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Special Topic

The IFMIF-DONES project: preliminary engineering design

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Abstract

The need of a neutron source for the qualification of materials to be used in future fusion power reactors has been recognized in the European Union (EU) fusion programme for many years. The construction and exploitation of this facility is presently considered to be critical to the construction of the DEMOnstration Power Plant (DEMO). This issue has prompted the EU to launch activities for the design and engineering of the International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source (IFMIF-DONES) facility based on and taking profit of the results obtained in the Engineering Validation and Engineering Design Activities (IFMIF/EVEDA) project, presently conducted in the framework of the EU–Japan Bilateral Agreement on the Broader Approach to Fusion.

These activities and research and development work for the IFMIF-DONES plant are presently taking place in the framework of a work package of the EUROfusion Consortium, in direct collaboration with the Fusion for Energy organization. The main objective of these activities is to consolidate the design and underlying technology basis in order to be ready for the start of the IFMIF-DONES construction as early as possible.

In this paper, an overview and the present status of the IFMIF-DONES engineering design is presented for a generic site, making emphasis on the recent design evolution from previous phases.

Keywords: high-intensity neutron source, accelerator technology, liquid metals technology, fusion materials

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

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Introduction

A fusion-relevant neutron source is a more than three-decades-long pending step for the successful development of fusion energy. In DEMO, like in future fusion power plants, the deuterium–tritium nuclear fusion reactions will generate neutron fluxes in the order of ~(1–5) $\times$ 10^{18} m^{-2} s^{-1}, with a peak energy of 14.1 MeV that will collide with the reactor first wall. Its in-vessel components (first wall, breeding blankets, divertor, diagnostics systems, etc), a complex combination of layers of different materials that aim at maximizing the conversion of neutrons into thermal energy and breeding tritium, will be the worst exposed, undergoing potentially >10 displacement per atom (calculated by the NRT model [1]) per year of operation [2, 3]. Safe design, construction, and licensing of a nuclear fusion facility by the corresponding nuclear regulatory agency will demand an understanding of the materials degradation under the neutron bombardment during the lifetime of the fusion reactor. The radiation-exposed components must withstand the severe operational conditions without significant impact on their dimensional stability or their mechanical and physical properties, together with the low presence of long-lived activation-prone constituent isotopes and moderate decay heat [4]. This needs to be demonstrated through material irradiations in a suitable neutron source facility under fusion-relevant conditions.

DONES will be a relevant neutron source which can provide such conditions as anticipated for DEMO. It will generate a neutron flux with a broad energy distribution covering the typical neutron spectrum of a (D–T) fusion reactor. This is achieved by utilizing Li(*d*,*xn*) nuclear reactions [5] taking place in a liquid Li target when bombarded by a deuteron beam with a beam footprint between 200 mm $\times$ 50 mm and 100 mm $\times$ 50 mm. The energy of the deuterons (40 MeV) and the current of the accelerator (125 mA) have been tuned to maximize the neutron flux (up to ~5 $\times$ 10^{18} m^{-2} s^{-1}) to get irradiation conditions comparable to those in the first wall of a fusion power reactor, at a volume of around 0.5 l, that can house around 1000 small test specimens.

The journey to achieve the current maturity of such a high-power neutron source has been long and winding [6]. The seminal proposal towards a fusion-relevant neutron source based on Li(*d*,*xn*) nuclear reactions was published in 1976 [7]. The US Fusion Materials Irradiation Test (FMIT) facility [8] produced the first experimental evidence of the feasibility of the concept. After FMIT's early termination in 1984, the International Energy Agency (IEA) fostered a series of meetings, at the end of which consensus was attained within the materials scientist community to endorse FMIT's Li(*d*,*xn*) concept [9]. Subsequently, a coordinated international program was conducted on the design of the International Fusion Materials Irradiation Facility (IFMIF) under the IEA Fusion Materials Implementing Agreement. This activity resulted in a report on the IFMIF conceptual design, issued in 1996 [10], followed by a comprehensive design report [11] in 2004.

The IFMIF Engineering Validation and Engineering Design Activities (EVEDA) project, under the Broader Approach Agreement between Japan and EURATOM, was approved in 2007 concurrently with the ITER Agreement. The mandate was to produce an integrated engineering design of IFMIF as well as the data necessary for future decisions on its construction, operation, exploitation, and decommissioning, and to validate the continuous and stable operation of key IFMIF systems. The engineering design activities were accomplished on schedule with the release of its Intermediate Engineering Design Report (IIEDR) in June 2013 [12, 13].

In parallel, for validating the developed design features, prototyping sub-projects were carried out which consist of the design, manufacturing, and testing of the following prototypical systems [14, 15]:

- An accelerator prototype (LIPAc) at Rokkasho, cloning IFMIF components up to its first superconductive accelerating stage (9 MeV energy, 125 mA of D^{+} continuous wave current). Successive commissioning of the accelerator systems started in November 2014, and is planned to be completed by integral commissioning and operational testing by March 2020. Results obtained up to now confirm that no significant obstacle can be identified in relation to the accelerator operation [16].
- The EVEDA lithium test loop at Oarai, integrating all elements of the IFMIF Li target facility, was commissioned in February 2011. The test program was completed in 2014 with the successful proof of the long-time stability of the liquid lithium jet forming the target [17], and complemented by corrosion experiments performed at a Li loop (Lifus6) in Brasimone [18].
- The high flux test module (HFTM) : two different designs to accommodate either reduced activation ferritic martensitic steels [19] or SiC [20]—with a prototype of the capsules housing the small specimens irradiated in the BR2 fission reactor of SCK-CEN Belgian Nuclear Research Center at Mol and successfully tested in 2015 under IFMIF design conditions in the cooling helium loop Helium Loop Karlsruhe (HELOKA) of KIT, Karlsruhe [19, 21]; complemented with the full-scale Creep Fatigue Test Module [22] manufactured and tested at Paul Scherrer Institut (PSI), Villigen.

