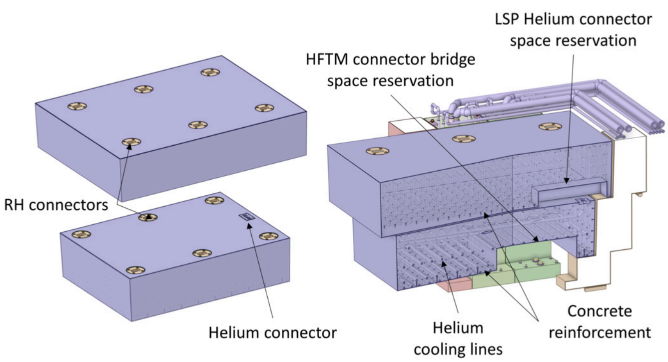

Fig. 5. USP and LSP detailed design.

4.2. Upper and Lower Shielding Plugs - USP and LSP

The USP and LSP (Fig. 5) provide the neutron shielding towards the Access Cell which is above the TC, together they have a thickness of 2.5 m heavy concrete. The USP is the heaviest component of the Test Cell exhibiting an overall mass of 120 t, while the LSP is 86 t. Sidewalls of plugs are inclined to provide easier positioning during remote handling operations. A thin liner provides structural rigidity and shielding of the concrete, while reinforcement bars and studs provide rigidity for the heavy concrete itself. In addition, the LSP needs cooling to maintain low temperature in the concrete base (target value is $< 100\,^{\circ}$C) to avoid cracking. As this component is inside of the Test Cell where it can have direct contact with liquid lithium in case of failure, therefore water cooling is not an option as it is highly reactive with lithium, so helium cooling is used instead. Early CFD calculations [20] showed that LSP is expected to deal with 22.1 kW of volumetric heating and 2.4 kW due to the heat plume effect in the TC cavity. Recent calculations with updated models showed that the volumetric heat effect is lower (9.4 kW) while the heat plume is causing similar conductive heat transfer (2.1 kW). The inlet helium cooling is set to 9 bar absolute pressure at $20\,^{\circ}$C to take away the excess heat of the LSP. Two pockets are present in the plugs, one in the USP giving space for the helium cooling pipe connections and one in the LSP giving space for the HFTM connector bridges. These two pockets reduce the effective amount of neutron shielding resulting in high streaming to the AC which can be mitigated below the allowable limit (1000 μSv/hr for controlled access) by the use of PE filling in the TCCP except for a few hot spots that are still present (Fig. 6). Further calculations are underway to optimize the dog-leg shapes of the RBSBs to reduce streaming to AC.

4.3. Piping and Cabling plugs - PCPs

The PCPs provide the means to route the cables (instrumentation, power, etc.) and piping (atmosphere control, helium cooling, etc.) in a way which also mitigates neutron streaming to the Access Cell (Fig. 7).

