IAEA nuclear fusion

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OPEN ACCESS
IOP Publishing | International Atomic Energy Agency
Nuclear Fusion
Nucl. Fusion **65** (2025) 125001 (32pp)
https://doi.org/10.1088/1741-4326/add172

The IFMIF-DONES Irradiation Modules

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Received 28 October 2024, revised 14 April 2025
Accepted for publication 28 April 2025
Published 30 September 2025

Abstract

The IFMIF-DONES Irradiation Modules consist of a set of systems designed to be tested in the IFMIF-DONES facility and which are thought to produce, in the future, an extensive, qualified and unique set of fusion-like irradiated experimental data associated to the materials and the structures to be used in specific breeding blankets (BBs) that are currently under consideration for the EU DEMO fusion reactor. The irradiation conditions (neutron fluence and spectra) at the position of the IFMIF-DONES Irradiation Modules inside the test cell, will be comparable to that expected as reference in the most exposed zones of the EU DEMO reactor. Nevertheless, medium and low flux regions will be also available. In this work, an introduction to the description of the main IFMIF-DONES Irradiation Modules is given. Particularly, the following 5 modules are described: the (IFMIF-DONES) High Flux Test Module, HFTM, tailored to powerful irradiate structural materials such as small specimens of Eurofer, the (IFMIF-DONES) Start-up Monitoring Module, STUMM, designed to monitor the radiation fields produced just behind the neutron source, under transient and steady state conditions, the (IFMIF-DONES) Blanket Functional Material Module, BLUME, which is a representative section of the Helium Cooled Pebble Bed (HCPB) blanket breeder zone, the (IFMIF-DONES) Liquid Breeder Validation Module, LBVM, for the irradiation of functional materials such as PbLi and anti-corrosion/anti-permeation barriers, and the (IFMIF-DONES) Tritium Release Test Module, TRTM, which is defined for the irradiation of lithium ceramic pebble beds associated to the HCPB BB.

[a] See the Appendix in Ibarra *et al* (https://doi.org/10.1088/1741-4326/adb864) for the Eurofusion WPENS Team.
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Keywords: IFMIF-DONES Irradiation Modules, High Flux Test Module HFTM, Start-up Monitoring Module STUMM, Blanket Function Material Module BLUME, Liquid Breeder Validation Module LBVM, Tritium Release Test Module TRTM, fusion materials and structures

(Some figures may appear in colour only in the online journal)

1. Introduction

IFMIF-DONES is a powerful neutron source able to provide a neutron flux up to the level of 1–5 × 10^{14} n cm^{-2} s^{-1} with a neutron spectrum similar to the one expected in the most exposed zones of the future fusion EU DEMO reactor. The base to produce the fusion-like neutron fields relies on the nuclear stripping reactions produced by a projected 125 mA and 40 MeV deuteron beam impinging and penetrating a liquid lithium curtain with nominal thickness of 2.5 cm flowing from top to bottom at nominal speed and temperature of 15 m s^{-1} and 300 °C respectively [1–3].

The construction phase of IFMIF-DONES started in Granada in 2023 in accordance with the schedule and phases established in the DONES Program [4].

The production of fusion-like neutrons is performed inside a controlled and shielded environment provided by the test cell (TC) system, which is described elsewhere [5, 6]. The TC shaped a prismatic volume where the target assembly (TA) and the IFMIF-DONES Irradiation Modules are located. The TA is a special chamber that contains the liquid lithium curtain and that receives the deuteron beam. Inside this chamber the neutrons are primary generated. The TA is part of the lithium systems, and it is described elsewhere [7]. The IFMIF-DONES Irradiation Modules are tailored structures physically located inside the TC and behind the TA. The production of neutrons shall be theoretically sustained up to 345 d at full power.

During the irradiation periods, a complete set of signals related to the IFMIF-DONES Irradiation Modules will be coming in and out from the TC as well as feeding pipes mainly providing helium as cooling media for specific structures and the gas of the controlled atmosphere inside the TC. The design of the TC is conceived following a modular and flexible approach [6], in the sense that in principle, it could be adapted to several predefined configurations of modules with different purposes.

On the basis of the TC modular approach, and the flexibility of the ancillary systems, single irradiation of a specific module shall be feasible within the IFMIF-DONES design as well as simultaneous irradiation of several modules. As a design hypothesis and from the engineering design point of view, currently it is considered that up to 3 generic irradiation modules should be possible to be simultaneously irradiated inside the TC. Simultaneous irradiation makes difficult the engineering design but benefits the neutron economy and the acceleration of the irradiation program.

The IFMIF-DONES Irradiation Modules are part of the test systems area of IFMIF-DONES and the introduction to their description and current engineering design status is the aim of this paper.

The IFMIF-DONES Irradiation Modules are conceived as the set of modules where irradiation experiments in IFMIF-DONES will produce relevant data in the fusion technology area. Just for clarification, it is important to mention that the components aimed to be irradiated in IFMIF-DONES with neutrons, but with purposes outside of fusion science and technologies discipline are hierarchically structured in the facility through the complementary experiments and they are outside of the IFMIF-DONES Irradiation Modules category and outside of the scope of this paper.

The IFMIF-DONES Irradiation Modules will be, in general, irradiated at the unique conditions in terms of the neutron fluence and spectra that IFMIF-DONES will be able to produce.

After the analysis of the irradiated experimental data produced, it shall be possible to understand the degradation and alterations in performance on specific materials and arrangements under fusion-like extreme irradiation conditions. In this sense, the different irradiation experiments aim to produce an unprecedent and unique set of experimental data and measurements that shall contribute to the improvement of EU DEMO breeding blanket (BB) design. Particularly, the design of the blanket shall be more predictable, reliable and safe, and some technological gaps shall be reduced.

In general terms, the IFMIF-DONES Irradiation Modules will contain either (a) samples of structural materials or other materials of interest, or (b) they will accommodate specific representative mockups/setups or functional materials of the breeder blankets to be used in the future EU DEMO reactor.

In the case (a) the results of the irradiation experiments will populate irradiated material databases and small specimens designed and carefully manufactured according to recognized international standards will be located inside the modules.

Baseline materials for EU DEMO are Eurofer for structures, tungsten materials for armor (of plasma facing components), and CuCrZr as heat sink [8]. IFMIF-DONES is specifically tailored to match dpa rate and He/dpa ratios of Eurofer (or other steels) in the first wall (FW) (see below, nuclear analysis section of HFTM). The possibility to irradiate W and Cu materials in DONES has also been explored [9–11] and found possible. For those materials however, irradiation conditions, especially transmutation, are not perfectly matched (i.e. too high He production).

In the case (b), 'unit sizes' of pre-defined complex structures associated to specific BB or configurations associated to functional materials will be located inside the modules to address specific BB technological issues. In this approach the irradiation experiments inside the TC shall check the performance of 'unit-size' structures under fusion-like neutrons so the components will be assessed in a harsh environment before using (in a scalable way) in a BB of the EU DEMO.

In the case of irradiation of 'unit-sizes structures' the maximum irradiation volume associated to the HFTM of 0.5 l can be exceeded (the TC has a deep of ∼1.5 m from the TA to the back wall of the TC liner). Currently, some 'unit-size structures' in the IFMIF-DONES Irradiation Modules are considering lengths up to 500 mm to be irradiated inside the TC.

The construction of the IFMIF-DONES Irradiation Modules due to the harsh environment should follow the higher quality standards and manufacturing process provided by the industry. In particular, nuclear related equipment standards shall be considered.

The following list of 5 IFMIF-DONES Irradiation Modules are described in this paper, which are at different design stages according to their lifecycles:

1. The (IFMIF-DONES) High Flux Test Module, **HFTM**, which is a tailored structure to initially irradiate Eurofer samples, with a neutron energy spectrum and fluence comparable to that experienced for this kind of structural material in EU DEMO fusion power reactor. Up to 50 dpa in 3 years are expected in a limited volume and controlled temperatures in the range of 250 °C–550 °C [11, 12].
2. The (IFMIF-DONES) Start-up Monitoring Module, **STUMM**, for measuring radiation fields at the position of the HFTM, behind the TA during the commissioning phase; it considers a wide set of diagnostics to monitor the neutron fluxes and the radiation field characteristics in its area of influence. It would be used as a powerful tool to learn about the radiation fields produced by the neutron source under transient and steady state irradiation [13].
3. The (IFMIF-DONES) Blanket Function Material Module, **BLUME**, for testing BB functional materials of the Helium Cooled Pebble Bed BB, HCPB BB.
4. The (IFMIF-DONES) Liquid Breeder Validation Module, **LBVM**, to address several R&D issues associated to the liquid BBs. Initial design, consider experiments for checking, among other purposes, the performance of functional materials such PbLi under intensive neutron irradiation and in relation to the water-cooled lithium-lead BB, WCLL BB.
5. The (IFMIF-DONES) Tritium Release Test Module, **TRTM**, for checking performance of functional materials acting as tritium breeder (lithium ceramics) and neutron multipliers (beryllides).

Each of the five modules covers one or several scientific cases in the sense that the experiments and measurements to be performed on it, inside the TC, shall be relevant to the EU DEMO design.

Respect to the design status, the engineering design for the first two modules in the list, HFTM and STUMM are currently considered more consolidated and outlined in terms that the design relies on neutronic, thermal, mechanical analysis and engineering judgements previously performed as well as other studies. Besides this, the design is accompanied by the definition and implementation of an extensive experimental validation program associated to each of these two modules.

In the particular case of the HFTM, experiments in HELOKA-LP facility (helium cooling loop [14]) for the HFTM-DC (double compartment) to experimentally evaluate cooling performance of the module and the refinement of the heater control loops were and are being developed as well as, experimental handling and manipulation of the activation foils as offline diagnostic, and handling and manipulation of the sodium in the HFTM capsules [15, 16]. Moreover, some experiments results and lessons learned from IFMIF-EVEDA phase are detailed in [17] and they have been used for the (IFMIF-DONES) HFTM engineering design. More details on the status of the engineering design of the HFTM are defined in section 2.

In the case of the STUMM, the experimental validation program is called STUMMEX (STUMM EXperimental Program) which mainly involves the construction and tests of a 1:1 scale prototype of the STUMM system, with a representative and reduced number of rigs fully instrumented with neutron, gamma and temperature detectors (up to 60 sensors are being considered). This component collects some of the main functionalities and boundaries of the STUMM and it is called STUMM-PROTO [18]. The design and construction of STUMM-PROTO started in mid-2022 and it aimed to be compatible with RCC-MRx requirements in terms of materials and main manufacturing processes.

The construction of the STUMM-PROTO will be followed by a complete set of non-irradiated and irradiation tests. STUMM-PROTO includes 35 m long coaxial cables to mimic IFMIF-DONES conditions where the sensors located inside the STUMM are far from their electronics, separated a similar distance due to the big biological shielding blocks and plugs that surround the STUMM in the TC and the thick walls of the main building. More information about the STUMM, STUMM-PROTO and STUMMEX is presented in section 3.

As a continuation of the developed work, the paper presents the conceptual approaches that are currently being developed for the rest of the modules (3, 4 and 5 in previous numbered list), which are categorized in this work as IFMIF-DONES Other Irradiation Modules. See section 4.

Unlike the HFTM and the STUMM, the Other Irradiation Modules (3–5) are in a pre-conceptual/conceptual design phase, and they are not yet explicitly included in the baseline of the IFMIF-DONES facility. The future development of the irradiation modules 3, 4 and 5 shall have a experimental validation program/strategy associated, including, the construction of selected prototypes and the implementation of irradiation experiments in research reactors or in other gamma/neutron source facilities. This procedure shall strengthen the engineering design of each module, producing a safer and reliable module, which behavior can be predictable and understandable up to some extent, before locating it in the TC for irradiation.

On the other hand, it is important to mention that the approach of considering several types of irradiation modules with different objectives inside a fusion-like neutron source is not new. Many years ago, in 1996, in the framework of the IFMIF Conceptual Design Activity (IFMIF-CDA) phase, it was identified as urgently needed the creation of a large experimental database of irradiated materials under fusion environment [19]. In this [19], between other topics, it is listing several materials to be irradiated in IFMIF such us: FW and blanket structural materials, ferritic-martensitic steels, vanadium alloys and SiC and SiC-composites at high flux regime, and ceramics and superconducting materials between others at medium and low flux regimes. Tritium diffusion and release online measurements were also identified as important. Post-irradiation tests and *in-situ* tests were also recognized in this early stage to analyze the influence of fusion-like irradiation on different materials properties.

Considering the design evolution over the years, it was produced, in 2004, the IFMIF CDR (Comprehensive Design Report), where the same irradiation parameters and materials listed in 1996 was traced down [20, p 3.1–1, table 3.1–1], and with this information several modules were pre-conceptually developed as well as the general characteristics of the associated irradiation experiments. The accumulated damage levels due to irradiation ranged from ∼0.001 dpa (for the rf windows and superconducting materials) to 150 dpa (for the FW and blanket structural materials). The temperature ranged from 80 K (for superconducting materials) up to 1100 °C (for tungsten alloys).

In a later major step, an outstanding hold point was the release of the Intermediate Engineering Design Report of IFMIF, result from EDA (Engineering Design Activities) phase in 2013 where the following seven modules were defined to be irradiated [21–23]. Particularly, the following modules were developed to an 'intermediate' level of engineering design [10]:

- IFMIF-EVEDA Tritium Release Test Module [24].
- IFMIF-EVEDA Liquid Breeder Validation Module [25].
- IFMIF-EVEDA Creep Fatigue Test Module.

Also, the neutron source, which is currently under design in Japan, A-FNS (Advanced Fusion Neutron Source) is considering up to 9 modules (8 test modules plus 1 measurement module) with several purposes according to [26, 27].

Finally, from the previous paragraphs, it can be stated that a considerable number of needs for irradiated material and structures data for EU DEMO clearly exist. Some of these needs can potentially be addressed by means of proper irradiation experiments inside the IFMIF-DONES TC. In this sense, the list of 5 IFMIF-DONES Irradiation Modules presented in this paper is not limited or closed at this moment and can potentially be extended and adapted in the future, in part, thanks to the flexible/modular design approach for the TC and its ancillaries. In any case, the future extension of IFMIF-DONES Irradiation Modules to more items shall be covered in future research and development plans.

2. The (IFMIF-DONES) High Flux Test Module, HFTM

2.1. Mission, mode of operation and requirements

The HFTM of IFMIF-DONES is the dedicated device to enable the irradiation of small-scale specimens in the zone of highest neutron flux (up to 5×10^{14} n cm^{-2} s^{-1}) directly behind the IFMIF-DONES neutron source. The irradiation characteristics of the HFTM are as follows:

- Long term, spanning 1–2.5 years, accumulating up to 50 dpa per campaign.
- At controlled temperature. The temperature levels in the range of 250 °C–550 °C during irradiation are of interest for ferritic-martensitic 9% Cr steels such as Eurofer (derived from temperature range intended in DEMO). Temperature spread is also limited in ±3%.
- No mechanical loads are actively applied to the specimens during irradiation.
- Specimens must be retrieved from the HFTM after irradiation for material testing (Post Irradiation Examination—PIE).

Due to the high level of radiation damage accumulated inside the HFTM structural and functional components, a HFTM is foreseen to service only a single irradiation campaign. The following phases make up one complete HFTM lifecycle:

1. Detail design adaptation of the (new) HFTM to the needs of the specific irradiation campaign.
2. New construction of all components of the HFTM structures.
3. Insertion of specimens and hermetic closing and quality assurance measures.
4. Insertion of the HFTM into the TC, connection to ancillaries and final quality assurance.
5. Irradiation with control of temperatures, recording of data from online radiation sensors; deviations from steady state only by beam power fluctuations.
6. Retrieval of the HFTM from the TC, extraction of material specimens and dosimetry specimens, sending to PIE.
7. Full dismantling and disposal (radiation waste) of all HFTM parts.

Some of the design driving requirements are the following:

- The HFTM must allow maintaining constant the temperature in the specimens during beam power fluctuations. Also, the temperature spread within the specimen stack must be limited. Relative uncertainty of the absolute temperature (Kelvin) experienced by a specimen is specified ±3%.
- Lifetime and reliability must enable the mission to obtain sufficient specimens at high doses (>20 dpa, up to 50 dpa) before a critical failure occurs.
- The design must support remote maintenance of the HFTM (installation inside the TC with high radiation load on remote handling equipment). Furthermore, limiting space constraints behind the TA and concerning connections to the TC must be observed.

2.2. General design approach

While irradiation rigs for specimens have a long history in research fission reactors, the conditions in IFMIF-DONES are unique. A set of 'design paradigms', basic statements and their consequences are discussed, that have led to the specific design of the HFTM as presented in this paper:

Statement #1: The HFTM must support neutron economy of sample irradiation, accounting for the fact that a very large equipment and energetic effort is required to provide neutrons for a relatively small irradiation volume.

Consequences:

1. The HFTM follows the flat backplate geometry and thus becomes a 'box like structure', as opposed to conventional cylindrical irradiation rigs.
2. The volume of parasitic structures such as heaters and coolant gaps is to be reduced, in order to guide the limited neutron flux through the specimens.
3. Neutron reflectors are implemented to reduce lateral neutron losses.

Statement #2: The HFTM must contribute to fulfil the top-level IFMIF-DONES mission to provide specimens irradiated to high doses (>20 dpa for Early DEMO, 50 dpa for second phase).

Consequence: The design must aim at a sufficiently high lifetime and reliability under irradiation, in order not to fail systematically before the high doses are reached in the specimens.

Statement #3: The HFTM will be the first ever pressurized equipment exposed to significant doses (>20 dpa) of fusion-like energetic neutrons (14 MeV) with significant He production.

Consequence: Some material properties will remain unknown prior to operation. The HFTM design therefore relies on existent (fission neutron) data/experience. Prudence must be applied, and knowledge gaps avoided, where possible. Requirements imposed by a possible safety important class (SIC) classification must be well weighed. Specifically:

1. Only structural materials contained in the RCC-MRx nuclear pressure vessel design code are used. That code considers irradiation effects up to 53 dpa and offers design rules specifically for box-like structures.
2. No elastic elements (i.e. gaskets, neither metal nor polymers), no connectors etc are used in/near the beam footprint. The HFTM has a long 'attachment adapter' (AA) to create distance between the neutron source and the necessary connectors.
3. Low pressure coolant ('0.3 MPa He') was chosen to reduce primary stresses on the structure.

Statement #4: IFMIF-DONES is expected to be the unique neutron source in Europe for '14 MeV' material data at relevant doses available for EU DEMO.

Consequence: The HFTM must provide measures to support high reliability of generated material data. Specifically:

1. Enable reconstruction of received dose, spectrum, temperature history and associated uncertainties per specimen. Sufficient and effective instrumentation must be provided and positioning accuracy (vs. neutron beam) guaranteed.
2. Unintended or even obscured additional loads (jamming, corrosion, annealing, etc) must be avoided during complete specimen history.
3. Processes of specimen insertion and retrieval must avoid confusion of specimens.

Some of the above stated objectives act in an opposing/-competitive manner on the design. Exemplary,

- Increasing the thickness of container and capsule structures promotes lifetime and reliability, but adversely affects neutron economy.
- Increasing the density of instrumentation (thermocouples, neutron flux/fluence sensors) reduces uncertainties in the key irradiation conditions but adversely affects neutron economy.