The roadmaps towards fusion power developed in different countries commonly foresees the construction of two fusion machines before the industrial prototypes: ITER and DEMO. It has also been recognized that material development and validation under irradiation are not only of the highest importance for economic success but are critical to the early use of fusion power. As a consequence, IFMIF, or an equivalent neutron source, is also considered an indispensable element of international roadmaps to fusion power.

The European Fusion Roadmap [23] is based on the objective of attaining electricity production from fusion reactors by approximately the middle of the century, speeding up the design and construction phase of DEMO (foreseen to be started around 2040) and, at the same time, reducing the neutron dose requirements of the materials. Thus, an initial DEMO phase is foreseen with a maximum dose around 20 dpa for components integration testing, and a second DEMO phase with a maximum dose around 50 dpa [24].

In this way, the requirements for the early phase of the neutron source are significantly reduced, opening the possibility of a staged approach to IFMIF in which its construction can be developed in phases—the first one focused only on DEMO needs, which in turn gives rise to the IFMIF-DONES project [25]. This staged approach will allow a wider distribution of the required investments over time as well as some relaxed specifications for the neutron source design.

The idea of a possible extension of the scientific objectives of the IFMIF-DONES facility has been also considered. A number of scientific cases for complementary research have been identified in different domains including applications of medical interest, nuclear physics and radioactive ion beam facilities, basic physics studies, and industrial application of neutrons [26].

This has become the reference approach in Europe. A specific activity was started in 2015, under the framework of the EUROfusion Consortium Workprogram, with the objective to develop the design of the DEMO-oriented irradiation facility up to such a level that it is ready for the start of construction as early as 2020.

In this paper, the present status of the IFMIF-DONES engineering design, completed for a generic site, is described. This is a preliminary step required to move forward with the engineering design activities for a specific site and the subsequent construction activities planned to be started in the early 2020s.

1. Design description

1.1. Mission, user's specifications, and top-level requirements

A Specific Working Group was established in 2009 in the framework of the IFMIF/EVEDA project in order to update the user requirements for the IFMIF. The results of the study, defining the requirements for IFMIF with justifications from the user´s point of view, were summarized and published in 2011 [27]. The assessment of the role of IFMIF and its expected contribution to the fusion roadmap upon which this study was based holds independently of the detailed definition of DEMO and the time scale, and thus is still valid for IFMIF-DONES though specific values may be subject to change.

The mission of IFMIF-DONES is therefore to provide a neutron source producing high-energy neutrons at sufficient intensity and irradiation volume in order to:

- Generate materials irradiation test data for design, licensing, construction, and safe operation of the fusion demonstration power reactor (DEMO), with its main characteristics as defined by the EU Roadmap [23] under a simulated fusion environment relevant to anticipated needs in radiation resistance for the structural materials in DEMO.
- Generate a data base for benchmarking of radiation responses of materials hand in hand with computational material science.

The consideration of ITER needs regarding irradiation materials during the IFMIF-DONES plant operation shall be also assessed in the future.

From this mission, a set of top-level requirements for IFMIF-DONES flows down as per the following:

- *Neutron spectrum:* Should simulate the first wall neutron spectrum of early DEMO as closely as possible so as to provide the same nuclear responses, which affect the material behavior under irradiation in terms of primary knock-on atom spectrum (PKA), important transmutation reactions, and gas production (He, H). This implies use of the D-Li stripping source.
- *Neutron fluence accumulation in the high-flux region*: neutron flux and temperature gradients in high flux region. Neutron fluences corresponding to a damage level of 20–30 dpa (NRT) in $<$ 2.5 years applicable to 0.3 liter volume and neutron fluences corresponding to a damage level of 50 dpa (NRT) in $<$ 3 years applicable to 0.1 liter volume.
- *Temperature range*: The high-flux region needs to be equipped with temperature-controlled test modules that can cover temperature ranges from at least 250 °C to 550 °C (based on the expected temperature design window for EUROFER materials, to be used as the main structural material for DEMO design).
- *Dpa and temperature gradients in high-flux region*: Over a gauged volume corresponding to standardized miniaturized specimens, dpa gradient $<$10% and temperature gradient within $\pm$3% with the long-time stability of the same order.
- *Lifetime of Plant*: IFMIF-DONES plant should be designed for 30 years of lifetime.
- *Accessibility*: Good accessibility of irradiation volume for experimentation and instrumentation.
- *Capacity of material characterization*: Adequate tools to allow the materials characterization in external laboratories should be made available.

1.2. Plant configuration

The DONES plant is defined to provide an accelerator-based D-Li neutron source to produce high-energy neutrons at sufficient intensity and irradiation volume to simulate as closely as possible the first wall neutron flux and spectrum of future nuclear fusion reactors.

The plant will produce a 125 mA deuteron beam, accelerated up to 40 MeV and shaped to have a nominal cross-section in the range from 100 mm × 50 mm to 200 mm × 50 mm, impinging on a liquid lithium target 25 mm thick and 260 mm wide, cross-flowing at about 15 m s^{-1} in front of it. The stripping reactions generate a large number of neutrons that interact with the material samples located immediately behind the lithium target in the test modules.

The main features of the IFMIF-DONES plant and the modifications with respect to the IFMIF design configuration are as follows:

- Only one accelerator is considered, but the angular configuration is maintained in such a way that a later upgrade to a two-accelerator layout could be feasible.