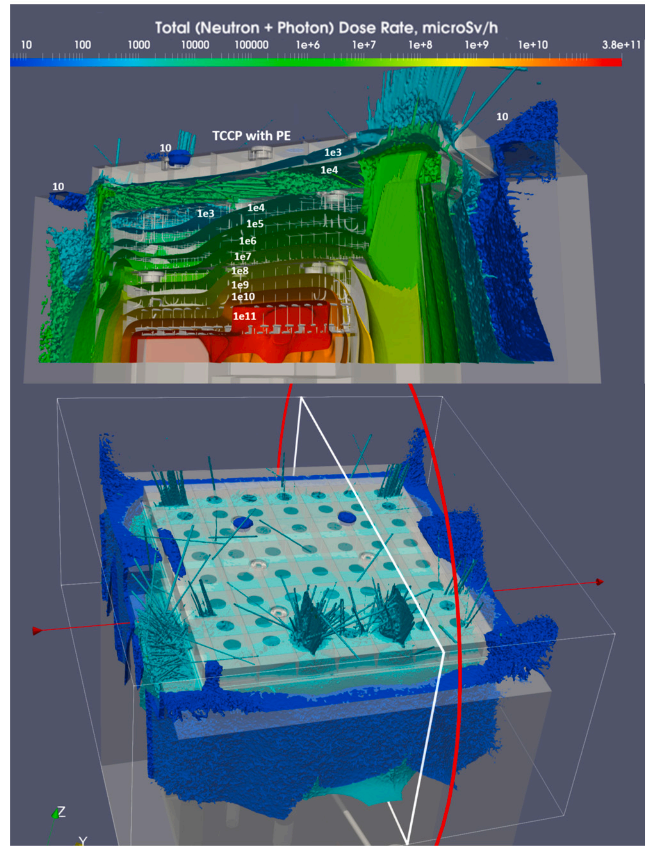

Fig. 6. Total dose rate (μSv/hr) in the Test Cell with PE filling - one beam case (Top figure is a section view of TC at the marked plane on the bottom figure).

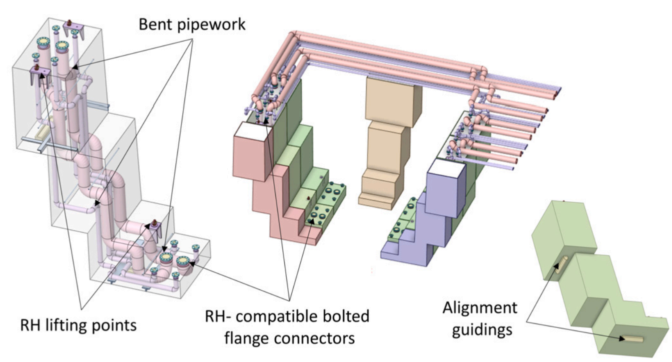

Fig. 7. PCP detailed design.

Currently, seven PCPs are foreseen for the supply of the test modules and some diagnostics are provided for the Target Assembly. The PCPs are made up of heavy concrete and a thin steel liner covering the outline, while the mass varies between 6 to 10 tons. Pipeworks are bent inside to aid neutron shielding (Fig. 7). All pipes and cabling are attached on the top of the PCPs using RH-compatible flange connectors and routed inside the TC so that components can be reached and replaced by remote handling operations without removing PCPs (Fig. 7). Alignment guidings help the positioning of the PCPs on the bottom during installation as 10 mm gaps are foreseen between blocks.

4.4. Test Cell Liner - TC Liner

The TC Liner provides the vacuum and safety boundary of the TC. Its unusual rectangular shape for a vacuum chamber shows interesting behaviour to vacuum loads. Initially, the liner had an overall thickness

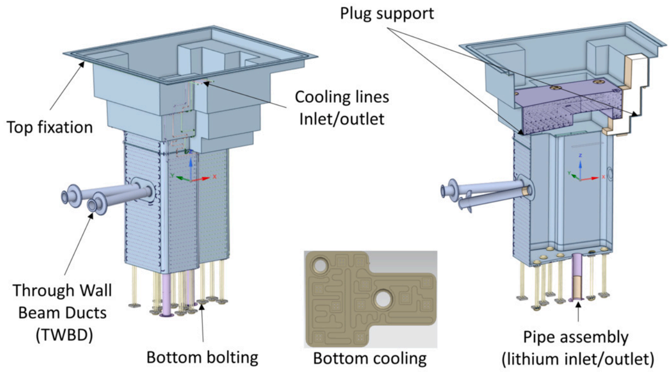

Fig. 8. TC Liner detailed design.