2.3. Design overview

The HFTM body, depicted in figure 1, is logically partitioned in the following sections:

- The part where specimens will be exposed to neutrons: the corresponding component is denominated 'container', which is a thin-walled box-like structure subdivided by stiffening walls (ribs) in eight slots (compartments). The compartments house the irradiation rigs, which in turn house the capsules. The container and the components contained therein shall be designed to limit moderation and attenuation of the neutron flux reaching the specimens.
- The part where the mechanical and electrical connection and the exchange of media occurs is called the 'interface head' (IH). The IH relies on cable feedthroughs, electrical insulator materials in electrical connectors, and gaskets at helium flange connections (that need to maintain elasticity/tightness) and need to be compatible with remote handling operations that can access the TC only from the top.
- The parts that bridge the necessary distance between the container at beam footprint level and the IH is denominated

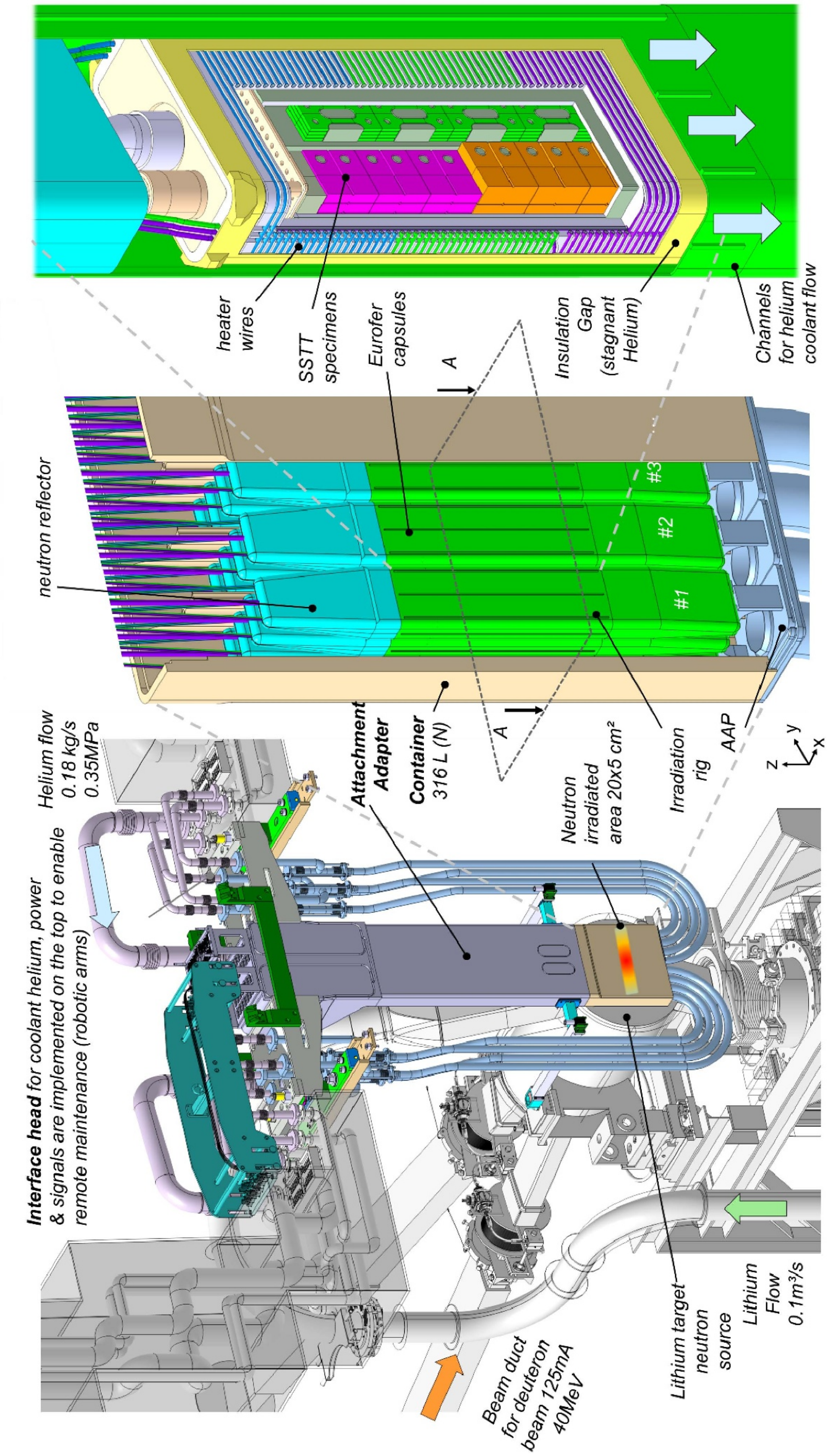

Figure 1. Bottom to top: (*a*) placement of HFTM in IFMIF-DONES facility, one cable bridge of the interface head (IH) is hidden for better overview, (*b*) irradiation rigs in cut-open container and (*c*) specimen stack inside cut-open capsule inside rig.

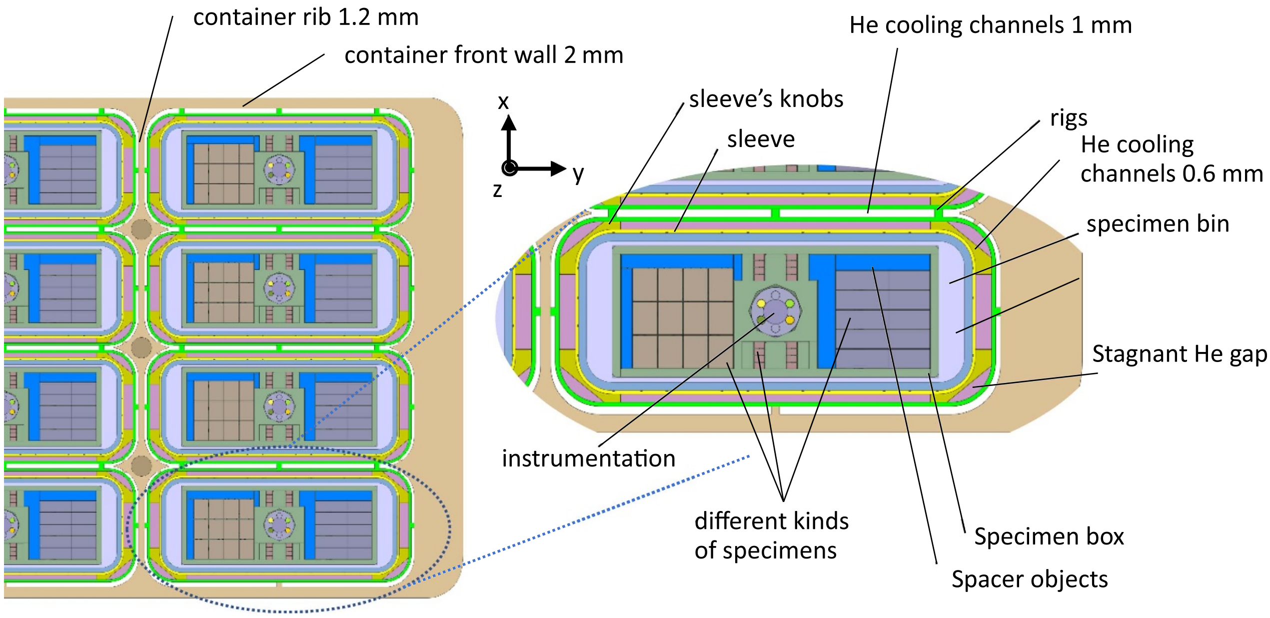

Figure 2. Sectional cut A-A (see figure 1(*b*)) of the HFTM. Different kinds of specimens are placed along with spacer objects into a specimen box, which is placed in the specimen bin which has electric heating wires and is placed inserted into the sleeve. Knobs on the top and bottom of the sleeve assure a stagnant heat gap between sleeve and rig. The coolant helium flows in channels that are formed between rigs and the container wall.

'AA'. It is a long prismatic channel that connects the container with the IH. It must conduct the feed-side helium flow and the electrical wires of the irradiation capsules. Its length provides distance between the neutron source and the IH in order to reduce the neutron flux experienced by the connectors in the IH to a level that sustains sufficient lifetime and reliability.

- Material specimens are placed into temperature-controlled capsules. Each capsule is enclosed into a thin-walled structure called irradiation rig, and four rigs are stacked/packed/bundled/arranged together into each of the 8 compartments of the HFTM container in the high neutron flux zone. The rig fulfills several important functions for the capsule temperature control (details are given in section 'temperature control'):
  - The outside surfaces of the stacked rigs and the container walls together form an array of minichannels, through which the helium flows, removing the heat (nuclear and electrical) from the capsules/rig and the container.
  - Gaps filled with stagnant helium between the capsule and the rig wall are dimensioned regarding their thermal insulation to achieve the high temperature difference between helium coolant and specimens with minimum possible electrical heating.

A cross-sectional view showing the rigs and the capsules within one container compartment is depicted in figure 2. After the capsule is inserted, the rig is closed by its upper neutron reflector, see figure 1(*b*). The neutron reflectors are essentially solids with wedge formed ends to help channeling the helium flow. The upper reflector has internal structures for anchoring the capsule and passing through the capsules' electrical cables which are routed upwards through the AA to the hermetic feedthrough plate at the IH. The assembled rigs are inserted through slots in the IH after the HFTM is nearly finished. Their final seating inside the container is achieved by manipulation through access openings in the AA, see figure 1(*a*). The access openings and slots in the IH are welded shut as last steps to finalize the HFTM.

The helium coolant is provided to the HFTM at the IH through DN100 tubes at 50 °C (±10 °C) at 0.35 MPa absolute pressure. The helium is guided downwards through the AA, which is kept at a low and homogenous temperature as result, keeping thermal induced deflections low. At the top of the container, the helium flow is split into an array of minichannels which are formed by the outer surfaces of the irradiation rigs, the container walls and the rigs. At the bottom of the container the helium flows from the minichannels and it is then collected again and guided by the AA Plate (AAP) into DN32 tubes, which guide the helium back to the IH. The helium finally leaves the HFTM and the TC and it is transferred to auxiliary systems outside the TC for treatment and recirculation.

The material specimens are stacked as packets into temperature controlled, near-isothermal hermetic capsules. Liquid metal (sodium) as well as filler pieces are used to increase thermal conductivity between the stacked specimens (gaps and holes occur) and thus reduce the temperature spread within the stack and between each individual specimen and the temperature measurement positions inside the capsule. The liquid metal filling requires appendices (see figure 1(*c*)) on the capsule head that enable liquid sodium filling, evacuation and final hermetic closing.

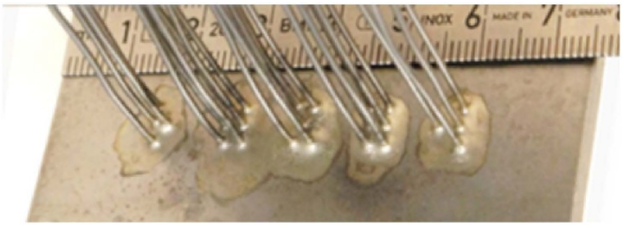

Figure 3. Cables brazed in a steel plug as expected to be done in some connections for the HFTM.

2.3.1. Electrical connections. The HFTM requires electrical power supply from Test Systems Ancillaries (TSA) into the capsules and signal transmission from/to the TSA. Passing the cables from the vacuum of the TC into the pressurized HFTM vessel under radiation conditions is challenging. For non-radiation purposes there are conventional electrical connectors available that combine the functionalities of sealing and connecting pairs of electrical conductors into one interface. The conventional plugs use, in general, polymers for sealing purposes and in the TC high-radiation-environment, this is not permissible. We have foreseen a functionality separation. Each capsule cabling sealing is carried out by passing every cable of the capsule through a separate hole in a steel plug. Each cable consists of a central conductor, an insulating layer and a sheath layer. The gap between the sheath and the plug is then filled by brazing (the result can be seen in figure 3). After brazing, the capsule is lowered through a dedicated opening in the feedthrough plate at the top of the AA into the container. Once the capsule has reached its final location, the plug is then welded onto the circumferential shoulder of its dedicated opening. The cables of each capsule are connected to an electrical connector which is then mounted to an electrical connector group, finally installed on top of the AA. The openings and the electrical connector group can be seen in figure 4. There is ongoing research on selecting the proper insulation material and designing the connectors. At the moment, Alumina is deemed the only insulator candidate for the connectors.

2.3.2. HFTM to TA connection. The HFTM shall be installed in TC with the help of remote handling cranes and robotic arms. The HFTM will be lowered into the TC until the Upper Attachment Devices (UAD) rest on TC structures. The UAD shall allow the HFTM to be positioned freely in the xy-plane within the bounds of ±40 mm and a rotation of $\pm1.3°$. This allows absorbing tolerances in the manufacturing and installation of the TC and the HFTM.

In order to assure correct positioning of the HTFM's container with regards to the backplate of the TA and limit thermal deformation due to anisotropic volumetric heating, an additional TA-Connector is attached to both lateral sides of the AA. The UAD and the TA-Connectors can be seen in figure 1(*a*). Each TA-Connector has a console in lateral direction to which a housing in beam-direction is attached, see figure 5. At the upstream-side of the arm there is a clamp which grabs onto a pin of the TA, at the downstream-side there is a bevel-gearbox which allows to rotate a threaded shaft via remote handling robotic arms. The TA-connector's clamp is fastened or loosened by the rotation of the shaft. The pin on the TA-side sits on a spindle mechanism allowing for axial adjustments in beam direction, see figure 6.

2.4. Materials strategy

The HFTM pressure bearing body is fabricated from RCC-MRx grade X2 CrNiMo 17-12-2 (N) austenitic steel (similar to AISI 316L(N)). This material is contained in the RCC-MRx pressure vessel code for use at temperatures up to 375 °C combined with neutron doses of 53 dpa. Many welding techniques are applicable, and no post weld heat treatment is necessary, which is favorable in view of its largest dimension at 2.745 m. To account for the loss of ductility observed in [28] especially around 330 °C, sufficient cooling is designed for the container to maintain its temperature below 150 °C. Empirical formulas in [29] for 18Cr10Ni austenitic steel predict the incubation phase of swelling to 46–52 dpa for the conditions of the HFTM container. The HFTM is designed as a SIC-2 component and it is therefore subject to modest safety requirements, meaning, specifically, that it must not compromise other systems under abnormal conditions.

Governed by the HFTM mission, the irradiation capsules must also endure around 50 dpa at temperatures between 250 °C and 550 °C. The capsule body material is RAFM steel as the contained irradiated specimens in the normal case. Therefore, they experience material properties degradation ranging from embrittlement at low temperatures $<$350 °C to radiation softening at high temperatures $>$400 °C. Swelling is expected $<$0.1% at 50 dpa [30]. Due to the expected degradation and high uncertainties, the strategy is to reduce loads on the capsules as much as possible. One consequence is the evacuation of gases before hermetic sealing to avoid internal pressurization by gas expansion during heat up. Welds are avoided in the design where possible, enabled by die-sink and wire-cut electric discharge machining.

The capsule heater wires are mineral insulated metal sheathed (MIMS) type with central conductors made of low-ohmic copper wires in the leads and high ohmic NiCr 80/20 alloy in the heating sections. They will have effective temperatures at and slightly above the setpoint irradiation temperatures. Their sheathing material must be ductile during production and is available in austenitic steel grades (i.e. AISI 321) or Inconel. While the wires are not loaded with any external mechanical loads, swelling is critical for austenitic steels at 450 °C $\leqslant T \leqslant$ 500 °C (see for example [29] and many others). Inconel grades [31] are explored as possible alternative sheathing materials for high temperature capsules.

The insulator material between the central conductor and the sheath is compressed ceramic powder. MgO, Al_2O_3 and SiO_2 are industrially available. MgO is the candidate material since its electrical resistivity in base conditions is highest. However, the resistivity decreases by more than 8 orders of magnitude between room temperature and 600 °C. Furthermore, radiation induced conductivity and radiation

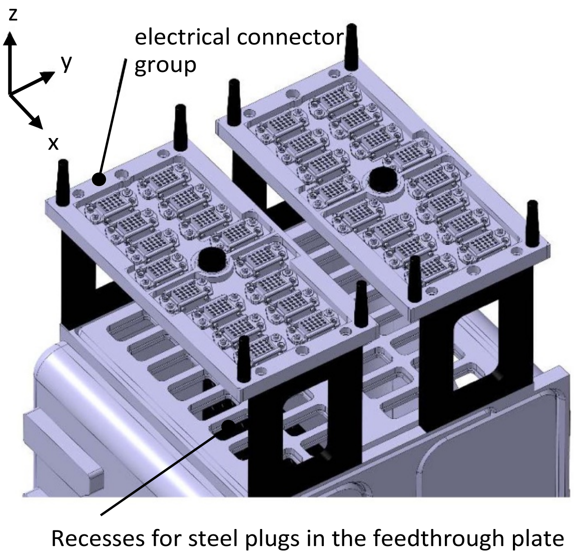

Figure 4. Top of the HFTM vessel. Openings and electrical connectors groups.

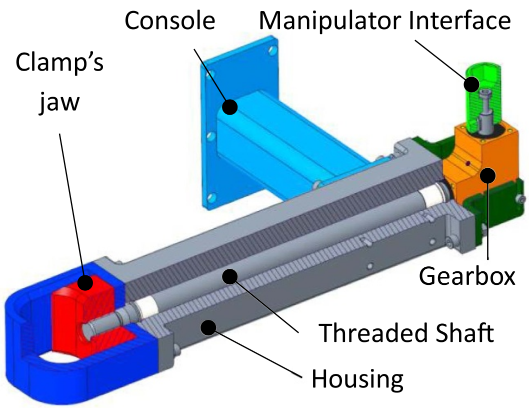

Figure 5. TA-connector of the HFTM.

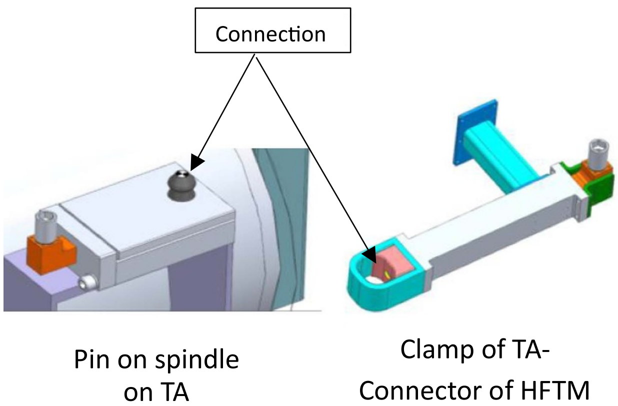

Figure 6. Connection between HFTM and TA.

induced electrical degradation (RIED) decrease the resistivity as dose-rate and accumulated ionizing dose dependent effects during operation. The absolute electrical insulation resistance must remain high enough so that no relevant bypass/cross currents will be able to flow through the capsule/HFTM metallic structures (all heater sheaths are electrically connected). Floating potential power supplies are used to enable operation when single heater wires experience an electrical breakthrough.

Also, the central conductor experiences radiation effects: at low temperatures, the electrical resistivity increases with the accumulation of irradiation, which means that the necessary voltage to obtain a certain required power increases during irradiation. In reactor irradiation tests of the HFTM heaters, the resistance increase was seen to saturate at a level of about +20% compared to unirradiated conditions.

The liquid metal used for thermal homogenization was formerly designated NaK eutectic alloy which is liquid at room temperature. It was recognized that potassium transmutes to a significant amount of Argon under fast neutron irradiation. Argon has low solubility. Generation of bubbles (that counteract the purpose of thermal homogenization) would be expected, and significant pressurization of the hermetic capsule (about 40 bar) was calculated. Therefore, pure sodium is now intended as filler material. The capsule filling must therefore be performed at 430 °C [16], to assure proper wetting of the specimens.