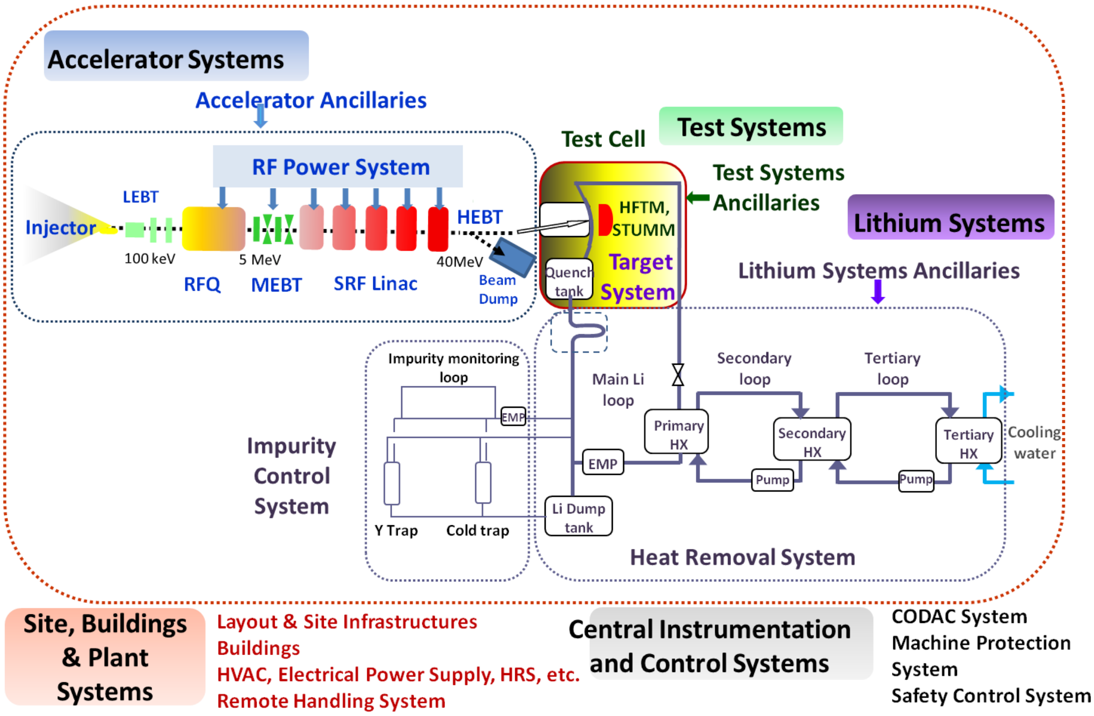

Figure 1. IFMIF-DONES facility schematic plant configuration.

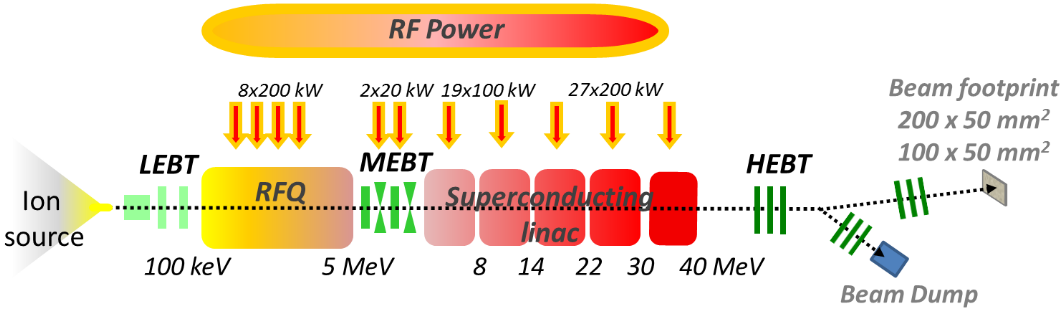

Figure 2. IFMIF-DONES accelerator systems configuration schema.

- The radiofrequency system is based on the solid-state amplifiers operating at 175 MHz in order to assure high-reliability operation.
- The liquid target of lithium will flow at a speed of 15 m s^{-1} nominal, as in IFMIF. The first approach is that the lithium target will have the same physical dimensions as that of IFMIF.
- The test cell (TC) will house the lithium target and the test module as well as the lithium quench tank (QT), which will be larger than the IFMIF one. It should be able to manage the full IFMIF power.
- IFMIF-DONES will be designed preferably aiming to provide high-flux irradiations of structural materials. Therefore, the current approach is that the HFTM will be the only irradiation module present in the TC, with an enlarged thickness as compared to the IFMIF IIEDR configuration to gain additional irradiation volume. In addition, the HFTM could be backed by a neutron reflector to improve its nuclear performance and reduce the radiation to the TC wall. Other irradiation modules or experiments could be included as well as a result of additional needs identified in the future.
- Unlike the IFMIF plant, where one beam footprint of $20 \times 5\,cm^2$ was foreseen, IFMIF-DONES systems (HEBT, lithium target, HFTM, etc) should be able to handle different footprints. The objective is to cover a range from 10×5 to $20 \times 5\,cm^2$.

Figure 1 depicts a schematic view of the current configuration of the IFMIF-DONES plant.

The IFMIF-DONES product breakdown structure (PBS) identifies five major groups of systems (PBS level 1): (1) the site building and plant systems, (2) the test systems, (3) the lithium systems, (4) the accelerator systems, and (5) the central instrumentation and control systems. The PBS is used as the reference structure of all engineering design documents of IFMIF-DONES plant.

1.3. Accelerator systems

The IFMIF-DONES accelerator is a sequence of acceleration and beam transport stages. A schematic accelerator configuration is depicted in figure 2.

A CW 140 mA deuteron beam is produced and extracted from an electron cyclotron resonance ion source at energy of 100 keV.

Table 1. Distribution of cavities and solenoid packages in the present IFMIF-DONES reference design.

Cryomodule	#1	#2	#3	#4	#5
Number of cavities	1×8	$2 \times 5 + 1$	$2 \times 4 + 1$	$2 \times 4 + 1$	$2 \times 4 + 1$
Number of solenoid packages	1×8	1×6	1×5	1×5	1×5
Cryomodule length (mm)	5866	6681	6736	6736	6736
Output energy (MeV)	8.3	13.9	22.3	30.3	40.0

Table 2. Main parameters of the IFMIF-DONES accelerator systems.