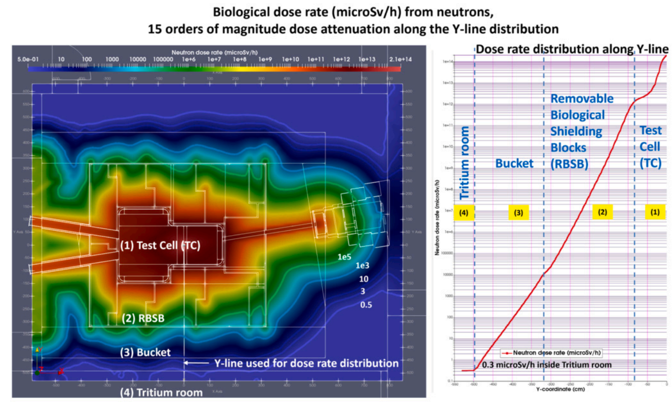

Fig. 9. Biological dose rate (μSv/hr) from neutrons in the Test Cell (one beam-on case).

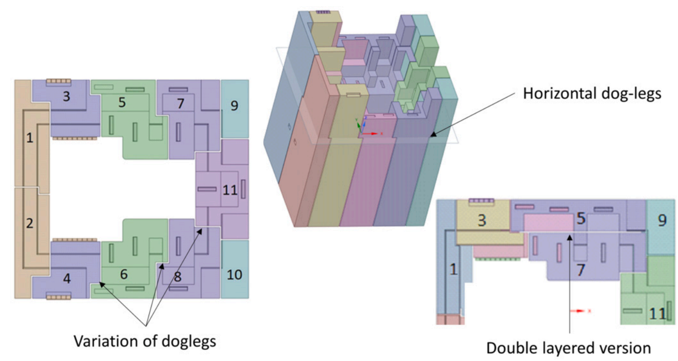

Fig. 10. Outline variation of RBSBs to optimize neutron shielding.

of 8 mm SS 316L which was adequate for a fixed liner and even for a partially fixed one [19], but in more recent analysis, where the liner was considered fully removable, the stresses went into the unacceptable regime as it turns into a vacuum vessel [21].

Different solutions have been evaluated to see which setup is the best candidate to assess structural integrity, seismic loads, heat distribution and welding outline. RCC-MRx design code is chosen to aid in the evaluation of loads and the use of best practices for the outline.

Different fixation setups have been evaluated: (a) Top fixation, (b) bottom fixation and (c) top + bottom fixation. Extensions were always considered fixed. Results showed that version (a) superimposes high deflections on the inner components supported on the TC Liner (HFTM and Target Assembly) compromising the alignment requirements of these; version (b) is more robust in terms of alignment, but not sufficient and buckling of the system is problematic. Version (c) yielded the best results and this has been implemented into the CAD model. The first approach of the fixation at the bottom consists of through bolting (Fig. 8), but other solutions are currently under investigation. The top fixation is not yet designed in detail, but investigations are ongoing also.

The structure is reinforced with thick SS plates varying between 25-35 mm generally, while the bottom plate is a 100 mm thick piece to also serve as a neutron shielding and heat sink component for the protection of the bottom permanent concrete. The ribbing of the liner for structural rigidity has been considered and finally turned down to have fewer welding seams that might need in-service inspection. The layering of the bottom currently consists of a thick TC liner bottom, copper plates under the bolts to support thermal contact, and the bucket liner studded to the permanent concrete and then the concrete itself. Evaluation is ongoing to see the thermal behaviour of the bottom layering and how the heat is distributed in the permanent layer as it is fundamental to avoid high heat flux and thus degradation of the concrete layer below. Cooling channels are also embedded into the bottom plate (Fig. 8). CFD analysis of the TC interior space showed that the TC liner experiences 7.6 kW of volumetric heating and 6.1 kW convective heat totalling a 13.7 kW heat load [20] in the case of one-beam operation, however recent calculations showed that the total heat load of the TC Liner is around 18 kW. The elevated heat load is mainly due to the increase in the wall thickness of the liner (resulting in a higher volume). The heat is dissipated by welded water cooling pipes (12 °C, 7 bar absolute pressure at inlet) on the outer surface of the liner. A calculation is ongoing to see the two-beam case loading of the components, particularly the liner.

The TC liner does not fit through the maintenance hatch of the Access Cell, therefore it needs to be assembled fully on-site, however, it can be partly pre-manufactured.