2.5. Summary of the analyses

2.5.1. Neutronic. Neutronic analyses have been reported in detail elsewhere [32–34] and in the neutronic analysis paper of this Special Issue [35]. A summary is given here highlighting the ability of the (IFMIF-DONES) HFTM to provide relevant irradiation conditions for the DEMO FW.

The neutron flux distribution inside the HFTM is characterized by the single-sided incidence of the neutrons on the front surface of the HFTM and the relatively strong attenuation inside the material in beam direction. As result, gradients of nuclear responses have to be accepted, and the geometric arrangement of specimens inside the capsules is subject to optimization. The aspect of nuclear response gradients in the HFTM is addressed in [32].

For the standard size of the deuteron beam footprint of 20 cm $\times$ 5 cm and single accelerator operation at 125 mA at 40 MeV, the incident peak neutron flux to the HFTM front wall is just above 5×10^{14} n cm^{-2} s^{-1}. The highest volumetric heating is $q''' = 17$ W m^{-3}.

The most attractive irradiation positions are the capsules of the four central compartments and the first 1–3 rows in the beam direction. In that region, the specimens experience 28 to $\sim$5 dpa/fpy [34].

Compared to the current values of the EU DEMO HCPB FW ([36, 37]) with $\sim$10 dpa/fpy, the HFTM allows both accelerated testing as well as testing at approximately equal damage rates (with the narrow beam footprint option of IFMIF-DONES at 10 cm $\times$ 5 cm, a peak damage dose of even 46 dpa/fpy can be reached). The volume of specimens that is irradiated at 8–12 dpa/fpy is 0.27 l [34]. A volume of 0.089 l of specimens are irradiated at >16.7 dpa/fpy, which is the rate at which 50 dpa (objective for DEMO phase 2) can be reached within 3 years.

Helium transmutation as a result of high helium cross section of Fe, Cr and other metals at high neutron energies is one of the most critical aspects of material R&D for D-T fusion and a major motivation for IFMIF-DONES. The helium production in the HCPB FW or generic reactor and DEMO studies is in the range of 10–12 appm(He)/dpa ([37–39]), so that about 100–120 appm(He) are produced per year. In the HFTM central region, about 12 appm(He)/dpa are produced near the neutron source, with a gradient leading to 14 appm(He)/dpa on the back side. The helium conditions of steels irradiated in the HFTM are therefore well adjusted, but slightly on the high side (conservative) compared to a D-T reactor. Hydrogen is produced typically with a rate of 55 appm(H)/dpa in the HFTM. This is also more than in a D-T reactor ($\sim$45 appm(H)/dpa). Due to the high mobility of H in steels, the H production is perceived less of an issue.

In [40], it is demonstrated that the primary knock-on atom energy spectrum (PKA spectrum) experienced by specimens in the IFMIF HFTM overlaps the one that is expected for the HCPB blanket in a D-T fusion power plant. Thereby, it is expected that the damage morphology in both cases, described for example by the fraction of damage that is produced in subcascades, is similar. Further discussion on the irradiation capabilities of the HFTM is given in [10].

2.5.2. Thermal. Thermal analyses assessed (i) the thermal field in the structures (to support thermal-mechanical analyses and clarify that temperature levels are in compliance with the used materials) and (ii) in the specimen stack, to evaluate adherence to the requirements.

The most update thermal simulations by computational fluid dynamics [41] predict that the peak container temperature is 157 °C (slightly above the objective of 150 °C) on a spot of one of the compartments dividing walls, but all the outer pressure bearing shells of the HFTM are at temperatures typically 50 °C–140 °C. With this result, currently a margin of >40 K is available to the mechanical design temperature of 200 °C during normal operation.

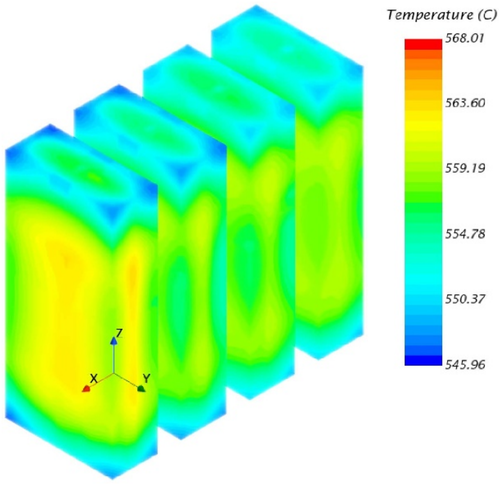

Figure 7. Simulated temperature spread within the specimen stacks (modeled as homogenized Eurofer/sodium) of the central compartment #5 at nominal temperature 550 °C.

From the same simulation, the temperature spread within the specimen stacks was obtained. This quantity is a measure for the quality of the irradiation, and a requirement is set to limit the spread of temperature within one capsule to less than $\pm 3\%$ of the absolute temperature. A lower limit of the achievable temperature spread is $\Delta T \propto \lambda \cdot q''' \cdot d^2$ (with thermal conductivity λ (W m^{-1} K^{-1}), volumetric heating power q''' (W m^{-3}) and characteristic length scale for heat conduction d (m), i.e. half capsule thickness), therefore the most critical capsule is the one with the highest volumetric heating, which are the central front ones (in compartment #4 and #5, see numeration nomenclature of figure 1(*b*)). In the simulations, the temperature spread in that capsule was 22 K (min. to max.), see figure 7. These results give evidence that the three (bottom/middle/top) individually controlled heaters (as visualized in figure 1(*c*)) can be effectively used to compensate the strong variations of the 3D nuclear heating profile. Relatively cold spots remain at the upper and lower capsule ends, especially in the corner, where conduction effects are increased, i.e., that heat removal towards the neutron reflectors cannot be counterbalanced.

Additional analyses were made to assess the effect of the liquid metal filling in a model with individually resolved specimens [42]. That study revealed that the temperature spread in a capsule where helium fills the gaps between the specimens would increase by a maximum of 10 K compared to the case where NaK is used as filler. On the one hand, this shows the usefulness of the liquid metal filling, but on the other hand it shows up the possibility to work without liquid metal fillers in cases where the effect of liquid metal interaction must be fully avoided (i.e. cross-checking).

Table 1. Load cases considered in the mechanical analysis of the (IFMIF-DONES) HFTM.

	Load case 1	Load case 2	Load case 3	Load case 4
Temperature	Homogeneous 20 °C (room temperature)	Homogeneous 200 °C	Inhomogeneous temperature field. Result from thermohydraulic analysis with 3D nuclear heating	Homogeneous 200 °C
Mechanical Load	Homogeneous 6.10 bar	Homogeneous 4.2535 bar	Pressure fields from thermohydraulic analysis	Constant high pressure in central compartments (#4 and #5), lower pressure in adjacent compartments
Motivation	The HFTM shall be tested at ambient temperature at a higher pressure. The increase in pressure should correspond to the increase in permissible stress at a lower temperature	HFTM should withstand maximum pressure supply possible at its assumed maximum operation temperature	HFTM should withstand predicted temperature and pressure fields that occur during its operation	The HFTM should withstand that one of the outlets of one compartment is turned off and the other outlets are open at its assumed maximum operation temperature

2.5.3. Mechanical. The mechanical assessment for the HFTM was renewed for the present design. We establish four load cases that the HFTM should withstand, which are listed in table 1.

First, we motivate '*load case 2*': The assumed inlet pressure of the helium coolant for the HFTM in the IFMIF-DONES facility is 0.30–0.35 MPa. An overshoot of the test systems low pressure helium cooling system (TS-LP-HCS) of 10% is permissible. The safety valve of the TS-LP-HCS is assumed to have a trigger pressure that is allowed within ±10% to its nominal design pressure ($\mathrm{PD}_{\text{nominal, safety valve}}$). Therefore, the pressure that the HFTM needs to withstand is

$$\mathrm{PD}_{\mathrm{HFTM,\,lc2}} = 0.35\ \mathrm{MPa} \cdot 1.1 \cdot 1.1 \approx 0.42\ \mathrm{MPa}.$$

We assume that the pressure bearing structure of the HFTM will only see temperatures ⩽150 °C. In order to have safety margin, we assume the temperature for load case 2 to be $T_{\mathrm{lc2}} = 200$ °C. The RCC-MRx requires a hydrostatic pressure test and according to REC 3257.4, the test pressure must be at:

$$\mathrm{PT} = \max\left[\left\{1.25 \cdot \mathrm{PD} \cdot \frac{S_{\mathrm{mA}}\left(T_{\mathrm{test}}\right)}{S_{\mathrm{mA}}\left(T\right)}\right\}; \left\{1.43 \cdot \mathrm{PD}\right\}\right].$$

We choose the test temperature $T_{\mathrm{lc1}} = T_{\mathrm{test}} = T_{\mathrm{room}} = 20\,$°C and retrieve the allowable stresses from section A3.1S.43 of the RCC-MRx: $(S_{\mathrm{mA}}(T_{\mathrm{test}})) = 147$ MPa and $S_{\mathrm{mA}}(T = T_{\mathrm{lc2}} = 200\,°\mathrm{C}) = 130$ MPa. Then, it is obtained that:

$$\begin{aligned}\mathrm{PT}_{\mathrm{HFTM,\,lc1}} &= \max\left(1.25 \cdot 1.31,\ 1.43\right) \cdot \mathrm{PD} \\ &= 1.43 \cdot \mathrm{PD} \approx 0.61\ \mathrm{MPa}\end{aligned}$$

which is denominated as '*load case 1*'.

In order to get realistic temperature and pressure fields for the HFTM, neutronics and thermohydraulic analysis are required. The neutronics analysis will provide the nuclear heating field which will be used by the thermohydraulic analysis. The results of the thermohydraulic analysis will be denominated as '*load case 3*'.

The outlets of the helium coolant can be regulated by valves. The outlet pressure of the coolant is assumed to be 2 bar. The container has ribs to reinforce its box-like structure. '*Load case 4*' aims at determining whether these rib structures can withstand the possible pressure differences between the compartments and is defined as follows: the two central compartments are chosen to be compartments where the outlet valves are closed. Therefore, the pressure inside these compartments is constant at $p_{\mathrm{cc}} = 3.5$ bar. It is assumed that the pressure drop between $p_{\mathrm{in}} = 3.5$ bar and $p_{\mathrm{out}} = 2.0$ bar predominantly occurs from the container top to the container bottom, due to the flow resistance of the capsule rigs. We therefore simplify that the pressure in the lower AA (LAA), $p_{\mathrm{LAA}} = 3.5$ bar and the pressure in the other compartments p_{oc} changes linearly from $p_{\mathrm{oc}}^{\mathrm{top}} = 3.5$ bar to $p_{\mathrm{oc}}^{\mathrm{low}} = 2.0$ bar as it can be seen in figure 8, where this change of pressure is represented in a quarter section of the HFTM's container, AAP and lower part of LAA.

In previous analysis of the former HFTM design, stresses had been found that went beyond the permissible stresses for 316 l (N), especially in the container. In this year's design iteration, the focus was therefore mainly on reducing stresses in the container. This has been achieved by increasing the height of the container's stiffening rim and by adding two stiffening ribs to the already existing first stiffening rib in the LAA, increasing the wall thickness of tubing and other miscellaneous changes. The main focus was on obtaining the container as the core structural component of the HFTM in compliance with the RCC-MRx. The analysis for the container was carried out by finite element method using ANSYS Mechanical 2024 R2, with 13 million tetrahedron elements with quadratic basis function at linear-elastic behavior to model a quarter of the container, AAP and lower part of LAA. Isotropic elasticity with the Young's modulus according to the RCC-MRx was assumed. For symmetry purposes the boundary on the cut plane normal to the x-axis are set for displacements in x-direction = 0 and for the cut plane normal to the y-axis the displacement in y-direction = 0.

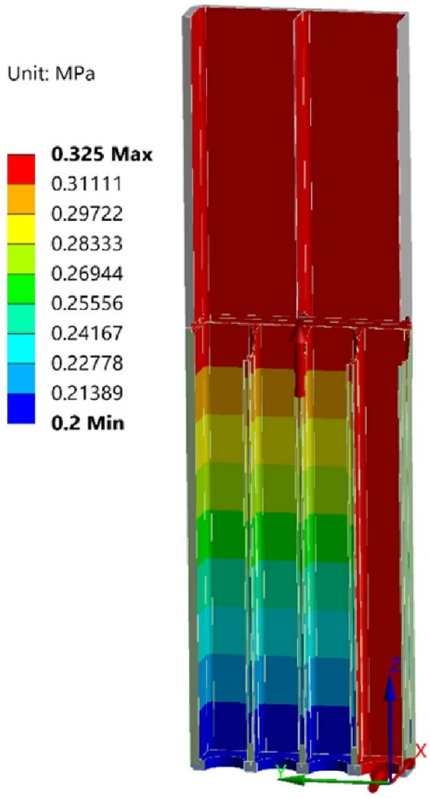

Figure 8. Visualization of applied pressure for '*load case 4*'.

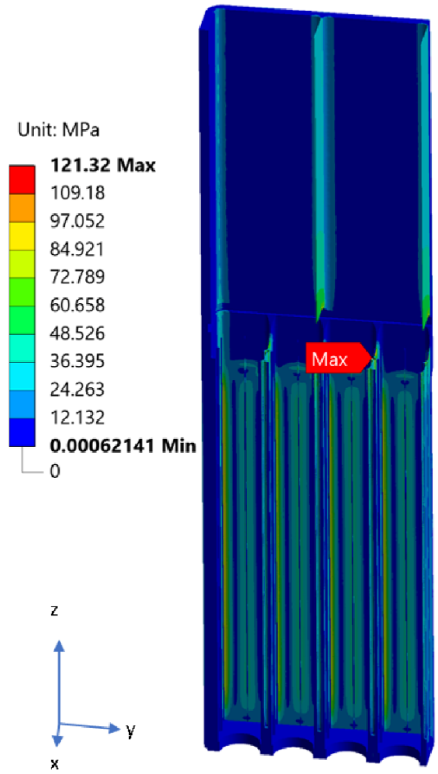

Figure 9. Von–Misses stress in container, AAP and lower part of the LAA for '*load case 2*' for a quarter section. Symmetry boundary conditions (BC) applied.

For the cut in z-direction we also set the displacement in z-direction $= 0$. This is justified, since the LAA continuous for a long distance in the same manner and therefore quasi-symmetry can be assumed. In order to resolve the stresses in the thin-walled structures accurately, a proximity meshing method has been applied assuring that there are at least two elements between every face and every edge of the meshed body. The maximum and minimum element sizes are 20 mm and 0.3 mm, respectively.

A convergence study has been carried out using finer meshes and observing minimal changes in the results, indicating sufficient mesh refinement and solution accuracy for two elements only between all adjacent faces and walls.

We also studied the entire HFTM vessel for '*load case 2*'. This analysis was also carried out by finite element method using ANSYS with 3.8 million tetrahedron elements with quadratic basis functions. Here we also applied a proximity controlled mesh with at least two elements between adjacent faces and edges. Pushing the stress peaks in the overall HFTM vessel required add in more materials for tube wall thicknesses as well as reinforcements and fillets in the UAA.

With respect to the results obtained, we found that all the von Mises stresses in the lower part of the LAA and the container are below the permissible stress of S_{mA} (200 °C) $=$ 130 MPa, visualized in figure 9. For compliance with RCC-MRx a comparison of the von Mises stresses against the permissible stress across the structure's domain is not foreseen. Instead, linear paths need to be defined and perpendicular to the center plane of thin-walled structures and then bending stresses denominated as P_b and membrane stresses denominated as P_{m} need to be defined and the RCC-MRx criteria is the combined fulfillment of the following inequalities:

$$\overline{P_{\mathrm{m}}} \leqslant S_{\mathrm{m}}, \quad \overline{P_{\mathrm{m}}} + \overline{P_{\mathrm{b}}} \leqslant 1.5\ S_{\mathrm{m}}$$

The RCC-MRx criteria is not equivalent to the von Mises criteria $\sigma_{\mathrm{vM}} < S_{\mathrm{m}}$, meaning that there can be cases were the RCC-MRx criterion is stricter than the von Mises criteria and vice versa. Therefore 131 paths have been defined along which the maximum bending and membrane stress have been calculated and the above stated inequalities have been validated. The paths have been positioned in areas with elevated von Mises stresses. **We have shown that the RCC-MRx criteria are fulfilled for all selected paths for the container.**

As it can be seen figure 10, the von Mises criterion is not yet fulfilled for the entirety of the HFTM. From the fact that both the von Mises criterion and the RCC-MRx-criterion were fulfilled for the container for all selected paths, we induce quasi-certainty that the entire HFTM vessel fulfils the RCC-MRx criterion (the two inequalities previously set).

2.5.4. Temperature control. The resultant temperature of specimens in the HFTM during irradiation depends on the following parameters:

1. The volumetric power released inside the specimens and capsule members by gamma and neutron radiation coming

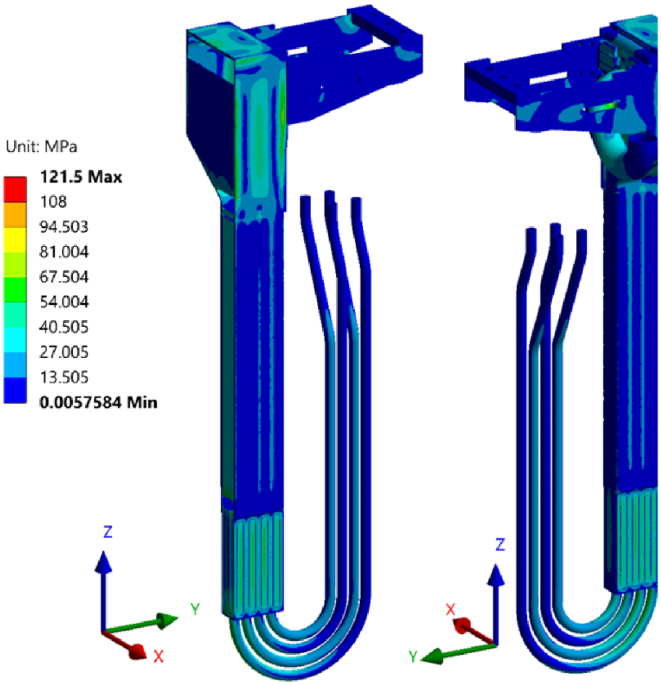

Figure 10. Von Mises stress in the HFTM for '*load case 2*'. Halves of the vessel structure depicted. Symmetry BC applied.

from the IFMIF-DONES Target. This power release has a pronounced spatial profile $q'''(x,y,z)$. In an ideal case, it would be constant during irradiation but must be expected to fluctuate over time especially during beam trips and other conditions of the accelerator. The fluctuation of beam power is a disturbance quantity for the specimen temperature control.

2. The effectivity of the insulating stagnant gas gap between the heated capsule and the coolant gas flow. Temperature gradients of several hundred Kelvin per millimeter are effective. The size of the insulation gap is determined during the design phase of the HFTM, but can deviate by manufacturing tolerances and even slight displacements due to thermal expansion, thermal stress relaxation, radiation-induced swelling, vibration, etc during operation.
3. The controlled power of the electrical heaters. The electrical heaters are designed to be able to compensate variability of the beam power (volumetric heating) in the range of 0%–110%. The electrical power is guided by the thermocouples that are placed inside the specimen stack. By providing three individually controlled heater segments per capsule (top/middle/bottom, see figure 1(*c*)), the heaters can partially compensate the spatial volumetric heat release distribution in the specimens in the vertical (z) axis. The heat release of the heaters can be regulated fast by controllers to respond to beam events.
4. The helium coolant flows through the module. The helium flow is the ultimate heatsink of the HFTM. The mass flow rate through each of the 8 compartments of the HFTM can be influenced by downstream valves. Since actuation of each valve influences also the mass flow through the adjacent compartments as well as the common pressure level at the inlet (top end) of the HFTM, it is not deemed feasible to utilize mass flow variation as automated means to control the temperature. Deviations from the pre-determined mass flow distributions can however be carried out by operators to react to unforeseen thermal conditions.