Parameters	Target Value	Comment
Particle type	D^+	H^+ for testing (avoids activation)
Accelerator type	RF Linac	175 MHz, 5 MeV RFQ followed by two re-bunching cavities and a 5–40 MeV, 175 MHz SRF Linac
Number of accelerator	1	Upgradable to 2
Output current	125 mA	Upgradable to 2×125 mA
Beam distribution	rectangular flat top with edges shaped	From 10 to 20 cm horizontal $\times$ 5 cm vertical (reference configuration 20×5)
Output energy	40 MeV	User requirement
Output energy dispersion	$\pm$0.5 MeV FWHM	Target requirement
Duty factor	CW	Pulsed tune-up and startup
Maintainability	Hands-on as far as reasonably achievable	For accelerator components up to the final bend in HEBT, with local shielding as required; design not to preclude capability of remote maintenance.
Design lifetime	>30 years	20 years of operation
Overall duty factor	100%	Possibility of pulsed operation
Short pulses	$\leqslant$1 ms Pulse Width	10 Hz maximum pulse repetition frequency
Long pulses	>1 ms	1 Hz/maximum duty cycle 50%

A low-energy beam-transport section guides the deuteron beam from the source to a radiofrequency quadrupole (RFQ) system. The RFQ bunches the beam and accelerates the full 125 mA current to 5 MeV. The RFQ output beam is injected through a medium-energy beam transport (MEBT) with two rebunching cavities and then transferred to a superconducting radiofrequency (RF) Linac, where it is accelerated to a final energy of 40 MeV. Finally, a high-energy beam-transport (HEBT) line guides the beam up to the target and, at the same time, shapes the beam to a rectangular shape with the help of non-linear magnet elements. The HEBT also includes a beam dump devoted to stopping the beam during some specific commissioning and startup phases.

Based on the results of the latest beam-dynamics analysis, the superconducting RF Linac will consist of five separate cryomodules which house superconducting cavities and solenoids with characteristics as given in table 1. All the accelerating RF cavities are powered by a radiofrequency system based upon use of 175 MHz high-power solid-state amplifiers with a CW output power level up to 200 kW. A total of around 54 such amplifiers are needed (one for each accelerating cavity and an additional eight for powering the RFQ). Additionally, the MEBT is powered by two smaller solid-state amplifiers rated at 20 kW CW. The main parameters of the IFMIF-DONES accelerator system are described in the table 2.

1.4. Lithium systems

The lithium systems are broken down into several subsystems according to their functions, as per figure 3.

The target system consists of the components situated in the test cell and the beam ducts up to the target interface room (TIR). The system shapes the lithium target and positions it inside the test cell with respect to the beam and the high-flux test module. The main component is the target assembly (TA), which includes the concave-shaped open channel (backplate) exposed to the accelerator vacuum, presenting a stable lithium jet to the beam in which the kinetic energy of the deuteron beam is deposited and where neutrons are produced.

The heat-removal system comprises the main Li loop and its dump tank, recirculating the lithium between the TA and a heat exchanger; and a secondary and a tertiary oil loop transferring the heat to the plant's general cooling water system. The system is designed to evacuate the heat deposited in the target and to control and maintain a constant lithium temperature at the TA inlet, irrespective of the beam power. All oil loops contain a branch line to bypass the heat exchangers and control the Li temperature.

The impurity control system consists of a branch line which extracts a fraction of the lithium from the main loop and reinjects it after purification and impurity analysis. The system is designed to condition the lithium after maintenance prior to startup, and control and maintain a defined level of purity. The purification branch contains cold traps to remove elements with temperature-sensitive solubility in lithium (mainly C, O, and metallic impurities mostly related to corrosion and activation products as binary or ternary compounds), and the hydrogen traps to remove hydrogen isotopes by chemical reaction with hydrogen-binding material (presently Ytria). It is also planned to maintain nitrogen content at a low-enough