4.5. Removable Biological Shielding Blocks - RBSBs

The RBSBs are a recent addition to the design due to the need for maintainable cooling lines that are embedded in the maintainable concrete. Moreover, the removable (heavy) and permanent (ordinary) concrete layer thicknesses have been chosen to mitigate neutron streaming to the neighbouring rooms and to aid the decommissioning phase (Fig. 9). The removable layer is divided into 11 blocks. These inhibit 40 mm gaps and dog-leg shapes to aid the radiological shielding. Various versions have been analyzed to see performance, especially in the case of the Access Cell shielding. Double dog-leg distribution was investigated, and results showed that it helped AC streaming to some extent. The introduction of horizontal dog-legs helped, but complicated the design, especially in case of failure (removal of several RBSBs needed before access to the failed one) and therefore this concept was dropped (Fig. 10). An effective shielding option is the use of PE filling in the TCCP (Fig. 6) as it mitigates better neutron streaming to the AC than the variation of dog-legs of the RBSBs [22], however after the addition of the LSP and USP pockets, local hot spots appeared in the design (Fig. 6) that imply the need for further optimization of the RBSB dog-legs. Another concept is the so-called double layer in which case the RBSBs are divided into two rows. In theory, only the first row needs embedded cooling circuits, which would decrease the probability of failure of these components. RBSB shapes are optimized to have similar weight varying around 70-75 t. An SS 316L liner encases the heavy concrete and the embedded cooling lines. The TC cavity-facing walls are thicker to concentrate the volumetric heating to this region and the embedded pipes are welded to this liner wall to ease the flow of heat.

The RH lifting solution and installation positioning of the RBSB are currently under development [22]. Investigations are conducted to improve the performance of heavy concrete to achieve better shielding conditions [23].

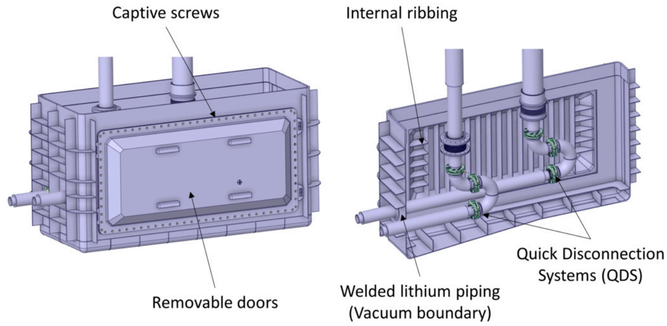

Fig. 11. TLIC detailed design.

4.6. Bucket liner

The bucket liner is in an early design phase currently representing a boundary between the removable TC components and the permanent concrete (which is the building itself). It ensures that no contact can occur between activated water and permanent concrete, while also providing smooth contact surfaces for the TC liner fixation at the top and the bottom. Current investigations are ongoing to see if the thickening of the bucket liner at the bottom could provide further protection against volumetric heating due to neutrons for the bottom permanent concrete.

4.7. Test Cell Lithium Interface Cell - TLIC

The TLIC serves as the vacuum boundary extension to the Lithium Room accommodating the lithium inlet and outlet piping inside. The primary need for this box is to provide a vacuum and safety boundary for the TC, thus separating the atmosphere of the lithium room during operation and maintenance. The detailed design is done by the use of RCC-MRx code [24], taking into account the RH needs of components, e.g. the door is designed to be removable using a double layered O-ring layout which otherwise ensures the vacuum boundary. These seals are not exposed to high neutron radiation as they are further away from the opening of the lithium pipings [18], but possibly need regular maintenance as the TLIC will be opened every 1 or 2 years to access lithium components inside. The TLIC is accessible from both sides to increase the reach of the RH robotic arms inside the box to maintain the lithium piping components. Ribs stiffen the structure of the TLIC, while the internal ribs on the doors make the removable doors lighter (approx. 430 kg each). (Fig. 11.)