Conjugated heat transfer simulations with 3D geometry models and heat release profiles are the basis to dimension the required mass flow rate per compartment and the insulation gap sizes of the capsule, as result of an iterative approach. The optimization objectives are (i) to maintain the temperature of the container low enough (<150 °C) and (ii) to minimize the required electrical heater power.

2.5.5. Neutron flux and fluence measurements. The instantaneous neutron flux can be measured inside each capsule by a self-powered neutron detector (SPND), with an active length approximately as long as the height of the specimen stack. Due to the strong spatial gradients intrinsic to the IFMIF-DONES neutron flux field, such a single measurement is not sufficient to characterize the dose or dose rate of the individual specimen in the capsule. Furthermore, the calibration factor of the SPND must be expected to vary strongly over time due to burnup. The signal of the SPNDs is thus used to detect and quantify the time structure of local flux intensity, for example induced by unintended shifting and change of the shape of the neutron beam, as additional measure to characterize the neutron flux history of the specimens. No final emitter material for the SPNDs to be used in the HFTM has been decided yet. However, an experimental line with several materials is being performed (see section 3.2 on STUMM-PROTO and STUMMEX program).

Apart from that, an experimental activity with several SPNDs was performed at NEAR/nTOF (CERN) considering the following emitter materials: Vanadium, Inconel, Rhodium-103, Cobalt and Platinum (same emitters as in the STUMM-PROTO plus Platinum) and with the detectors located at both sides of the pure lead target, inside the concrete shielding. The treatment of these data produced by neutron irradiation of the detectors is on-going and further analysis is also needed to reach an optimal candidate to be used in IFMIF-DONES.

Finally, it is also important to mention that the main means for documenting the received dose and energy spectrum information will be sets of activation specimens placed at some locations within each specimen set. Such a set of activation foils can encompass several elements with different dosimetry reactions, that can enable the reconstruction ('unfolding') of the received neutron energy spectrum [15]. The selection of materials must consider sufficiently high half-life of the activated isotopes in order to cope with the relatively long times between beam off and the time of retrieval (from inside the HFTM capsules) and activity measurement. Currently, the elements Fe, Ni, Y, Nb, Mn, Co, Bi, and Au are foreseen. Due to the very high neutron fluxes in the HFTM, the required respectively recommended quantities of materials would be in the range of 0.4 mg (Y, Fe)–120 mg (Nb) to effect an activity in the range of $1 \cdot 10^8$ Bq that can be conveniently measured. Each set of activation foils would be hermetically encapsulated into a container that enables reliable positioning and protects the activation specimens from corrosion and contamination, as prerequisite for meaningful activity measurements. One set of encapsulated activation specimens displaces one fracture toughness SSTT specimen (4.6 mm thickness) from the specimen stack. It is therefore interesting to note that each material specimen provides an additional measure of its received dose by its own activity [43], that can at least be used for comparative purposes among a set of specimens of the same material composition.

2.6. Summary of the validation activities

The HFTM has undergone several phases of prototyping and validation activities. The most intensive progress was achieved during the IFMIF/EVEDA phase [17, 44].

Complete capsules with electrical heaters, filled with specimens and liquid metal NaK have been fabricated (2013 version). The high temperature vacuum brazing of the heater wires and capsule body required special attention and is nowadays mastered by an approach that provides the brazing material via an appended vessel.

The loading of capsules with specimens, filling with NaK (2013 version) and final hermetic closing was performed, as well as the subsequent retrieval of the specimens with removal and cleaning of liquid metal (see figure 11). As consequence of the change to pure sodium instead of NaK as filling metal, wetting and filling tests with sodium were performed [16].

Single rigs with instrumentation to measure local pressure and temperature profiles were built, tested, and used as validation basis for computational tools [42, 45].

Finally, a prototype of the HFTM with two compartments, each containing 3 rigs was built and tested [14, 44, 46, 47]. These activities proved the possibility to fabricate and assemble all parts of the HFTM. The testing program showed that the full range of temperatures 250 °C–550 °C could be reached, control of beam-on/off events (simulated with surrogate electric heaters) could be well handled by the control system, and that temperature homogeneity in the capsules was to specifications, also under condition of realistic mechanical tolerance chains of the insulation gaps and helium channels.

Irradiation programs of capsules were performed in the BR2 reactor and recently, results of irradiation of heaters in the MARIA reactor became available. In both cases, heaters failed prematurely, however, the testing conditions do not allow to fully identify the causes.

2.7. Ongoing design evolution

The following steps of optimization are being pursued:

- The heater lifetime was identified as a possibly limiting factor to the HFTM lifetime under irradiation. Therefore, the capsule design is planned to be changed to accommodate thicker heater wires. As result, lower operation voltages together with ticker insulation layers reduce the electric field and thus counteract the threat of RIED effects. Furthermore, the wires become more robust. This improvement in lifetime and reliability is however at the cost of specimen payload.
- There are ongoing design changes for the rigs and the container to accommodate load case 4.
- We seek to further reduce the temperatures of the HFTM structures in the next design iteration, to create further margin versus neutron induced degradation of plastic properties and swelling.
- The upper interfaces arrangement is under adjustment in close collaboration with the TC designers.
- The electrical connectors based of fully ceramic insulators (no plastics) and compatible with the remote maintenance available in the TC is under development by Industry, guided by ENEA. An irradiation program in the MARIA reactor is under preparation.

2.8. Summary and outlook

We consider the HFTM as a relatively mature design that has profited largely from extensive prototyping and testing activities. An analysis of 2024 [48] concluded that the HFTM central components have obtained a technology readiness level (TRL) of TRL5, while some components, like the electrical connectors, are still at TRL2. It is the objective to obtain TRL7 before placing the procurement. This implies an extensive prototyping and testing program planned at KIT, accompanied by industrialization of the peculiar manufacturing technologies. The scheduling of the DONES planning foresees the delivery of the HFTM to IFMIF-DONES around 2034.

3. The (IFMIF-DONES) Start-up Monitoring Module, STUMM

3.1. Current design of the STUMM module

The STUMM is a measuring/monitoring module populated with different types of neutron, gamma radiation, temperature and strain diagnostics with the main objective of monitoring the radiation field characteristics just behind the TA, in the highest flux zone of the IFMIF-DONES neutron source.

The STUMM will be placed inside the TC in the same position as the HFTM, i.e. 2 mm behind the TA [13]. It should measure the radiation fields characteristics during steady-state operation at full power and during transient conditions.

The STUMM will be used during the commissioning phase of the facility with the following main goals:

- To characterize the neutron source in the highest flux zone during steady-state and transient conditions.
- To validate the neutron models used for the neutronic calculations or tune them if needed.
- To verify thermal conditions in its area of influence.

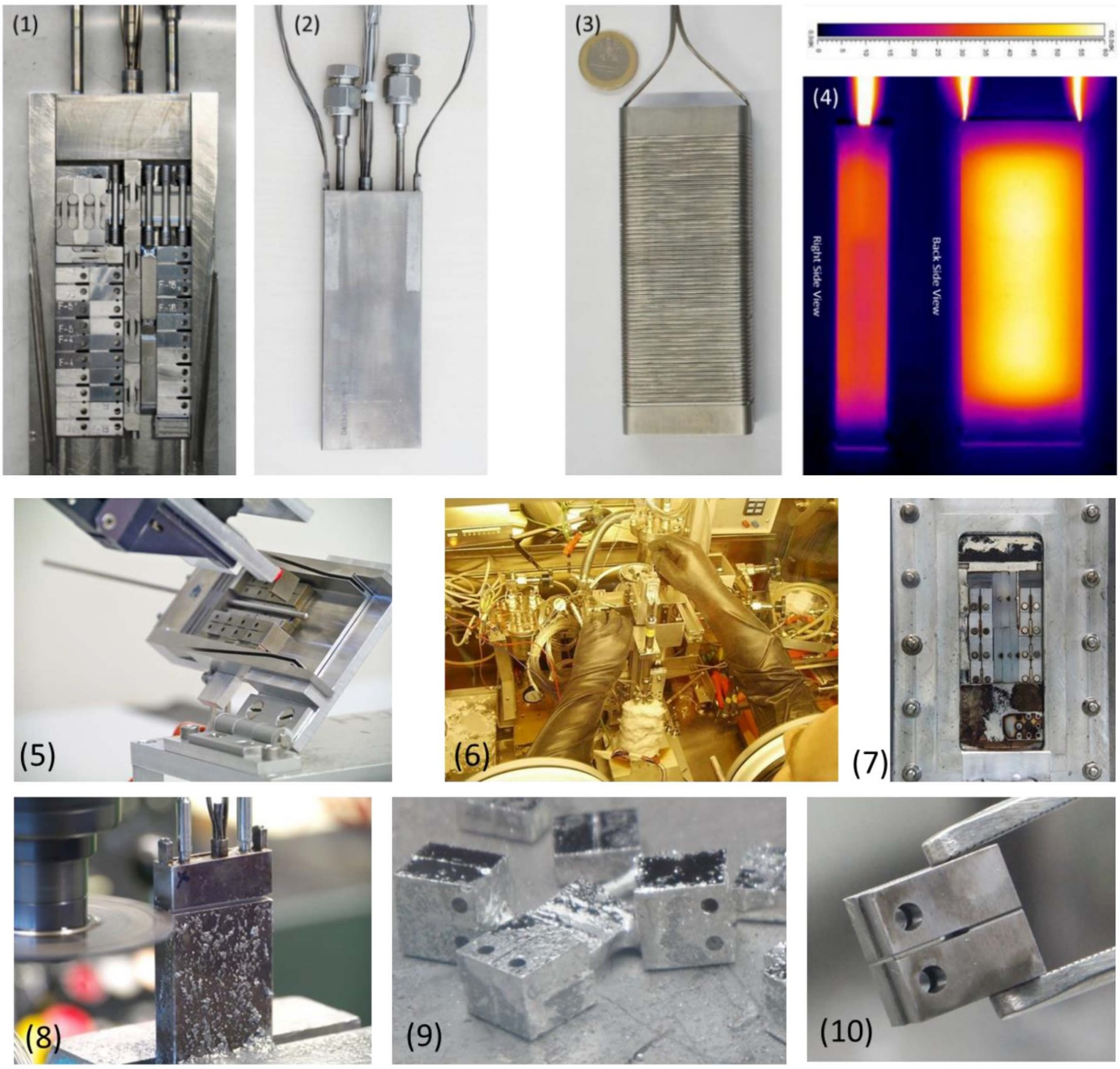

Figure 11. Validation of capsule manufacturing and handling: (1) assembly of specimen stack with instrumentation in an assembly tray. (2) Capsule (2013 version) filled with specimens and NaK. (3) Electrical heater wires wound in spiral groves of capsule bin (2020 version). (4) Infrared imaging during transient heat-up to detect possible flaws in brazing of the heater with capsule parts. (5) Assembly of a specimen stack with pneumatic tools and telemanipulator (in hot cell simulation). (6) Filling of capsule inside glovebox with NaK liquid metal (2013 version). (7) Filling of mock-up capsule with glass windows with liquid Na. (8) Cutting open of capsule (see (2)) to retrieve specimens. (9) Specimens removed from capsule still sticking with liquid NaK (2013 version). (10) Finally retrieved and cleaned specimen.

For that, the following experimental measurements shall be performed during the irradiation experiment: thermal and fast neutron fluxes, nuclear heating and gamma dose rates, temperatures, and deformations at selected locations.

The external dimensions and shape of the STUMM are like the HFTM, with a few differences related to the different missions of both modules. The STUMM design consists of the following elements: the container, the AA, the support trusses, and the helium cooling system.

The current design of the STUMM with main dimensions can be seen in figure 12. The casing structure of STUMM will be made of X2 CrNiMo 17-12-2 austenitic steel defined in the RCC-MRx code, as in the HFTM. The same shape and materials are foreseen for both modules to test the behavior of the construction under irradiation conditions. The container is a box dedicated to housing all foreseen measuring systems. The interior of this element is divided into eight parts by stiffening plates. The front and back walls have 2.0 mm thickness, while the lateral walls are used for stiffening and to accommodate joining provisions and have 10.0 mm thickness.

The basic elements of the container are the flange to the cooling pipes, the main body, and the flange to the adapter. The AA is designed to guide cables, Rabbit System pipes, and cooling gas between the container and the upper part of STUMM. This compartment consists of the lower and upper parts of the AA assembly, pressure plate, gasket profile, sealing screws, and pins for remote handling (figure 13). On the

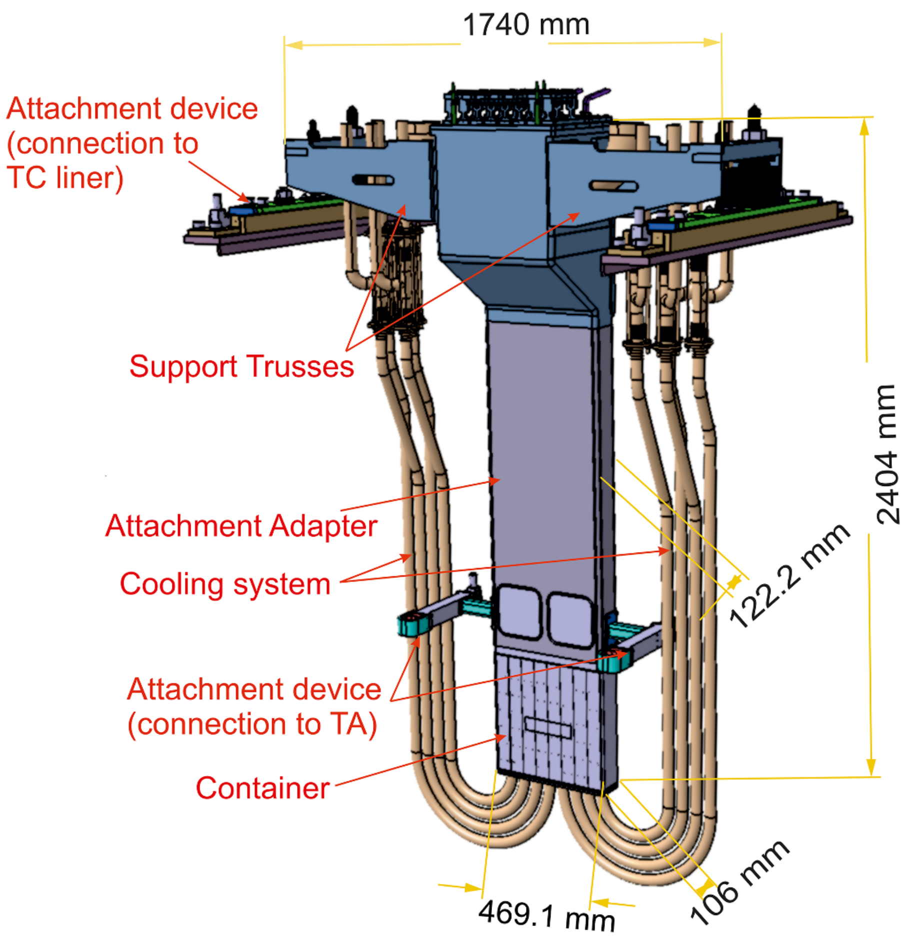

Figure 12. General 3D view with the main dimensions of the STUMM module (front view) and with its main components tagged.

pressure plate, the rigs and electrical connectors will be mounted as can be seen in figure 13.

Support trusses assembly in STUMM is expected to be the same as in the HFTM and is designed to provide handles for transport and positioning the STUMM in the TC. The support on the bottom part of the AA container level called the Attachment device (connection to the TA) is the second element to ensure a proper STUMM positioning in the TC. This element is analogous to the one foreseen for HFTM (see figures 5 and 6).

The cooling system is necessary to ensure appropriate thermal operating conditions for the detectors and it is based on ten pipes: eight small pipes (outwards on the sides of the STUMM) and two large pipes (on the top of the AA). The flow of helium gas will be possible in two directions: in the first case start from the eight outside pipes to the bottom part of the Container (1st flow direction) and in the second case from the two larger pipes downwards to the container (2nd flow direction). The hydraulic and thermal performance of the two directions of flow is analyzed in [49, 50].

STUMM has been designed to meet predefined requirements. The challenging issue is to ensure simultaneous STUMM tightness and the possibility of exchanging a single rig. Considering tightness, two areas are sensitive: the space between the upper part of the AA and the pressure plate and between the pressure plate and the rigs. For sealing these regions, dedicated gaskets are foreseen. The significant impact on the complexity of this problem is the huge number of detectors installed inside the container and the high level of radiation and safety regulations that impose that remote handling must do all maintenance operations.

Due to the mission of STUMM (detailed characterization of the irradiation fields in its interior), the most important internal components are the measuring systems located inside. The STUMM internal structure is based on eight rigs, each of these rigs in the bottom part is divided into 5 levels, which gives 40 rectangular segments inside the container (figure 14(*a*)). The central region of the container, four middle segments on the third level, is situated centrally in front of the beam and it is called the beam footprint area (rectangular area with dimensions of 20 cm $\times$ 5 cm with a possibility of a reduction to 10 cm $\times$ 5 cm).

The active part of a single rig is presented in figure 14(*b*) and consists of the following main elements: the support plates, the connecting elements, the Eurofer slabs (material foreseen for HFTM construction material), and the measuring systems (Rabbit System and detectors).

The space between two support plates forms a segment that can be distinguished into three spaces: the front, the central, and the rear space. The instrumentation installed in the front

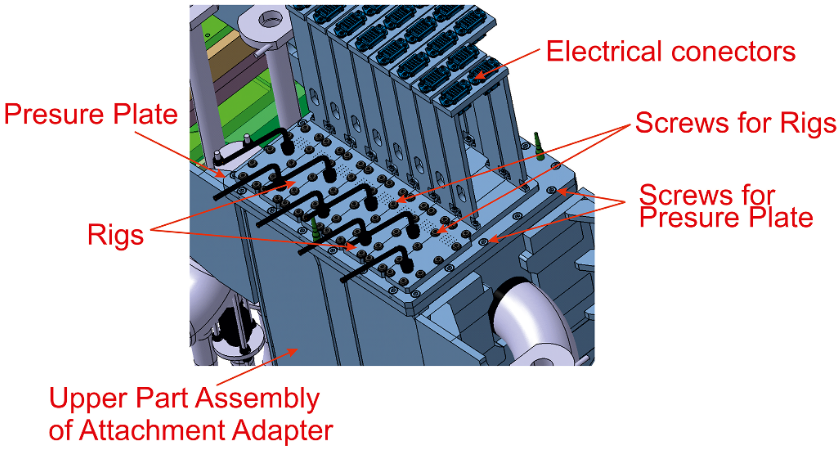

Figure 13. A 3D view of the top part of the STUMM.