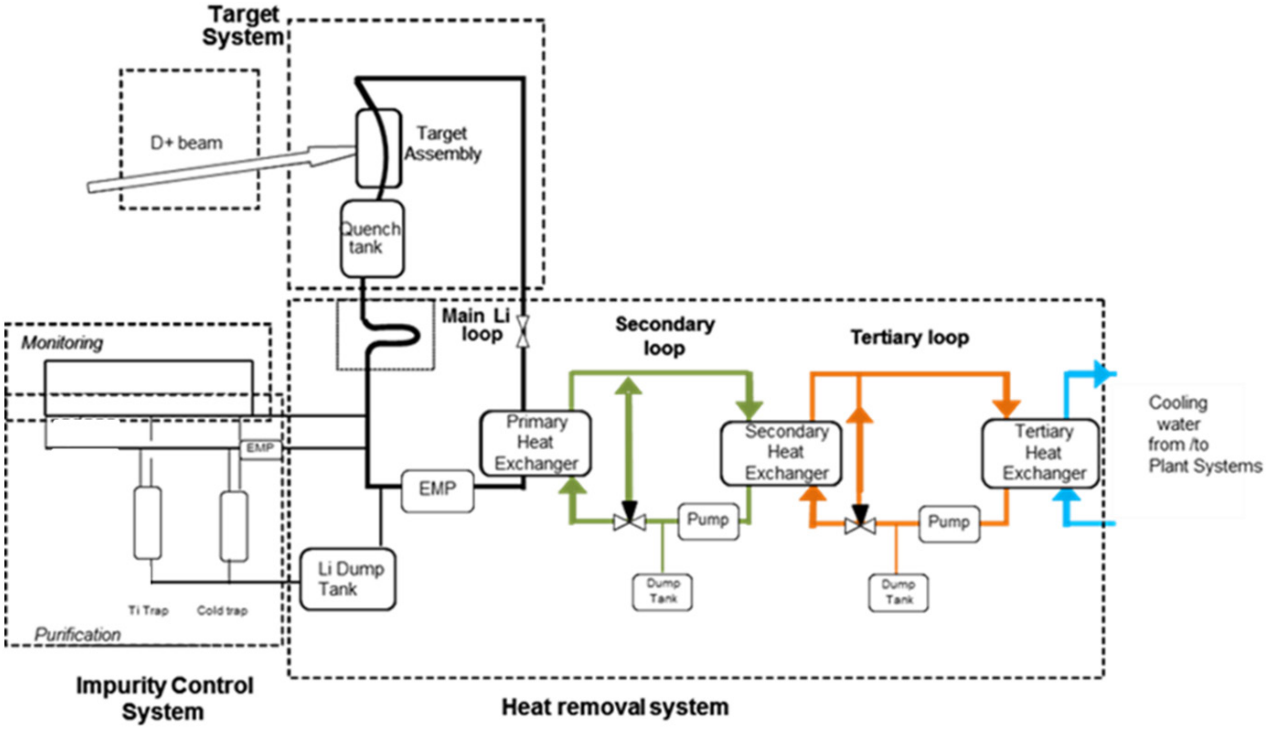

Figure 3. Basic configuration of the lithium systems.

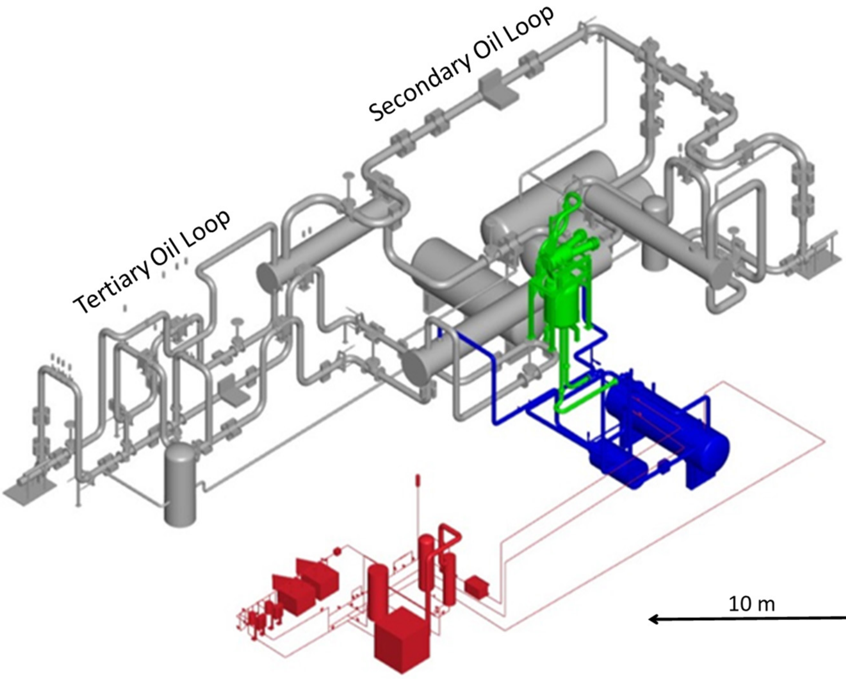

Figure 4. Expanded view of the IFMIF-DONES Li systems including target system (green), Li loop (blue), heat removal oil loops (gray), and impurity control system (red).

concentration (in the range of 30 ppm) by installing a nitrogen-binding material (presently titanium) inside the Li loop dump tank to be used during the maintenance operations.

Lastly, the gas and vacuum, heating, electric power supply, and Li and oil recovery system make up the so-called lithium systems ancillaries.

Figure 4 shows an expanded view of the complete lithium systems.

1.5. Test systems

The test systems form the core of the plant, and include the systems required to accommodate a HFTM under controlled environment and conditions for irradiation, as well as the systems required for handling the HFTM and transporting the irradiated HFTM for further external processing and post-irradiation experiments. A set of ancillary systems provides

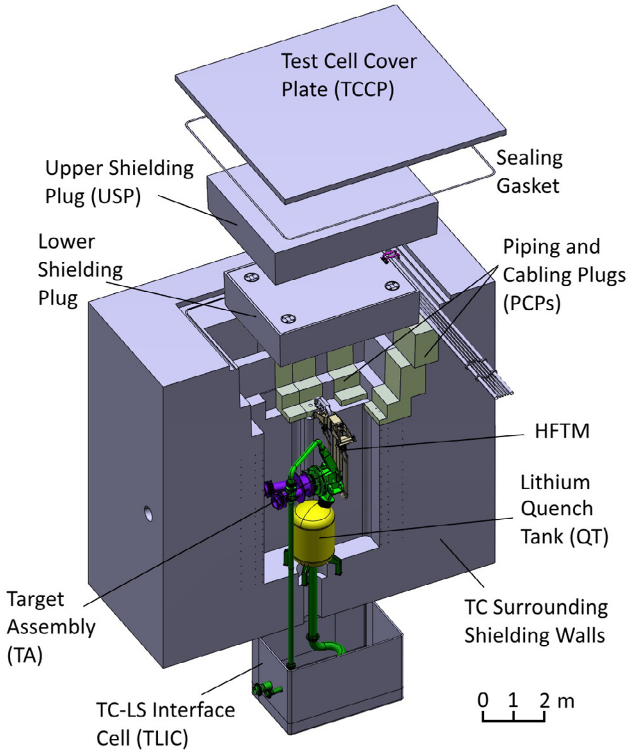

Figure 5. Expanded view of the IFMIF-DONES test cell [28]. Reprinted from [28], Copyright 2018, with permission from Elsevier.

the electrical distribution, cooling, vacuum, and supply and purification of gases.