4.8. Interaction between the TC components

The interaction between the TC components is crucial to be known to understand how the system responds to external and internal loads, therefore ultimately knowing what impact the system has on the alignment of the deuteron beam, the Lithium Target and the Test Modules, respectively.
The TC outer shell is the permanent concrete which is part of the main building and seismically isolated [18]. The bucket liner is studded to the permanent concrete making it a firm layer of stainless steel. The RBSBs are positioned in the cavity and then fixed to each other to mitigate seismic excitations. The TC liner is fixed to the permanent concrete at the bottom by bolts and at the top. The TWBDs and lithium piping openings of the TC liner are also welded on the outer side of the permanent concrete to continuing steel liners. The TC liner is not in mechanical contact with the RBSBs during any operational state of DONES. The inner components (lithium target assembly components and test modules) are fixed to the TC liner either at the bottom or at the PCP level. The PCPs are supported on the TC and the positioners at the bottom help limit the movement of the PCPs. PCPs are connected to the top feedthrough and inner components through piping connections, however, in crucial cases such as the HFTM, a bellow-like connection is planned to be installed between components to mitigate impact on alignment. The LSP and USP are supported again on the TC liner and are decoupled from other inner components, except for PCP 3 which supplies helium cooling to the LSP through piping connections, but this component is not foreseen to supply any media to the HFTM. Finally, the TCCP is positioned at the top of the TC liner and is fixed in its place by the vacuum load during normal operation.

5. Results

Substantial design work has been performed on the Test Systems of IFMIF-DONES throughout the years. So far, the focus has been on the safety and vacuum-bearing elements of the system (TCCP, TC Liner, TLIC) and the neutron shielding elements' shielding performance evaluation (RBSB, LSP, USP) while also taking into account connecting points to other systems (interfaces, e.g. RH needs). These components have undergone systematic and detailed analysis and design updates. PCPs connected to the HFTM are also detailed, but other PCPs connecting to the other irradiation Test Modules are in an early development stage.
Significant investigations have been done for the one-beam load case (IFMIF-DONES), however, all components need to be analysed and designs need to be validated against a two-beam load case (IFMIF) version.

6. Discussion

The main components of the Test Systems are on an advanced design level, however, some aspects are still not included. These encompass mainly the diagnostic needs of the Test Cell which have been mapped, but the detailed design of instrumentation remains a work to be done [25]. Activities are underway to see the commissioning and decommissioning needs of components too, while the control system is also under definition and design [26].

7. Summary

The Test Cell is the convergent space of the IFMIF-DONES facility providing space for the testing of materials while also providing the vacuum and safety boundary. It has a direct connection with several systems interacting with them actively. The Accelerator Systems provide the deuteron beam that enters through the TWBDs on the side of the Test Cell and impinges a liquid lithium target inside the TC cavity. The materials inside the Test Modules are irradiated by the stripping neutrons and then the remaining exits through the opening to the FCE. The liquid lithium is supplied from the Lithium Room that is situated below the TC. Assembly and remote handling operations are mainly done through the top and marginally from the lithium room where the TLIC is situated. Each TC component's design and purpose are detailed in corresponding chapters. Interaction between components is also detailed to see the impact on the alignment of inner components that directly corresponds to the material irradiation procedure. Finally, results are detailed and future work is discussed.

CRediT authorship contribution statement

A. Zsákai: Writing – original draft, Investigation, Conceptualization. **C. Meléndez:** Validation, Methodology. **S. Becerril:** Supervision, Formal analysis. **T. Dézsi:** Validation, Methodology, Investigation. **D. Kovács:** Investigation. **R.S. Simon:** Investigation. **A. Korossy-Khayll:** Methodology. **D.Z. Oravecz:** Writing – review & editing, Visualization, Conceptualization. **I. Katona:** Methodology, Conceptualization. **J. Castellanos:** Supervision, Project administration, Data curation. **A. Serikov:** Formal analysis, Conceptualization. **Y. Qiu:** Formal analysis, Conceptualization. **G. Micicché:** Formal analysis. **M. García:** Supervision, Project administration, Data curation. **A. Ibarra:** Supervision, Project administration.

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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