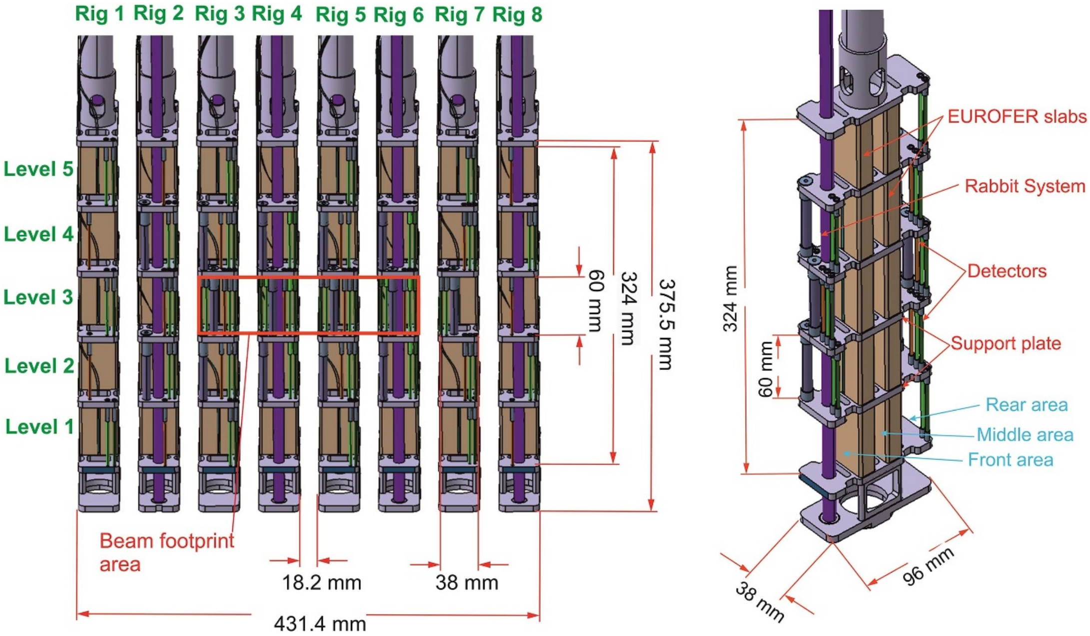

Figure 14. Left to right, the active part of rigs: (*a*) the whole set of the eight rigs, (*b*) a single rig. Reproduced with permission from [13]. CC BY-NC-ND 4.0. Reprinted from [51], Copyright (2025), with permission from Elsevier.

area will deliver information about direct neutrons from the IFMIF-DONES source. In the middle space, the two Eurofer slabs (material planned as structural elements of HFTM) will be installed. The instrumentation installed behind the Eurofer slabs, in the rear area, will collect information about the radiation conditions expected inside the HFTM.

The need for the sensors to be used in STUMM is determined by the operating conditions of the module. The sensors must be characterized by radiation resistance and a relatively small radiation sensitivity (to avoid detector saturation). Most of the systems proposed for STUMM are commercially available, however some new solutions, purpose-prepared for IFMIF-DONES, need to be considered. For STUMM needs, the following detection systems are proposed:

- A Rabbit System (RS) for measuring the thermal, epithermal, and fast neutron flux density.
- Pairs of micro-fission chamber (MFC with U238) and ionization chamber (IC) for fast neutron flux density.
- Pairs of micro-fission chambers (MFC with U235) and IC or SPNDs for thermal and epithermal neutron flux density.
- Gamma thermometers (GTs) for nuclear heating measurements.
- Thermocouples for temperature measurements.
- Strain gauges for deformation measurements.

The MFC and the (gamma) IC are working in pairs inside the STUMM due to their principle of operation. The MFC can be considered modified IC that besides the filling gas (Argon), it also contains a thin layer of fissile material (Uranium 235 or Uranium 238) and they are sensitive to the whole radiation field (mainly the sum of the neutron and gamma fields). On the other hand, the IC are only sensitive to gamma fields (no fissile material inside, only Argon). The approach is that the neutron measurements will be done by the differential measurement between each pair of MFC and IC. The design requirements assume to have MFC and IC with the same dimensions and operating requirements. For more details about the detection systems the [13, 18] can be consulted.

3.2. The STUMM-PROTO and the STUMMEX program for validation of the STUMM

The detectors housed in the STUMM have been typically working in fission neutron and gamma fields and their performance, mainly concerning MFCs, ICs and SPNDs, is well known in those environments. Nevertheless, the neutron fields produced in the TC reach a wider range of energies, thus including the fast neutron range, above 1 MeV, up to 55 MeV with special interest in the plateau 10–20 meV, where the crucial fusion-related, 14 MeV neutrons are inscribed.

In [52] the performance of MFCs and ICs under intense fast neutron fields has been analyzed. In this work small rigs housing a small quantity of detectors were shielded with gadolinium and working at room temperature under the neutron and gamma fields in BR2 Belgian reactor. The detectors (mainly MFCs, ICs and SPNDs) tested and reported at [52] have been developed and customized for the STUMM needs at IFMIF-DONES, which has led to a significant envelope miniaturization to obtain 3 mm as the outer diameter.

Quite importantly, a step forward in the knowledge of those detectors lies in the high number of them and the high density population inside the STUMM Container as well as the working temperature range applicable during the DONES commissioning phase IV. Furthermore, due to the very harsh radiation environment inside the TC, mineral-insulated (MI) cables must be used for the transmission lines from the STUMM to the closest location where acquisition electronics hardware can be placed (R145-1) in the facility. These very long MI cables produce attenuation and other effects that can very much handicap the low signals reaching the acquisition electronics. These are the main reasons why a prototype of the STUMM system, called STUMM-PROTO is needed. Apart from them, the STUMM-PROTO could also benchmark manufacturing processes and techniques for the construction of a real-sized device, which would be very significant as compared to the final STUMM system in IFMIF-DONES. On this regard, the mechanical construction of the STUMM-PROTO should include high quality standards of special interest like the ones based on RCC-MRx. On the other hand, and due to cost constraints, the STUMM-PROTO was foreseen to house as many as one fourth of the detectors foreseen for the STUMM system.

All these main requirements and constraints applicable to the STUMM-PROTO were defined in a relatively early phase of the STUMM design, around the end of 2021. Later, some attempts to optimize the STUMM design have been implemented, like the minimization of the amount of the detectors needed for the commissioning. Nevertheless, these outputs were not captured for the specification, design and construction of STUMM-PROTO. On this regard, the prototype may fall on the conservative side as compared to a future fully optimized STUMM. Therefore, the main requirements driving the STUMM-PROTO design are listed next [18]:

- Real size as compared to the STUMM baseline design. Figure 15 (left) shows a 3D view of STUMM-PROTO with its assembly-supporting structure (in yellow).
- RCC-MRx compatibility as per class NRx3 with some upgrades from NRx2 class: In particular, this translates into e.g. the welding configurations accepted in RC 3834.32 and volumetric examination of all the pressure-retaining weldings.
- Cooling pipes are available for eventual integration in dynamic He cooling loops.
- One fourth of the detectors foreseen for the STUMM will be housed in the STUMM-PROTO, i.e. 15 ICs, 12 MFCs, 6 SPNDs and 11 GTs. No Rabbit System was required in the STUMM-PROTO. Figure 15 (right) shows a 3D view of the active area of STUMM-PROTO (inside the container) with the 2/8 slots populated with sensors.
- Tunable bias voltage from 150 V to 250 V for the MFCs and ICs.
- Floating and grounded options for the electrical configuration of the rigs containing the detectors.
- MI 35 m long, coaxial cables for the transmission lines from the STUMM-PROTO container up to the acquisition electronics to simulate the distance constraints existing in IFMIF-DONES.
- Heating capacity to provide a working temperature range between 20 °C and 350 °C inside the prototype's container.
- Dual atmosphere working mode: under vacuum (1×10^{-3} mbar), or at 3.5 bar (absolute pressure).
- Low temperature differential amongst the detectors housed in an instrumented cell.
- The signal acquisition requirements are defined in [18].
- Alarm trigger in less than 10 μs under a step-like signal change in MFC/IC: this requirement aims to provide a beam shutdown capability in case of an incidental sudden shift of the beam.

The expected signal ranges are, in the interval of 10–4000 nA in the case of MFC/IC and in the interval of 20–500 pA for the SPNDs [18], rather driven by the eventual irradiation facilities where the STUMM-PROTO may be tested. Indeed, the prototype will be subjected to different irradiation campaigns, with the particle and neutron flux density being orders of magnitude lower than the values expected in the high-flux region at DONES. Therefore, the signals expected during the experimental program of the prototype (STUMMEX) will also be a few orders of magnitude lower so the transmission and acquisition issues may become more relevant as compared to the final performance of the detectors at DONES. Therefore, the requirements listed above lie on the conservative side and open the possibility to place MFC, IC and SPNDs in locations other than the high-flux region. Concerning the SPNDs, those requirements translate into a very low signal, in the range of few tens of pA, to be transmitted and acquired above the noise background, which means a very high technical challenge.

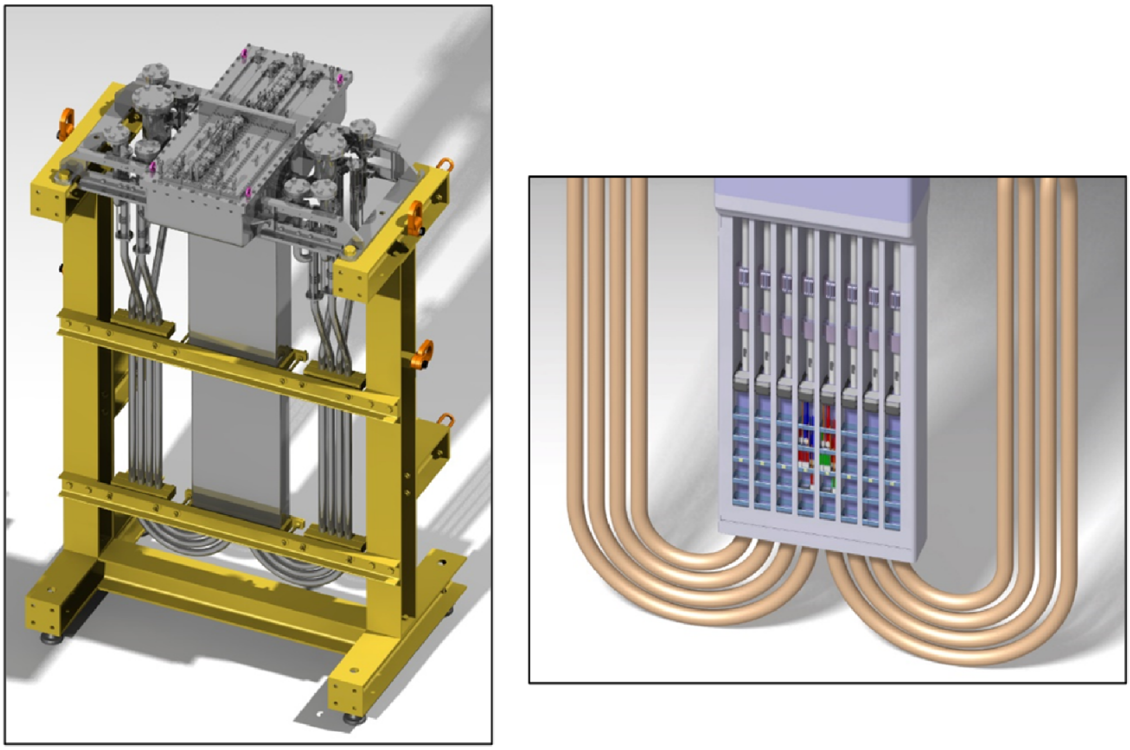

Figure 15. (Left) General 3D view of the STUMM-PROTO. (Right) Tentative arrangement of detectors inside the container (transparent view for clarity reasons).

The STUMMEX program will include three main phases with the STUMM-PROTO as a main actor. The first one (cold test campaign) will consist of measurement of background signal and leakage current d the different detectors under different configurations in terms of detector population density inside the STUMM-PROTO container as well as along a wide range of temperatures. Noticeably, the SPNDs do provide very low signals and they do not need to be polarized while the MFCs and ICs need typically a bias voltage around 150 V. The high population density may then induce cross-talk undesired signals to the SPND coming from polarized neighbor detectors. Capturing this kind of complex interaction is at the bottom of the need for STUMMEX. From the cold tests experimental campaign, the lowest signal readable for each kind of detector will be defined, which will provide a crucial output for the selection of the facilities for the STUMM-PROTO to be irradiated in the next phases.

The second phase will be based on the irradiation of the prototype in gamma sources. This phase will be the longest one since the components will not get activated so comprehensive testing can be implemented. For every different irradiation campaign, MFCs and ICs need specific bias voltage calibration where, under a constant irradiation field, the bias voltage is varied within a range between e.g. 100 V and 250 V, the signal being acquired at each voltage level. Afterwards, the plateau region of the voltage range is identified to settle the bias voltage for further measurements. In the case of STUMM-PROTO, the MFCs and ICs will be grouped, each of the groups being commonly power supplied. Otherwise, providing a single power supply to each MFC or IC would have led to a very expensive electrical layout. Once the bias voltages have been defined for the MFCs and ICs, important parameters like the signal response linearity, the signal response repeatability and the signal-to-noise ratio will be measured. Quite importantly, correlations between MFC and IC responses will also be captured during these gamma irradiation runs. Concerning the SPNDs, they are mostly sensitive to neutron interactions although some interactive modes with gammas are also expected; in particular, concerning the gamma prompt response. Similarly to the previous campaign, all these measurements can be implemented in a wide range of temperatures and under different spatial configuration of the detectors.

The third campaign involving STUMM-PROTO will be based on irradiation in a neutron source. This campaign will likely induce materials activation, so it needs to be very carefully planned. The eventual neutron source to irradiate STUMM-PROTO is, nowadays, not yet decided. For MFCs and ICs, measurements during this campaign would be focused on the same parameters as the gamma irradiation campaign, although, at this point, neutron-induced and gamma-induced signals should be distinguished. Concerning the SPNDs, the most relevant working mode, fission production on the emitter's material by means of neutron interaction, will be enabled, neutron-induced signals being produced. Furthermore, signal correlation between the MFCs, ICs and SPNDs will be possible.

The STUMMEX program include also campaigns other than the STUMM-PROTO ones, where single or few detectors are the components under testing. In fact, an IC was irradiated under a pulsed beam in LIPAc facility at Rokkasho. The main aim of this campaign was to measure the performance of the current-mode IC (all the MFCs and ICs in STUMM-PROTO are current-mode) under a low duty cycle, pulsed beam to know whether current-mode devices could be used from the very beginning during phase IV of the integrated commissioning at DONES. Indeed, phase IV will not start with the continuous wave (CW) working conditions, but some pulsed beam stages will be implemented to avoid any damage in the machine. Thus, keeping the same MFCs and ICs for the pulsed-beam and CW stages of the commissioning phase IV would allow a much more efficient use of the STUMM in DONES. Nowadays, data produced during the irradiation of the current-mode IC at LIPAc are being processed so no results have been published so far.

In addition, with respect to the SPNDs, the STUMMEX program currently considers the following 4 emitter materials for SPNDs to be installed in the STUMM-PROTO: Vanadium, Inconel, Rhodium-103 and Cobalt. The SPNDs will be subject, installed in the STUMM-PROTO or in other configurations, to cold tests, gamma irradiation tests and neutron irradiation tests. This experimental activity shall provide final answer to select the best candidate emitter material for SPNDs to be installed in the HFTM.

From the developments done during the design and construction of the prototype, the main achievements concern, on one side, the electronics in terms of the low background signal obtained in the different prototyping phases, and, on the other side, the mechanical performance of the vessel in the very demanding pressure tests according to RCC-MRx standards.

On the first topic, electronics responses as fast as 6 μs have been captured for a threshold detection of 500 nA as well as background noise as low as 3 nA for the MFC/IC acquisition electronics. Regarding the SPNDs, background below 40 pA was measured although a very easily identifiable systematic component can be removed for a much better performance [18]. Concerning the second point, the vessel was submitted to 5.4 bar (absolute pressure) during 30 min without any incident coming up.

Currently, STUMM-PROTO (figures 16 and 17) has been already manufactured, assembled and integrated and the site acceptance testing (SAT) phase being ongoing at the UGR-DONES facility recently built in front of the DONES site in Escúzar (Granada, Andalucía, Spain). Once the SAT phase is finished, the cold tests experimental campaign will take place in the current facility.

Figure 16. General view of the STUMM-PROTO assembled and mounted over its handling structure at UGR-DONES site in Escúzar.

4. General characteristics of the most relevant IFMIF-DONES other irradiation modules

4.1. The Blanket Functional Material Module, BLUME

The Tritium BB, is one of the key components for any D-T fusion electricity-producing device. As BB serves the three major functions: (1) produce tritium to ensure tritium self-sufficiency; (2) extract high-grade heat to generate electricity and (3) contribute to shield the sensitive components (vacuum vessel, superconducting magnets) behind BB. Despite the importance of the BB, its TRL is relatively low. Up to now, there is no BB built or tested [53]. The TRL of Europe's most advanced EU DEMO BB concepts (HCPB [36] and WCLL [54]) currently remains between 3 and 4 [53], which is relatively low.

An irradiation test well defined and performed in IFMIF-DONES for the blanket concept will contribute to raising its TRL. Given the scarcity of nuclear irradiation facilities and the limited space for testing blanket mockups, the IFMIF-DONES provides a unique opportunity to test BB mockups with high neutron flux. A blanket functional materials module (BLUME, German word for flower) [55] for the EU DEMO HCPB BB is proposed to be tested in the IFMIF-DONES TC.

The irradiation experiments in IFMIF-DONES facility for the BLUME Irradiation Module search to address some technological issues in relation to the HCPB BB exposed to fusion-like neutrons in terms of energy and total dose. In particular, the main testing goals for BLUME are shown in table 2.

4.1.1. Preliminary design and analysis. The current HCPB BB uses 8 MPa helium as coolant, lithium ceramic breeder pebbles as tritium breeder and titanium beryllide ($TiBe_{12}$) as neutron multiplier. It is based on a fuel-breeder pin configuration. For the design description of the HCPB BB, please refer to [36]. In a preliminary neutronics analysis, 7 full-size pins of the HCPB BB were integrated into the MCNP model of the TC of IFMIF-DONES, shown in figure 18. This initial BLUME mockup (BLUME-v0) is placed behind the HFTM,

Figure 17. Pre-assembly tests of the STUMM-PROTO at UGR-DONES site in Escúzar.

as shown also in figure 18. In order to moderate the neutrons thus increase tritium breeding, a neutron spectrum shifter (NSS) is inserted before the BLUME mockup.

The neutron flux map on BLUME-v0 is shown in figure 19. Compared to the peak neutron flux (4.8×10^{15} n cm^{-2} s^{-1}) of HCPB in EU DEMO, the neutron flux in BLUME is lower (5–8×10^{13} n cm^{-2} s^{-1} in the most exposed zone). However, with clever design, the EU DEMO-relevant temperature gradient in the breeder zone can be achieved.

The nuclear heating on BLUME-v0 is shown in figure 20; it can be observed that there is a radial gradient of nuclear heat within the pins at the periphery. For the central pin, the nuclear heating is relatively radially homogenous. In order to avoid the temperature gradient in the radial direction across the pins, only the location of central pin is therefore considered as appropriate location for the BLUME-v0 mockup. The periphery will be filled with neutron-reflector materials. This new configuration of single-pin design with surrounding neutron reflector materials ensuring a more homogeneous power distribution is subsequently named as BLUME mockup version 1 (BLUME-v1).

The design of the honeycomb capsule of BLUME-v1 is shown in figure 21. According to the simulations, the tritium generation rate is about 4×10^{-6} mg s^{-1}, which means 1 daily tritium production would be 0.34 mg. The total power is about 1044 W. The power density on BLUME-v1 is shown in figure 22. As it can be seen, there is an asymmetry in nuclear heating due to the 9° inclination of deuteron beam.