The test cell (depicted in figure 5) is the closed cavity or chamber for housing the lithium target assembly, lithium quench tank, and HFTM. At the top, two shielding plugs are designed to close the TC during the irradiation period for protecting the access cell (AC), which is located directly above the TC, from radiation. A test cell cover plate (TCCP) and a rubber-based sealing gasket are applied to tighten the TC so that a controlled atmosphere inside the TC can be achieved. Gas pressure in the TC is different in the different plant states, but during operation it will be around 200 mbar (main criteria is that slight underpressure is required in relation with the one in the target assembly).The internal surface of the TC concrete shielding walls is covered by a closed stainless steel liner to maintain the gas tightness and to protect the concrete from contacting with lithium in case of a lithium spill inside the TC. Removable piping and cabling plugs (PCPs) are designed to accommodate all of the cables and pipe penetrations, as well as to shield from gammas and neutrons. The major biological shielding includes the surrounding shielding walls, shielding top plugs, PCPs, and the TC floor between the TC and the lithium loop room. Below the TC floor, a test cell–lithium system interface cell (TLIC) is arranged to accommodate thermal compensation sections of the inlet and outlet lithium pipes [28].

The basic configuration of the HFTM is illustrated in figure 6, including one of its irradiation capsule assemblies which enclose hermetically the material specimen stacks to be irradiated in the test module. The capsules thereby are installed in the container in so-called compartment slots. To achieve the temperature control of the specimen stack in the irradiation capsules, each capsule is equipped with at least three heaters, and each heater is monitored by two thermocouples located inside the capsule (in an inner vertical tube close to the center). The electrical power supply for each heater of a capsule is selectable independently to the others. Furthermore, capsules are filled with Na (besides the samples under irradiation) in order to promote the heat transfer, and each capsule is also surrounded in each slot by an insulation gap whose dimensions depend on the temperature of the corresponding compartment (550 °C, 450 °C, 350 °C, and 250 °C). In addition to the heaters and the insulation gaps, each slot is surrounded by mini cooling channels. The foreseen coolant is helium at a pressure of 3.5 bar in the inlet. Very different specimen sets can be arranged in this configuration depending on the specific irradiation needs at each campaign. Typical proposals presently considered can be found in [29, 30].

A total of 24 capsules are installed in an 8×3 container (having a ~74 mm thickness in beam direction, three capsules in a row) or 32 capsules in a container 8×4 (~102.2 mm thickness in beam direction, four capsules in a row), and are grouped in a capsule set.

The container is supplied, as described previously, by helium to remove heat (nuclear and electrical) from the capsules. The container itself is mechanically fixed to the attachment adapter assembly, which is positioned inside the TC by the support-trusses assembly.

A dedicated startup monitoring module (STUMM) is foreseen to be used during the commissioning phase of DONES to characterize the neutron/gamma flux and spectrum, and to validate neutronics calculation models. The STUMM will be equipped with a wide set of instrumentation and positioned similarly to the HFTM as close as possible to DONES neutron source, i.e. just behind the lithium target backplate. Once the commissioning is completed, the STUMM will be replaced by the HFTM.

The mechanical design of the STUMM will be very close to that of the HFTM. It will be fully compatible with the design of the TC and the foreseen connections for others modules inside the TC.

The characteristics of the sensors to be used in the STUMM are dependent on the regime of work of the module; however, long radiation resistance and relatively low radiation sensitivity are required. On the other hand, since the module will be used in the commissioning phase, where different operation regimes are foreseen, the adapted sensors must be characterized by a wide dynamic range of sensitivity so as to allow detection and characterization of even small neutron fluxes. Most of the planned sensors are commercially available, but some of them will require ad hoc modifications for IFMIF-DONES application (such as microfission chambers). New solutions are also being considered.

Additionally, a collimated neutron beam facility which takes advantage of the neutron flux behind the HFTM has been incorporated into the IFMIF-DONES layout at this stage of the design. A dedicated experimental area has been planned behind the TC on the first floor of the IFMIF-DONES main building to accommodate a program of complementary experiments.