4.1.2. Thermal and mechanical analysis. In case of rupture of coolant pipeline of BLUME in TC, a pressure of 80 bar would over-pressurize the TC volume quickly and complicate the safety requirement. Also, in order to share the infrastructure in the compact TC, the pressure of the helium coolant is 3.5 bar, the same as with HFTM. The inlet temperature is set at 380 °C, same as EU DEMO HCPB. The helium mass flow rate is 1.7 g s^{-1}, resulting in an inlet velocity of 57 m s^{-1}. The thermal analysis is conducted using ANSYS Mechanical. The flow is modeled using fluid line. The temperature field of different materials can be seen in figure 23. The temperature of Eurofer is in the range of 407 °C–497 °C, relevant to EU DEMO HCPB temperature conditions.

Only the structural material Eurofer is considered in the mechanical analysis. The mechanical analysis shows that the stress level is low due to the low-pressure load and homogenous temperature field. The stress field distribution on Eurofer is showed at figure 24, for nominal full power operation. The stresses at the central honeycomb capsule are within stress allowable.

As main conclusion, a blanket functional materials module, BLUME, for the EU DEMO HCPB BB is proposed. Preliminary design and analysis show that the BLUME mockup under IFMIF-DONES conditions can be relevant for EU DEMO design and the structure is robust.

4.2. The (IFMIF-DONES) Liquid Breeder Validation Module, LBVM

The objective of the Liquid Breeder Validation Module (LBVM) is to address various R&D needs of Liquid Breeder Blankets in a versatile setup. These needs include irradiation experiments under a significant neutron environment and the expected operational temperature conditions for EU DEMO. The module is being designed to achieve the required temperature range and other operational conditions for each experimental capsule. Additionally, the LBVM aims to provide flexibility to accommodate potential changes in the irradiation test matrix as R&D needs evolve.

Initially, the LBVM will focus on experiments related to the EU DEMO WCLL blanket concept, which utilizes eutectic Pb-15.7Li alloy as liquid breeder material and Eurofer as structural material, operating at temperatures between 300 °C and 550 °C. However, in the future, it may also be possible to conduct experiments related to other liquid breeder concepts.

The first mock-up of the LBVM was proposed by CIEMAT in 2013 [25, 56]. This module consisted of an irradiation area designed for 16 test capsules to hold several irradiation experiments appropriate to provide relevant information to the development of liquid breeder blanket technology. However, for various project-related reasons, the design of modules for the medium and low flux areas was halted. Furthermore, the delay of the D-T phase of ITER has reignited the need to relaunch projects aimed at testing the technology associated

Table 2. Testing goals of BLUME module (associated to HCPB BB).

To investigate	Goal
Breeder/structure thermo-mechanical/chemical interactions	To study thermomechanical interactive effects on component behavior and to validate in-house pebble bed modeling tools
Tritium behavior in thermal and flow transients	To investigate the tritium inventory and permeation behavior during thermal and flow transients and to validate tritium transport tools
Blanket response to coolant transients	To assess the effect of loss of flow or loss of coolant conditions on the fuel-breeder pin and to validate the numerical tools
Neutronics prediction validation (tritium generation, nuclear heating, activation)	To verify and validate neutronics predictions for tritium breeding, nuclear heating and activation
Heat transfer experiments	To address heat transfer in realistic fuel-breeder pin geometry and to validate numerical predictions

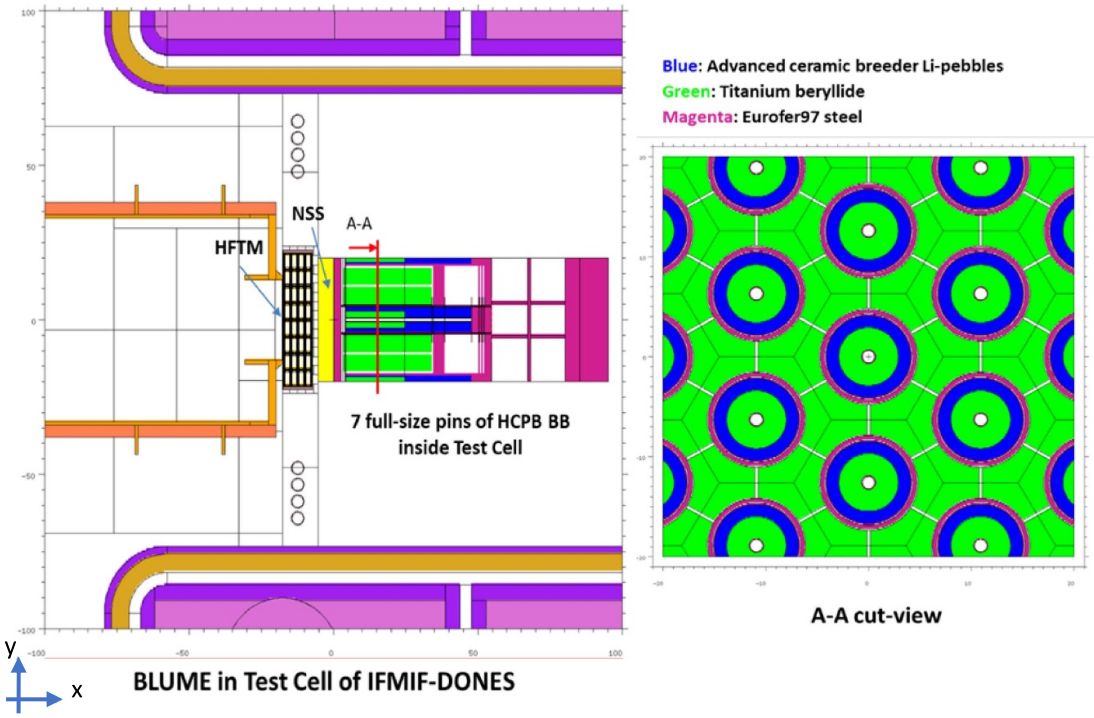

Figure 18. (Left) Integration of BLUME-v0 3D model into the TC of IFMIF-DONES (plant view). (Right) Detail of the transversal cut-view (A-A section) of the BLUME-v0 3D model, with 7 complete honeycomb capsules shown. In blue, the advanced ceramic breeder Li-pebbles zone, in green the titanium beryllide zone and in magenta the Eurofer steel case.

with breeder blankets focused on the EU DEMO design. In this framework, the LBVM mock-up proposed in 2013 is being adapted to the new IFMIF-DONES TC radiation environment and the approach presented in this paper is developed within this context.

The functional operation of the module includes a cooling and a purge system provided by recirculating helium, a tritium measurement station and a electrical power supply device to feed electrical heaters and instrumentation. See [25, 56] for more details. The 2013 version of the module includes 16 experimental Eurofer capsules cylinders which are 80 mm height, 22 mm external diameter and 1 mm thick walls, distributed in two rows. The capsules are partially filled with lithium lead up to 50 mm which is the theoretical height of the neutron footprint and maintained at 300 °C–550 °C. The rest of the volume works like a chamber to accumulate the gases produced during irradiation for an 11 month campaign. Each capsule is equipped with an electrical heater to reach its specific temperature and is installed inside a cylindrical rig which supports and positions the capsule.

The tritium generated and permeated in each capsule during irradiation is swapped for the purge gas to the tritium measurement station situated out of the TC. One second loop of Helium acts as a cooling system and keeps tritium diffusion within the safe margins (50 °C–150 °C) and guarantees its mechanical integrity. The calculations of the tritium permeation through each wall capsule are values between 1.8×10^{-4} Ci m^{-3} and 4×10^{-2} Ci m^{-3} which could be measured with commercial ionization chambers [25].

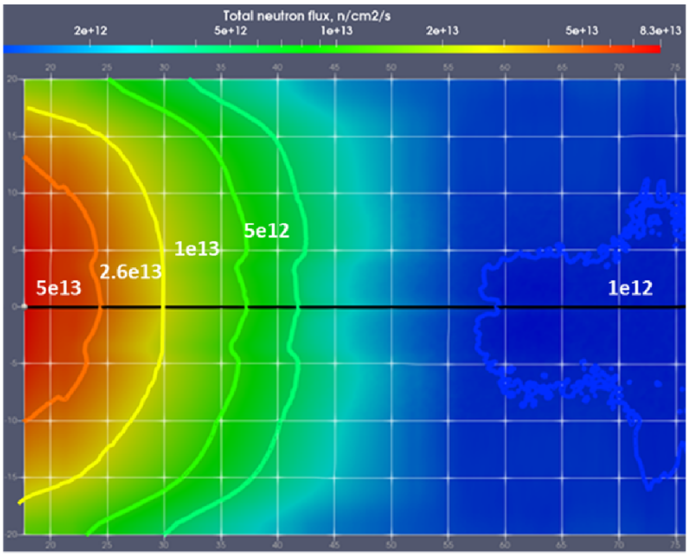

Figure 19. Central neutron flux distribution (n cm^{-2} s^{-1}) on the BLUME-v0 at full power operation with the module located behind the HFTM and the NSS (neutron footprint: 400 × 400 mm^2).

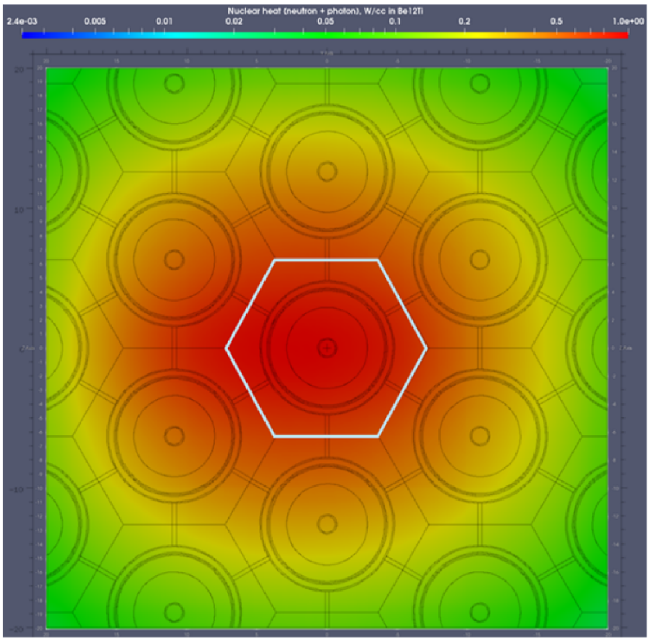

Figure 20. Nuclear heating (neutron + photon) on the BLUME-v0 (front view) at full power operation with the module located behind the HFTM and the NSS.

The conceptual configuration of the three types of experiments to be proposed in the Liquid Breeder Validation Module are schematically represented in figure 25 and described in more detail in the following three points:

(a) Experiment 1. Tritium breeding performance and tritium production rate assessment:
In this experiment, the tritium production rate will be online monitored during operation. To monitor the tritium produced in the eutectic Pb-15.7Li alloy, it will be dragged by helium (He with a small amount of H_2O, in the order of appm, to effectively extract the tritium) flow through a coaxial cylindrical channel, and the measurement will be taken outside the TC. The purge helium flow will need to contain a small amount of water molecules to effectively extract the tritium. Since the eutectic Pb-15.7Li alloy capsule will not be covered by an anticorrosion or anti-permeation coating, the Eurofer steel capsule will have a thickness of 2 mm, based on corrosion rate studies [57]. Additionally, the transmutation of the eutectic Pb-15.7Li alloy will be measured by means of PIE.

(b) Experiment 2. Coating materials assessment:
In this experiment, the tritium permeation will be measured online to assess the degradation of the anti-permeation barrier. Tritium permeation will be continuously monitored during operation to evaluate the effectiveness and longevity of the coating materials. Additionally, PIE will be conducted to characterize their damage and corrosion. Currently the proposal will be manufacturing the capsule with coating.

(c) Experiment 3. Bulk materials assessment:
In this experiment, the electrical resistivity of a ceramic bulk sample will be measured online during operation. This real-time monitoring will provide valuable data on the material's performance under irradiation. Additionally, PIE will be carried out to assess the anti-permeation properties and corrosion of the bulk materials.

Although the starting point is the design presented in 2013, as it is mechanically and fluid-dynamically optimized, the dimensions of the capsules will be reevaluated considering different factors:

- Instrumentation needs: definitions of the number and characteristics of thermocouples to monitor the temperature, size and characteristics of the heaters to control the temperature, and diagnostics to measure radiation.

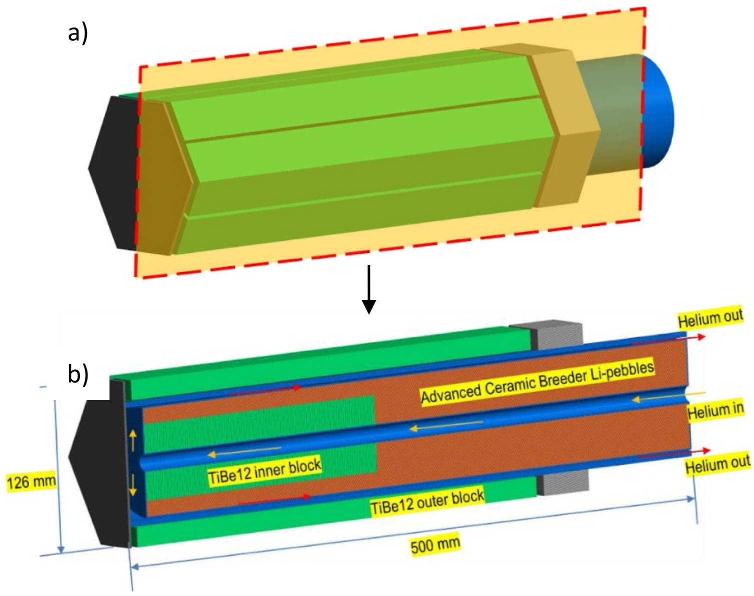

Figure 21. (*a*) 3D model of a honeycomb capsule of BLUME-v1 and (*b*) longitudinal central section of a capsule with main dimensions and materials shown.

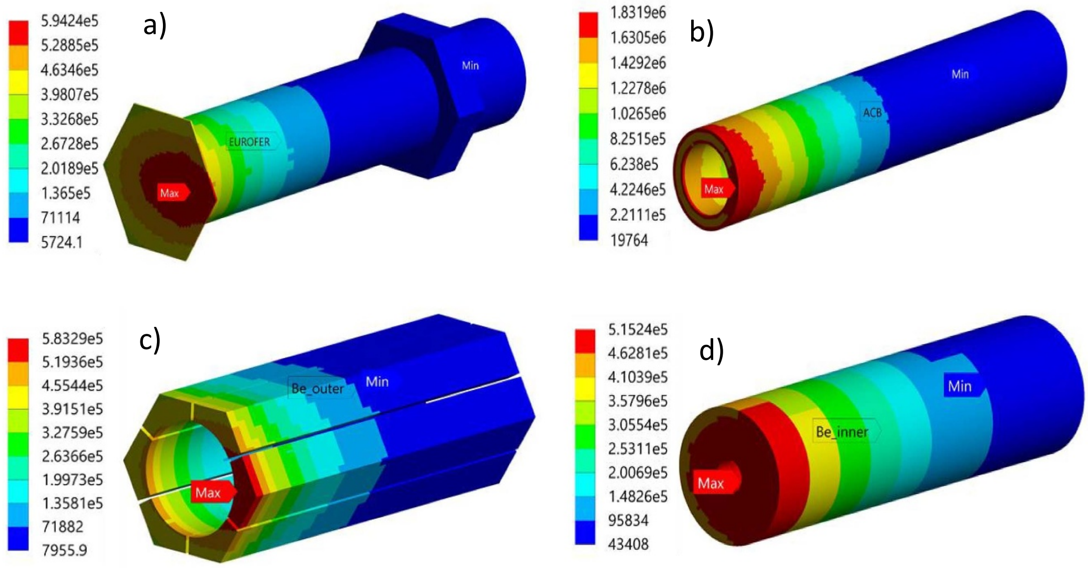

Figure 22. Power density (W m^{-3}) at full power operation for the different materials of BLUME-v1, central honeycomb capsule: (*a*) Eurofer, (*b*) Li-pebbles, (*c*) $TiBe_{12}$-outer and (*d*) $TiBe_{12}$-inner.

- Manufacturing and technological limitations: unions of materials with different behaviors and remote control as main technological topics.

By taking into account the neutronic calculations performed at that time [25, 56], the medium flux area has been found to be the best position to install the LBVM inside the TC of IFMIF-DONES, behind the HFTM and a NSS module [58]. The NSS is a module used to modify the neutron spectrum in this area to adapt the radiation effects to the one expected in the BB of the future EU DEMO. In that position, the LBVM will achieve a significant number of dpa, with values aligning with those expected in the EU DEMO breeder zone. However, the gas production ratios (He/dpa, H/dpa) will be higher than those in EU DEMO due to the relatively fast neutron spectrum in the IFMIF medium flux area, as gas production is a threshold reaction [56]. However, these calculations have to be adapted to the new irradiation TC environment due to the changes in the dimensions of the HFTM in respect to the one used in the IFMIF-EVEDA phase.

In this framework, preliminary neutron transport calculations have been developed to enhance the irradiation conditions, considering the new radiation environment. Accordingly, the adjustment of the thickness of the NSS

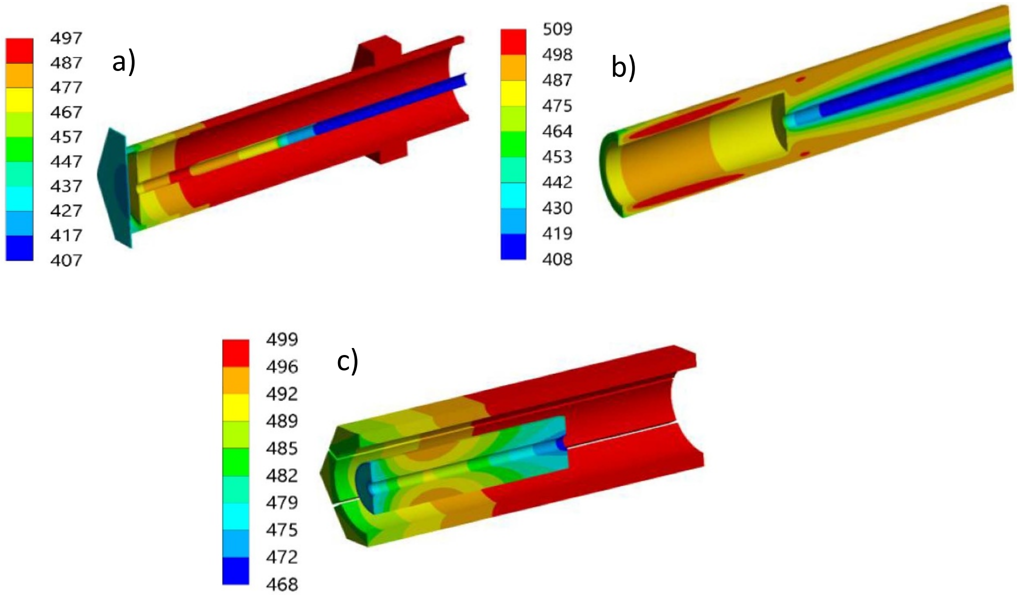

Figure 23. Temperature field (°C) at full power operation for the different materials of BLUME-v1, central honeycomb capsule: (*a*) Eurofer, (*b*) Li-pebbles and (*c*) $TiBe_{12}$.

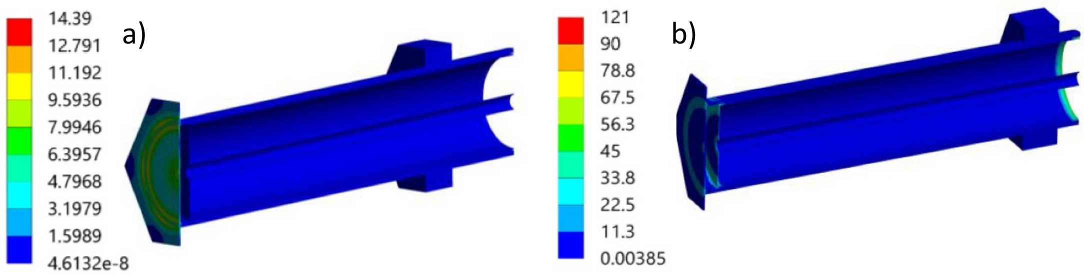

Figure 24. Stress field (MPa) at full power operation for Eurofer case of BLUME-v1, the central honeycomb capsule, (*a*) pressure load case, (*b*) pressure and temperature load case.

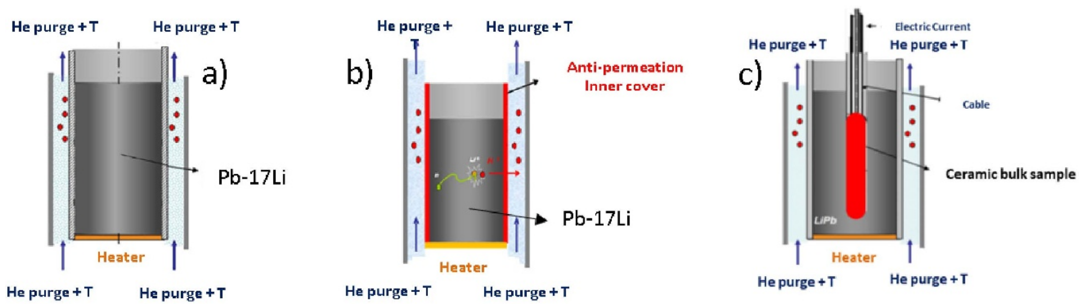

Figure 25. Conceptual configuration of the three types of experiments to be proposed in the LBVM: (*a*). Experiment 1. *Tritium breeding performance and tritium production rate,* (*b*) Experiment 2. *Coating materials assessment* and (*c*) Experiment 3. *Bulk materials assessment*.

tungsten plate has been performed to maximize the tritium production rate.

Figure 26 shows the horizontal cross section of the MCNP model used to carry out the NSS thickness assessment. The neutron transport calculations have been made using McDeLicious code 2017 (based on MCNP6.2) developed by KIT laboratory to reproduce the IFMIF deuteron–lithium neutron source [59]. The nuclear data library used for neutron transport and tritium production calculation was FENDL3.1 [60]. The MCNP geometrical model used was the mdl9.8, in which the NSS and LBVM models were installed.

An assessment of the tritium production rate in the most irradiated capsule of the LBVM as a function of the NSS thickness is shown in figure 27. Although the most optimized NSS thickness of IFMIF-EVEDA phase is 6.4 cm [56], the most optimized NSS thickness for IFMIF-DONES phase is 2.4 cm, where the maximum tritium production is reached. This change in thickness is mainly due to the

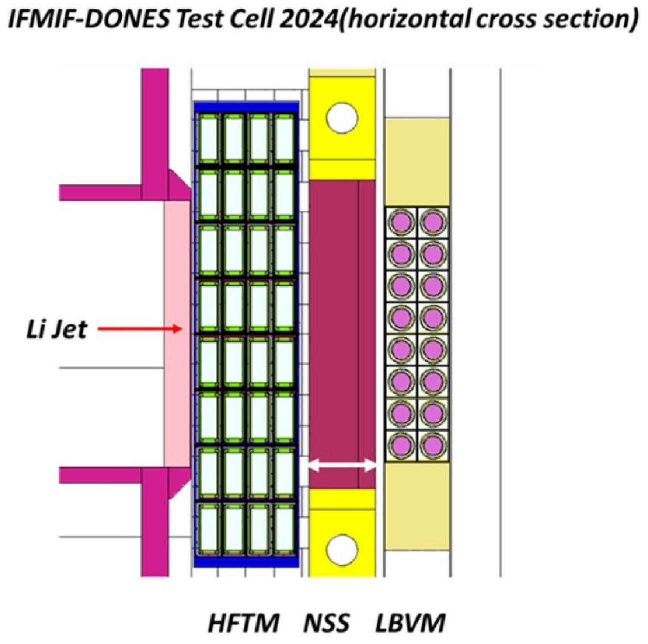

Figure 26. The horizontal cross section of the irradiation area in the TC, at $z = 0$ (in the middle of the deuteron beam). In this reference configuration, the LBVM is located behind the NSS and the HFTM.

HFTM size being different in respect to the IFMIF-EVEDA phase.

Furthermore, the neutron transport calculation has been performed to compare the tritium production rate expected in EU DEMO WCLL and Dual Coolant Lithium Lead (DCLL) with the one obtained in the capsules of IFMIF-DONES and using different nuclear data libraries, FENDL3.1d, JEFF3.3 and ENDFVII.1, table 3. Consequently, the neutrons spectrum of the FW of the WCLL and the DCLL, are similar just before the BB zone. The neutron spectrum was provided by personal communication [61, 62] based on the CAD models of the DCLL [63, 64] and the WCLL [54, 65] BBs.

From table 3 it is obtained that, on the one hand, there are a few uncertainties due to the use of different nuclear data libraries, and on the other hand, in the LBVM, the tritium production reached is one order of magnitude lower than the one expected in the future EU DEMO. This difference in tritium production may not be relevant, as the experiments can be easily scaled to obtain relevant results for the development of breeder blanket technology.

4.3. The (IFMIF-DONES) Tritium Release Test Module, TRTM

The Tritium Release Test Module, TRTM, is being designed under IFMIF-DONES conditions to contribute to the validation of tritium breeding technologies of the EU DEMO HCPB BB. The irradiations experiments with the TRTM inside the TC will provide experimental measurements in relation to the performance of tritium production and subsequent extraction of solid breeders (lithium ceramics) to be used in the HCPB BB. The volume of the irradiated material in the TRTM should be sufficient to consider the objectives and functions of the TRTM as defined below. Besides, the environmental conditions in the TRTM (mainly temperatures and irradiation conditions) should be representative of what is expected to be found at the HCPB BB.

The objectives and functions of the TRTM are defined as follow:

- To irradiate functional material samples of cylindrical/annular pebble beds of solid lithium ceramics during transient operation at accumulated dpa's and dpa rates close to the situation expected in HCPB BB.
- To provide blanket-relevant temperature range at the location of the material samples (e.g. $\sim$300 °C – $\sim$1000 °C) for several months of irradiation.
- To determine the time structure and characteristics of the tritium/hydrogen species release rate from lithium ceramic pebble beds, as reaction to transients in the irradiation conditions (for example, beam on/off) as well as function of the boundary conditions of temperature and purge gas compositions. This will be done by on-line measurements at different times during the irradiation period.
- To determine the chemistry of the purge gas and tritium/hydrogen species (fractions of HT, HTO etc) during irradiation by on-line measurements.
- To determine the change on mechanical, physical and microstructural properties, and chemical compositions of the irradiated material during PIE.

It is important to mention that the study of *in-situ* fragmentation of lithium ceramic pebbles and dust formation is not foreseen as primary test objective, due to the limited irradiated volume available. Also, the irradiation experiment in IFMIF-DONES with beryllides (with titanium or chrome) as neutron multiplier material is not included in the current design of the TRTM.

With respect to the modes of operation of the TRTM, the pre-conceptual design considers:

- Load the irradiation capsules with specimens of lithium ceramics.
- Integrate the TRTM into the IFMIF-DONES TC and perform the pre-operational onsite tests.
- Start the irradiation of the TRTM and during the irradiation phase:
  - Control setpoint changes (temperature, purge gas flow, neutron flux measurements …),
  - Record the time-dependent parameters such as tritium activity, temperature and purge gas flow conditions.
- Retrieve the TRTM and extract the irradiated specimens for PIE. PIE measurements include dimensional stability, microstructural characteristics, crushing load performance, fracture toughness and others general mechanical properties. Also, examination of macroscopic appearance of the irradiated material, as well as determination of the chemical composition (including tritium/hydrogen species), thermal conductivity, tritium diffusivity, density and size distribution of the pebble beds and crystal density as function of

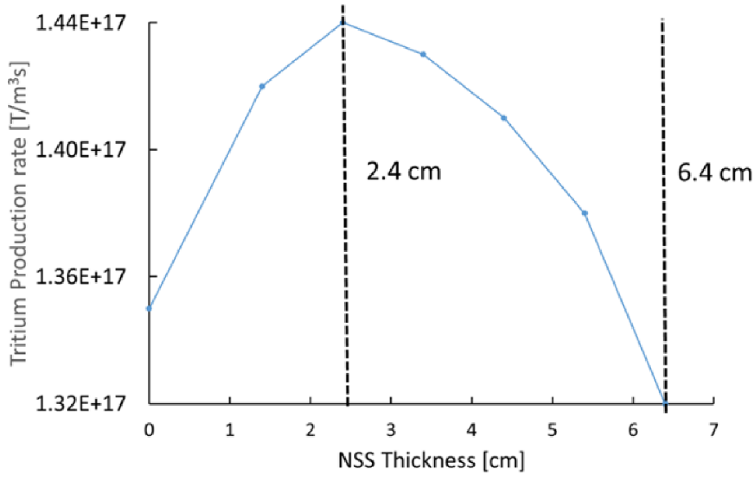

Figure 27. Assessment of the tritium production rate (T $(\mathrm{m}^3\mathrm{s})^{-1}$) in the most irradiated capsule of the LBVM as a function of the NSS thickness at nominal full power operation.

Table 3. Tritium production rate (T $(\mathrm{ms})^{-1}$).

Nuclear data libraries	WCLL	DCLL
FENDL3.1d	5.32144×10^{18}	3.14881×10^{18}
ENDFVII.1	5.32143×10^{18}	3.15020×10^{18}
JEFF3.3	5.32240×10^{18}	3.15068×10^{18}

the irradiation history and the temperature and purge gas conditions.

The time scales for transient operations could typically be similar to those expected in EU DEMO with normalized pulsed operation with 2 h of burning time and 10 min of dwell time [66]. However, longer time scales of days, weeks or months can be of interest to measure the residence time of tritium in the pebbles at low temperatures, where the release time scales are expected to be very long.

The irradiation of the solid lithium ceramics under long-term irradiation at constant parameters, to identify burn-up and ageing characteristics is not under the current defined objectives of the TRTM and this technological issue it is now proposed to be studied in another different irradiation module.

The engineering design of the TRTM to be irradiated in the TC of IFMIF-DONES is derived and updated from the previous configuration developed in the EVEDA phase [24, 67, 68]. In this sense, the current conceptual design of the TRTM, under IFMIF-DONES conditions, including its internal rigs and capsules, are illustrated in figures 28 and 29. These illustrations are based on detailed CAD drawings where the following main elements can be identified:

- A central module container that provides 8 slots (2×4) for installing 8 cylindrical rigs as well as three internal neutron reflectors.
- Eight cylindrical rigs with a stainless steel case, holding at its center a cylindrical heated and instrumented capsule. Inside each capsule the material aimed to be irradiated, the pebble beds of the breeder ceramic pebbles are located. The reference material is KALOS advanced ceramic breeder which is a solid solution of two-phase materials consisting of lithium orthosilicate (Li_4SiO_4) and about 35% mol of lithium meta-titanate (Li_2TiO_3) [36]. KALOS is provided in form of pebbles with an average diameter of 750 μm. A total effective volume of around 0.15–0.16 l is available for material irradiation which means almost 250 g of ACB pebbles in the whole module, considering a pebble bed density of 1.62 g cm^{-3} [69].
- Pipes that feed/return the helium coolant flow through the module container.
- Two (optional) lateral boxes filled with carbon-graphite bars, also supplied with a coolant flow and with the objective of acting as neutron reflectors.

Each capsule (see figure 29) is provided by electrical (ohmic) heaters, that can sum up heat to the specimens apart from that self-heating of the specimens and the structures mainly due to the gamma radiation. The heater powers can be controlled by the signal provided by several thermocouples installed per capsule. The purge gas first flows from bottom to top and enters each rig by means of a central pipe penetrating up to the bottom of the capsule. Then, the purge gas flows inside the pebble beds from bottom to top, leaving the specimens at the top and continuing with its own close circuit recirculation. In addition, the temperature of the capsules and the container structure are decoupled by a section of stagnant helium that can be used as insulation layer.

The purge gas in its journey through the pebble beds will pick up and carry the hydrogen species released (included tritium) from the specimens out of the capsule and towards a hydrogen chemistry analysis station situated outside of the TC, time-resolved measurements of hydrogen species including tritium release will be performed. There is an intermediate

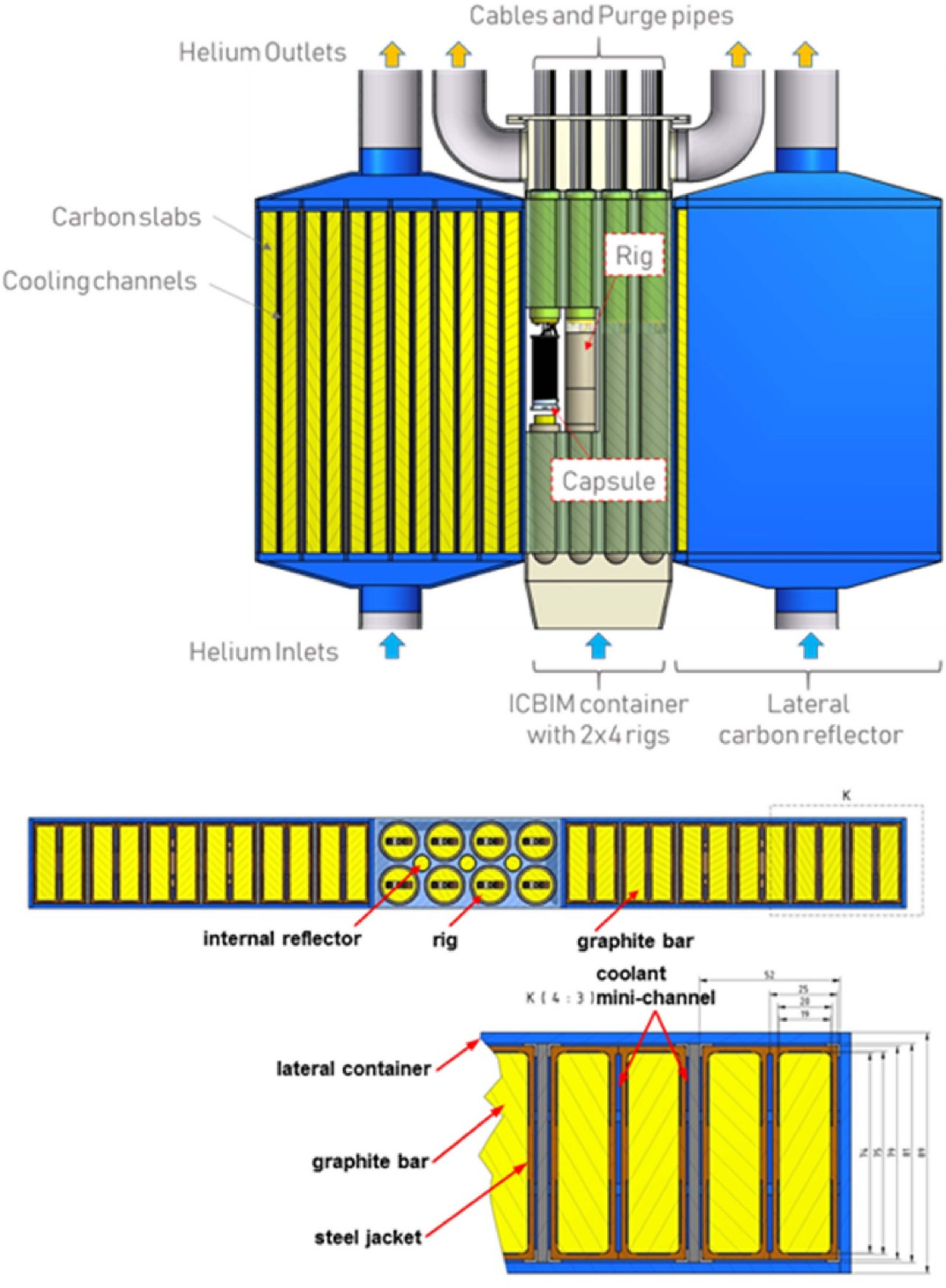

Figure 28. Conceptual layout of the (IFMIF-DONES) Tritium Release Test Module (TRTM) with a container of 2 × 4 rigs (in green) and two lateral carbon reflector boxes (blue and yellow). Adapted from [24], Copyright (2013), with permission from Elsevier.

gas volume (the first thermal insulation gap) where tritium, lost by permeation from the capsule, is collected and re-injected into the purge flow, to minimize losses.

Adjacent to each capsule, in the current mechanical design (figure 29), is located a rig head (at the top) and a rig foot (at the bottom) that will be filled with carbon (graphite) which can actuate as additional neutron reflectors.

First neutronics analyses have been already performed considering IFMIF-DONES conditions (1 year of full power) in order to have upper limits for the nuclear heating (to be used in thermal analysis) and activation, contact dose rates and decay heat. The basic configuration considers the TRTM being irradiated alone and with a so-called tungsten spectrum shifter module placed just after the TA and in front of the TRTM. The purpose of the spectrum shifter is to tailor the incident neutron spectrum to be more alike to the spectrum experienced in the breeding zone of the HCPB BB, where the sharp 14 MeV peak in the neutron spectra has already been moderated by

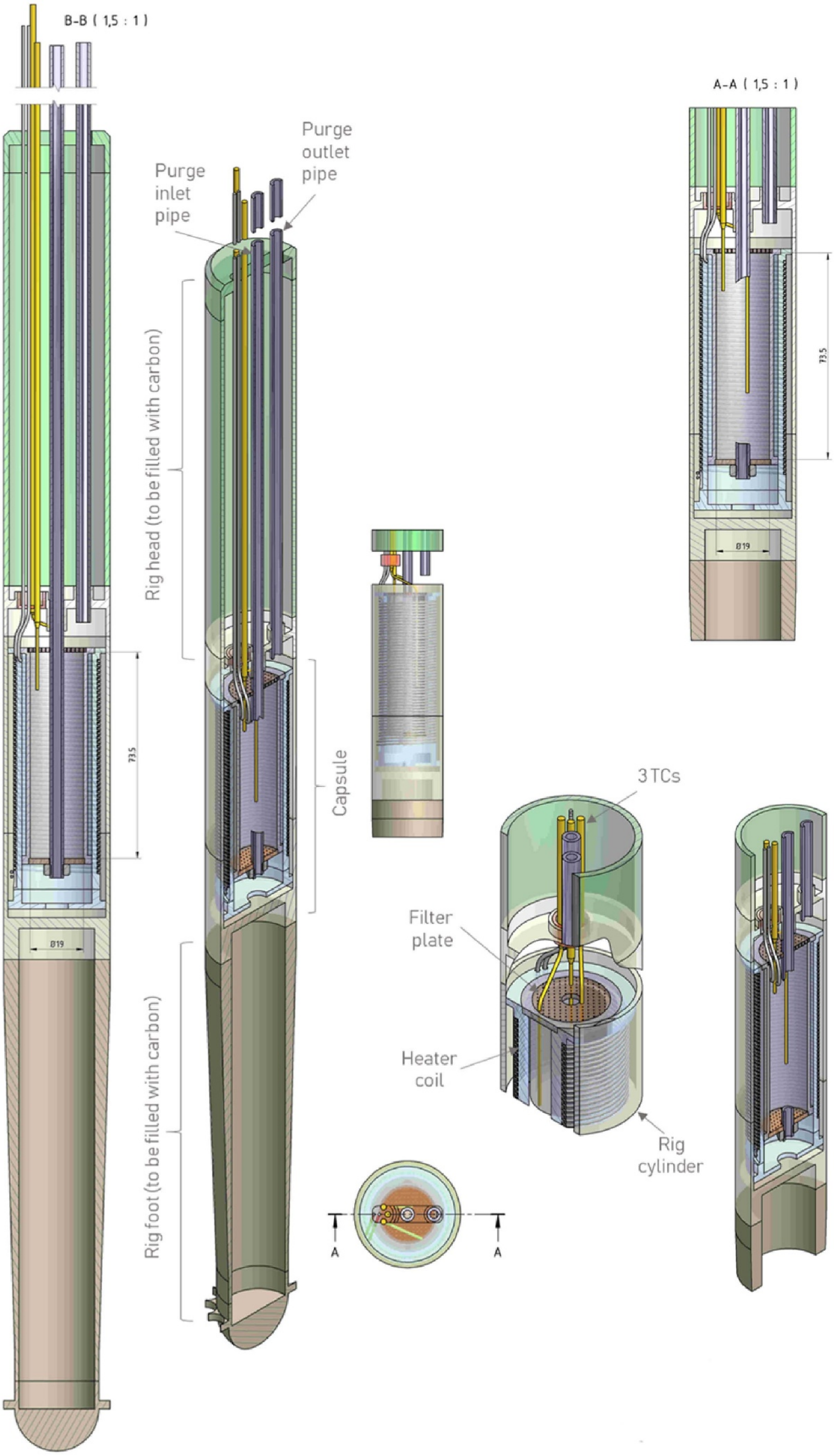

Figure 29. The (IFMIF-DONES) Tritium Release Test Module (TRTM) rig and capsule design. Adapted from [24], Copyright (2013), with permission from Elsevier. Adapted from [67], Copyright (2013), with permission from Elsevier. Rig foot and rig head are to be filled with carbon to act as neutron reflectors [70].

the materials of the FW and BB itself. This is a change on the design configuration respect to previous approach, while in IFMIF/EVEDA the TRTM was sitting behind the HFTM and the CFTM (Creep Fatigue Test Module), in the third row, in IFMIF-DONES, the TRTM is located closer to the neutron source in order to attain tritium relevant production rates.