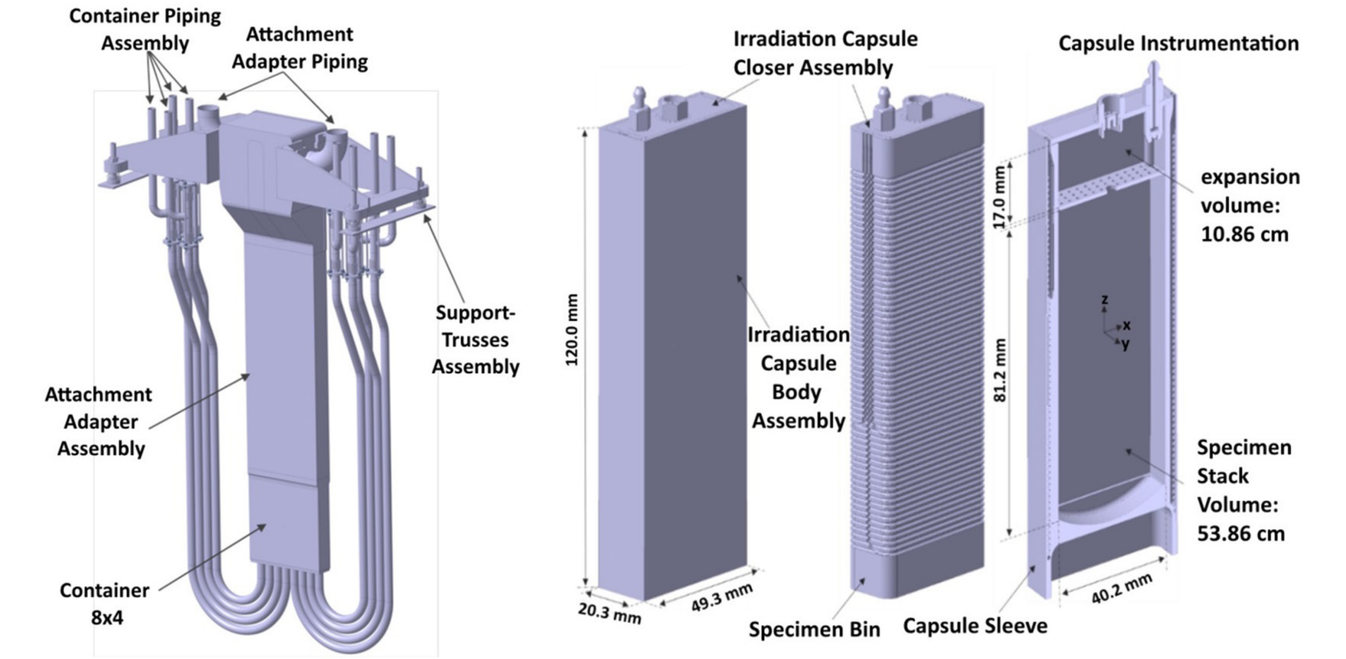

Figure 6. From left to right: high-flux test module, irradiation capsule with thin-walled sleeve, specimen bin with helix grooves for heater wires, cut of capsule assembly.

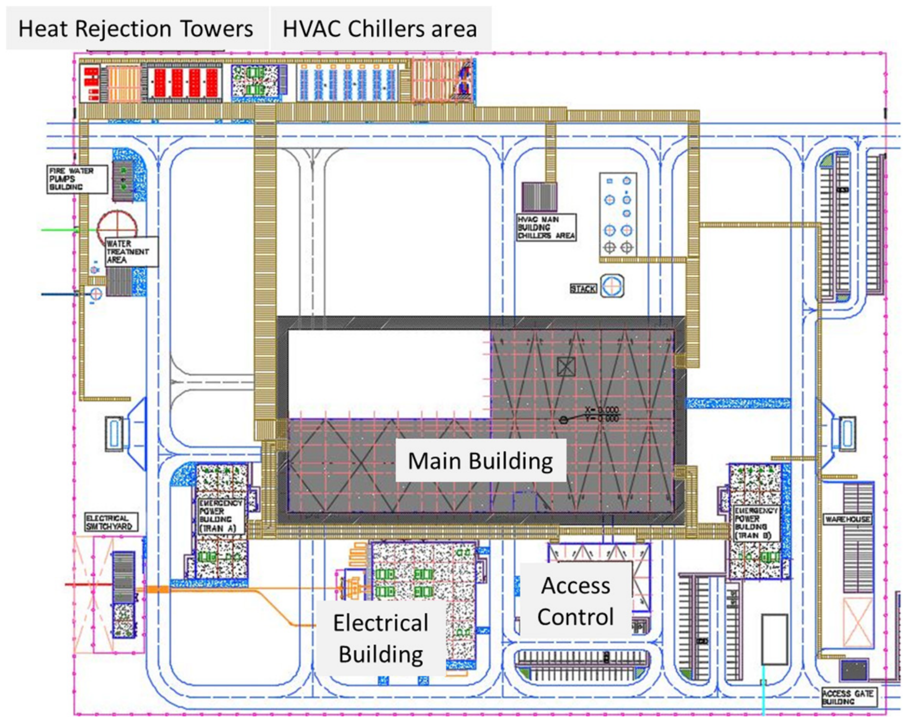

Figure 7. IFMIF-DONES site layout (only the most relevant buildings are emphasized).

1.6. Central instrumentation and control systems

The IFMIF-DONES instrumentation and control systems are designed with a hierarchical structure starting from the top level, the central instrumentation and control system (CICS), down to the local instrumentation and control systems level. The CICS consists of three systems: (1) control data access and communication (CODAC), (2) machine protection, and (3) safety control.

Each system at the central level is in a continuous, bidirectional communication with the corresponding one at the local level by means of dedicated instrumentation and control networks and/or buses: CODAC network, Interlock Bus network, and Safety network. At the local level, the instrumentation and control is mainly given by a local controller with a set of sensors and actuators.

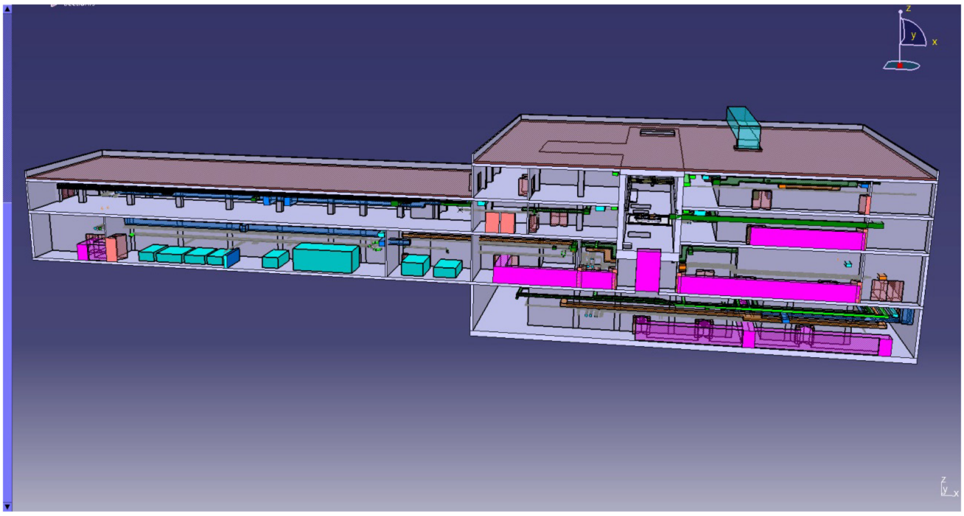

Figure 8. Cut-out view of the IFMIF-DONES main building. Accelerator systems are located in the left side of the figure (blue boxes). Lithium systems are located on the lower floor and test systems are mainly located on the second floor, on top of the lithium systems. Some key paths for the movement of big components inside the facility are also indicated (pink color).