Particularly, under IFMIF-DONES conditions, in the most irradiated capsule 5.5×10^{20} T atoms/fpy (9.8×10^{11} Bq/fpy, 32 kBq s^{-1}) are generated and volumetric nuclear heating is comparable to that obtained in IFMIF (in the range of 80%–120%). In any case, thermo-structural analysis under IFMIF-DONES conditions will be specifically performed with the latest design. With respect to the shutdown dose rate after 7 d for the most highly activated components of the TRTM is 1000 Sv h^{-1} which are level comparable to those expected in the HFTM.

The previous design description and analysis are compatible with the boundary conditions set at IFMIF-DONES TC and ancillaries, and from this point of view, the irradiation experiment of the TRTM with KALOS Advanced ceramic breeder can be performed within the current baseline configuration.

5. Conclusions/summary

The IFMIF-DONES Irradiation Modules constitute a group of systems in the IFMIF-DONES facility which are currently under design according to the IFMIF-DONES program.

On this work, the current description and status of the main IFMIF-DONES Irradiation Modules have been presented. Particularly, five modules have been described: HFTM, STUMM, BLUME, LBVM and TRTM.

The list of the irradiation modules to be experimentally tested in IFMIF-DONES is not limited or close at this moment and it can potentially be extended in the future to mainly attend EU DEMO irradiation needs.

The STUMM and the HFTM with Eurofer samples are the first modules planned to be installed inside the TC for irradiation at the facility. Consequently, their engineering status is currently considered as well advanced and accompanied by experimental validation programs under development. The rest of the IFMIF-DONES Irradiation Modules described on this paper can be found in the pre-conceptual/conceptual design phase.

The development of the IFMIF-DONES Irradiation Modules mentioned in this work, from their conceptual design up to the end of their design lifecycle (after finished the irradiation) and including the production and treatment of the irradiated data are being/will be performed by continuous and extended efforts of international teams of scientists and engineers.

It is foreseen, that the production of extensive fusion-like irradiated databases, coming from the irradiation experiments performed (inside the TC) in the 5 IFMIF-DONES Irradiation Modules described in this paper as well as another modules that can be developed in the future, can decisively contribute to (a) qualify the materials used in the most exposed components of the EU DEMO reactor and (b) address several BB technological issues associated to the level of radiation that this part of the EU DEMO reactor will experience. These fusion-like irradiated databases were identified as urgently needed at least almost 30 years ago.

Acknowledgment

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200—EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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References

[1] Ibarra A. *et al* 2019 The European approach to the fusion-like neutron source: the IFMIF-DONES project *Nucl. Fusion* **59** 065002
[2] Królas W. *et al* 2021 The IFMIF-DONES fusion oriented neutron source: evolution of the design *Nucl. Fusion* **61** 125002
[3] Ibarra A., Królas W., Bernardi D., Cano-Ott D., Becerril-Jarque S., Álvarez I., Qiu Y. and (EUROfusion WPENS Team) 2025 DONES performance, experimental capabilities and perspectives *Nucl. Fusion* **65** 122006
[4] IFMIF-DONES España 2024 What is DONES programme? (available at: https://ifmif-dones.es/dones-programme/)
[5] Becerril S. *et al* 2025 Update on the status of the IFMIF-DONES test systems *Nucl. Fusion* **65** 122010
[6] Zsákai A. *et al* 2024 Evolution of the IFMIF-DONES heart: system overview of the test cell *J. Nucl. Mater.* **598** 155185
[7] Nitti F.S., Maestre J., Dezsi T., Gordeev S., Holstein N., Brenneis B., Buligins L., Molla J., Ibarra A. and (EUROfusion WPENS Team) 2025 The lithium systems of the IFMIF-DONES facility *Nucl. Fusion* **65** 122004
[8] Pintsuk G., Aiello G., Dudarev S.L., Gorley M., Henry J., Richou M., Rieth M., Terentyev D. and Vila R. 2022

Materials for in-vessel components *Fusion Eng. Des.* **174** 112994

[9] Mota F., Palermo I., Laces S., Molla J. and Ibarra A. 2017 Potential irradiation of Cu alloys and tungsten samples in DONES *Nucl. Fusion* **57** 126056

[10] Arbeiter F. *et al* 2018 Planned irradiation capabilities of IFMIF-DONES *Nucl. Mater. Energy* **16** 245–8

[11] Terentyev D. *et al* 2022 Recent progress in the assessment of irradiation effects for in-vessel fusion materials: tungsten and copper alloys *Nucl. Fusion* **62** 026045

[12] Bernardi D. *et al* 2022 The IFMIF-DONES Project: design status and main achievements with in the Eurofusion FP8 work program *J. Fusion Energy* **41** 24

[13] Wiacek U. *et al* 2021 New approach to the conceptual of STUMM: a module dedicated to the monitoring of neutron and gamma radiation fields generated in IFMIF-DONES *Fusion Eng. Des.* **172** 112866

[14] Schlindwein G., Arbeiter F., Dolensky B., Klein C., Schwab F. and Zinn K. 2017 Mechanical testing of the IFMIF HFTM-DC prototype during operation in the HELOKA-LP helium loop *Fusion Eng. Des.* **124** 1077–81

[15] Klix A., Arbeiter F., Majerle M., Qiu Y. and Štefánik M. 2019 Measurement of neutron fluence in the High-Flux Test Module of the Early Neutron Source by neutron activation *Fusion Eng. Des.* **146** 1258–61

[16] Abou-Sena A., Arbeiter F., Schwab F. and Zinn K. 2019 Using sodium as filling and heat-conducting material in the irradiation capsules of the fusion materials irradiation facility IFMIF-DONES *Fusion Eng. Des.* **146** 1848–52

[17] Arbeiter F. *et al* 2018 The accomplishments of lithium target and test facility validation activities in the IFMIF/EVEDA phase *Nucl. Fusion* **58** 015001

[18] Becerril-Jarque S. *et al* 2024 A real-sized start-up monitoring module prototype for comprehensive test and irradiation campaigns of miniaturized neutron detectors according to the IFMIF-DONES baseline *Nucl. Mater. Energy* **40** 101712

[19] Kondo T., Shannon T.E. and Ehrlich K. 1996 Materials development and testing aspects of IFMIF in the conceptual design stage *J. Nucl. Mater.* **233–237** 82–91

[20] IFMIF International Team 2004 IFMIF Comprehensive Design Report: An Activity of the International Energy Agency (IEA) Implementing Agreement for a Program of Research and Development on Fusion Materials

[21] Knaster J. *et al* 2015 The accomplishment of the engineering design activities of IFMIF/EVEDA: the European–Japanese project towards a Li(d, xn) fusion relevant neutron source *Nucl. Fusion* **55** 086003

[22] Knaster J. *et al* 2017 Overview of the IFMIF/EVEDA project *Nucl. Fusion* **57** 102016

[23] Yamamoto M. *et al* 2013 Current status of the engineering design of the test modules for IFMIF *Fusion Eng. Des.* **88** 746–50

[24] Abou-Sena A. and Arbeiter F. 2013 Development of the IFMIF Tritium Release Test Module in the EVEDA phase *Fusion Eng. Des.* **88** 818–23

[25] Casal N., Mas A., Mota F., García Á., Rapisarda D., Nomen O., Arroyo J.M., Abal J., Mollá J. and Ibarra Á. 2013 Present status of the Liquid Breeder Validation Module for IFMIF *Fusion Eng. Des.* **88** 863–7

[26] Sato S., Kasugai A., Ochiai K., Masuda K., Nakamura M.M., Ohta M., Oyaidzu M., Kwon S., Sakamoto K. and Ishida S. 2021 Conceptual design of advanced fusion neutron source (A-FNS) and irradiation test modules *Nucl. Fusion* **61** 106026

[27] Kwon S., Sato S., Ohta M., Nakamura M., Oyaidzu M., Ochiai K. and Kasugai A. 2020 Conceptual design of DEMO blanket materials test modules for A-FNS *Nucl. Mater. Energy* **25** 100800

[28] Robertson J.P. *et al* 1997 Temperature dependence of the deformation behaviour of type 316 stainless steel after low temperature neutron irradiation *Effects of Radiation on Materials: 18th Int. Symp., ASTM STP 1325* (*Hyannis, MA, United States*, *25–27 June 1996*) ed R.K. Nanstadt, M.L. Hamilton, F.A. Garner and A.S. Kumar (American Society for Testing Materials)

[29] Kalchenko A.S., Bryk V.V., Lazarev N.P., Voyevodin V.N. and Garner F.A. 2013 Prediction of void swelling in the baffle ring of WWER-1000 reactors for service life of 30–60 years *J. Nucl. Mater.* **437** 415–23

[30] Toloczko M.B., Garner F.A. and Eiholzer C.R. 1994 Irradiation creep and swelling of the US fusion heats of HT9 and 9Cr-1Mo to 208 dpa at ∼400 °C *J. Nucl. Mater.* **212–215** 604–7

[31] Powell R.W., Peterson D.T., Zimmerschied M.K. and Bates J.F. 1981 Swelling of several commercial alloys following high fluence neutron irradiation *J. Nucl. Mater.* **103–104** 969–74

[32] Qiu Y., Arbeiter F., Fischer U. and Schwab F. 2018 IFMIF-DONES HFTM neutronics modeling and nuclear response analyses *Nucl. Mater. Energy* **15** 185–9

[33] Mota F., Ibarra Á., García Á. and Molla J. 2015 Sensitivity of IFMIF-DONES irradiation characteristics to different design parameters *Nucl. Fusion* **55** 123024

[34] Álvarez I., Anguiano M., Mota F., Hernández R. and Qiu Y. 2024 Neutronic assessment of the IFMIF-DONES HFTM specimen stack distribution *Fusion Eng. Des.* **200** 114212

[35] Qiu Y. *et al* 2025 Status of DONES neutronics, source terms analyses and radiation protections *Nucl. Fusion* **65** 122013

[36] Zhou G., Hernández F.A., Pereslavtsev P., Kiss B., Retheesh A., Maqueda L. and Park J.H. 2023 The European DEMO helium cooled pebble bed breeding blanket: design status at the conclusion of the pre-concept design phase *Energies* **16** 5377

[37] Pereslavtsev P., Hernández F.A., Zhou G., Lu L., Wegmann C. and Fischer U. 2019 Nuclear analyses of solid breeder blanket options for DEMO: status, challenges and outlook *Fusion Eng. Des.* **146** 563–7

[38] Gilbert M.R., Dudarev S.L., Zheng S., Packer L.W. and Sublet J.-C. 2012 An integrated model for materials in a fusion power plant: transmutation, gas production, and helium embrittlement under neutron irradiation *Nucl. Fusion* **52** 083019

[39] Stork D. *et al* 2014 Materials R&D for a timely DEMO: key findings and recommendations of the EU Roadmap Materials Assessment Group *Fusion Eng. Des.* **89** 1586–94

[40] Vladimirov P. and Möslang A. 2004 Comparison of material irradiation conditions for fusion, spallation, stripping and fission neutron sources *J. Nucl. Mater.* **329–333** 233–7

[41] Gordeev S., Schwab F., Arbeiter F. and Qiu Y. 2019 Numerical study of conjugated heat transfer for DONES high flux test module *Fusion Eng. Des.* **146** 609–13

[42] Chen Y. and Arbeiter F. 2012 Numerical simulation on gas-cooled closely-packed solid specimens *AIP Conf. Proc.* **1479** 78–81

[43] Qiu Y. personal communication (KIT) (available at: https://indico.ifmif-dones.es/event/29/contributions/781/attachments/535/779/YQU_DPA_activation_correlations_v0.3.pdf)

[44] Arbeiter F. *et al* 2016 Design description and validation results for the IFMIF High Flux Test Module as outcome of the EVEDA phase *Nucl. Mater. Energy* **9** 59–65

[45] Klein C., Arbeiter F., Martin T. and Taubmann P. 2016 Hydraulic and thermal testing of different helium cooled

irradiation rig models for the IFMIF High Flux Test Module *Fusion Eng. Des.* **104** 71–75

[46] Schwab F., Arbeiter F., Klein C. and Schlindwein G. 2017 Manufacturing of the IFMIF HFTM double compartment prototype *Fusion Eng. Des.* **124** 1068–72

[47] Klein C., Arbeiter F., Schlindwein G. and Schwab F. 2017 Steady state and transient thermal-hydraulic performance of the IFMIF-HFTM irradiation rigs and container with modeling of nuclear heating *Fusion Eng. Des.* **124** 969–74

[48] Brañas B. *et al* 2024 TRL analysis of IFMIF-DONES *Fusion Eng. Des.* **202** 114328

[49] Ortwein R., Kotula J., Wiacek U., Swierblewski J. and Bocian D. 2021 Hydraulic analysis of the start-up monitoring module (STUMM) for IFMIF-DONES *Fusion Eng. Des.* **171** 112601

[50] Ortwein R. and Wiacek U. 2023 Conjugated heat transfer analysis of the Start-Up Monitoring Module (STUMM) for IFMIF-DONES including heat generation mapping *Fusion Eng. Des.* **188** 113451

[51] Wiacek U. *et al* 2025 STUMM – monitoring module for DONES neutron source – technical challenges *Fusion Eng. Des.* **216** 115125

[52] Rapisarda D., Vermeeren L., García Á., Cabellos Ó., García J.M., Ibarra Á., Gómez-Ros J.M., Mota F., Casal N. and Queral V. 2011 Study on the response of IFMIF fission chambers to mixed neutron-gamma fields: PH-2 experimental tests *Fusion Eng. Des.* **86** 1232–5

[53] Federici G. 2023 Testing needs for the development and qualification of a breeding blanket for DEMO *Nucl. Fusion* **63** 125002

[54] Arena P. *et al* 2021 The DEMO water-cooled lead–lithium breeding blanket: design status at the end of the pre-conceptual design phase *Appl. Sci.* **11** 11592

[55] Zhou G. *et al* 2024 BLUME: a blanket functional materials module for the helium cooled pebble bed breeding blanket in IFMIF-DONES *Int. Conf. on Radiation Applications, RAP* (*Granada, Spain*, *10–12 June 2024*) (https://doi.org/10.5445/IR/1000172206)

[56] Mota F., Casal N., García A., Mas A., Vila R., Molla J. and Ibarra A. 2013 Neutronics study for the installation of the LBVM in the medium flux area of IFMIF *Fusion Eng. Des.* **88** 233–42

[57] Khanchych K. and Schroer C. 2023 Compatibility of EUROFER97 and lead–lithium eutectic *Nucl. Mater. Energy* **37** 101527

[58] Mas A., Mota F., Casal N., García A., Rapisarda D., Arroyo J.M., Molla J. and Ibarra A. 2014 Preliminary design of the Neutron Spectral Shifter that is dedicated to the IFMIF Liquid Breeder Validation Module *Fusion Eng. Des.* **89** 1728–33

[59] Konobeyev A.Y., Korovin Y.A., Pereslavtsev P.E., Fischer U. and von Möllendorff U. 2017 Development of methods for calculation of deuteron-lithium and neutron-lithium cross sections for energies up to 50 MeV *Nucl. Sci. Eng.* **139** 1–23

[60] Schnabel G., Capote R. and Trkov A. FENDL-3.1d: fusion evaluated nuclear data library Ver.3.1d (available at: www-nds.iaea.org/fendl/)

[61] Palermo I. personal communication (CIEMAT)

[62] Simone N. personal communication (ENEA)

[63] Fernández-Berceruelo I., Palermo I., Urgorri F.R., García Á., Rapisarda D., Moya L., Rueda F., Alonso D. and Ibarra Á. 2021 Alternatives for upgrading the EU DCLL breeding blanket from MMS to SMS *Fusion Eng. Des.* **167** 112380

[64] Rapisarda D., Fernández-Berceruelo I., García A., García J.M., Garcinuño B., González M., Moreno C., Palermo I., Urgorri F.R. and Ibarra A. 2021 The European Dual Coolant Lithium Lead breeding blanket for DEMO: status and perspectives *Nucl. Fusion* **61** 115001

[65] Moro F. *et al* 2021 Nuclear performances of the water-cooled lithium lead DEMO reactor: neutronic analysis on a fully heterogeneous model *Fusion Eng. Des.* **168** 112514

[66] Barucca L., D'Alessandro A., Burlando A. and Traverso A. 2024 The new layout and regulation of the 'pulsating' power conversion system of EU DEMO WCLL for an effective and safe control of pulse-dwell transitions and increase in plant efficiency *Nucl. Fusion* **64** 086070

[67] Arbeiter F., Abou-Sena A., Chen Y., Freund J., Klix A., Kondo K. and Vladimirov P. 2013 Preliminary dimensioning of the IFMIF Tritium Release Test Module *Fusion Eng. Des.* **88** 2585–8

[68] Kondo K., Abou-Sena A., Arbeiter F., Brand J., Fischer U., Große D., Klix A. and Lu L. 2014 Neutronic analysis of the IFMIF Tritium Release Test Module Based on the EVEDA design *Fusion Sci. Technol.* **66** 228–34

[69] Leys O., Leys J.M. and Knitter R. 2021 Current status and future perspectives of EU ceramic breeder development *Fusion Eng. Des.* **164** 112171

[70] Arbeiter F. 2021 Supplementary document #2 to the deliverable report of D8.3–2 (Report on the conceptual design of other irradiation module for DONES): design description document of the *in-situ* ceramic breeder irradiation module, project DONES-Prep (European Commission)