Each of the three control systems (CODAC, machine protection, and safety control) is composed of several independent subsystems.

1.7. Site, building, and plant systems

The IFMIF-DONES plant configuration and the design of the layout, buildings, and site infrastructure have been optimized based upon the requirements and assumptions made for the entire plant and for each of its main systems. It is assumed that IFMIF-DONES will not require long-term storage of solid and liquid radioactive waste, and therefore these wastes shall be taken out to an external storage facility.

The site layout (figure 7) consists of a usable, rectangular-shaped surface area of around 10 hectares. The main building is erected at its center, and it is directly connected to the adjacent access control building, in front of which a small parking area exists. The main electrical building is placed very close to the main building to facilitate the routing of cabling. Connected to the main building through service galleries and distributed all along the perimeter of the site, the different services areas are laid out as follows: transformer area, electrical switchyard area, emergency power building, fire water area, industrial water area, warehouse, cooling towers area, etc. At the bottom right corner of the site, the administration building and another parking area are erected.

The overall dimensions of the main building are 158.9 m $\times$ 74.75 m (figure 8), and it is a four-story building. Additionally, it has one basement level occupying only a reduced area of the total footprint of the building. In general terms, it can be divided into two different parts: accelerator and irradiation areas. The building has a basement/foundation slab (EL.$-$18.000), three suspended floors at different elevations (EL.$-$9.000 m, EL.$+$0.000 m, EL.$+$6.000 m), and one additional roof slab (EL.$+$12.000 m). There are different stairwells with elevators for both material and personnel, evenly distributed throughout the building. The building structure lies above a stepped foundation slab that carries all the loads of the building to the ground. The main structural system of the building is formed by a combination of bearing walls, columns, suspended slabs, and beams, all of them *in situ* cast with concrete. Some bearing walls have, in addition to the structural role, other safety functions such as confinement barriers and/or shielding protection.

The IFMIF-DONES plant systems include the following services: (1) heating, ventilation and air conditioning system (both industrial and nuclear); (2) heat rejection system; (3) electrical power system; (4) service water and gas systems; (5) radiation waste treatment system (including both solid and liquid waste as well as a gas radioactive waste treatment system); and (6) fire protection system.

2. Design integration and plant-level analysis

2.1. Safety objectives and approach

High deuteron reaction rates and secondary neutron fluxes lead to production of radioactive products with different degrees of mobility, such as tritium, beryllium, and argon, which are locally transported by the facility subsystems. In addition, the high neutron fluxes themselves mean a radiation risk in some parts of the facility. As a consequence, IFMIF-DONES will be a first-class type radioactive facility requiring application of a complete and efficient package of safety principles in the design phase to prevent harm to employees, the public, and the environment, both from radiation and conventional threats. Therefore, IFMIF-DONES has formally adopted the following project-wide general safety objectives:

- To protect individuals, society, and the environment from harm arising from the construction, operation, and decommissioning of the IFMIF-DONES facility.
- To ensure that in normal operation, exposure of personnel to hazards within the facility is controlled, kept within prescribed limits, and minimized.
- To prevent accidents with high confidence.

- To ensure that any abnormal operational event has minimal consequences for IFMIF-DONES personnel and for the public.
- To minimize the hazardous waste arising from the operation and decommissioning of IFMIF-DONES, both in its quantity and level of potential hazard.

These overarching goals will guide IFMIF-DONES through all phases of its multi-decade life cycle. They apply to all aspects of safety at the facility, including radiation, cryogenics, chemicals, heavy loads, and other hazardous items or situations. The security systems of the facility will be designed to meet basic in-house security needs such as deterrence of theft and vandalism, and to comply with regulatory requirements, while also taking into account the need for users and personnel to work in an open and friendly atmosphere.

Regulatory approval by the national safety authority where IFMIF-DONES will be built must be obtained before starting the facility construction and operation, which will be classified according to national legislation. This also means that specific mandatory documentation must be provided for safety demonstration.

However, before a site is selected, top-level international guidance as to general plant safety requirements is being followed from institutions such as IAEA, ICRP, and Euratom. Additional standards from European, American, and other countries are being followed based on their wide acceptance in the international community. Additional Euratom directives, United States Department of Energy standards and guidelines, International Organization for Standarization or International Electrotechnical Commission standards, etc, are used for application to relevant systems, organization of design, and development of analyses according to the specific features of IFMIF-DONES. Plant safety requirements, standards, and norms to be followed during design activities are presently collected in the General Safety Guidelines document, which also provides a full scope of the safety approach applied in IFMIF-DONES design phase.

The general safety approach in IFMIF-DONES is summarized as follows:

- A broad set of general and specific safety criteria and requirements are adopted to ensure that safety objectives are met.
- An important example of adopted criteria is that stringent dose-rate values for the worker and the public are established for several plant conditions, from normal operation to very-low-probability situations.
- Consideration of internal and external events in design basis analysis is another important example of the general safety criteria. Systematic failure mode and effect analyses are performed for all systems in the facility. Postulated initial events are screened and reference accident scenarios are identified for deterministic analysis and demonstration of compliance with dose limits.
- Safety functions are defined as necessary to accomplish the preceding criteria. 'Confinement of radioactive materials' and 'limitation of exposure' are the top-level implemented safety functions, while additional supporting safety functions are provided.
- The 'confinement of radioactive material' function is mainly developed according to ISO standards, which essentially works out the concept of dynamic confinement and provision of several layers of containment under specifications of chained subpressure levels in atmosphere. In addition, due to the mobility characteristics of tritium (permeation, etc), nominal and emergency vent detritiation systems will be implemented for operation under nominal conditions and hypothetical design basis accidents.
- An important chapter linked to the 'limitation of exposure' safety function is that systematic shielding analysis of structures is performed. Design of building walls and local shieldings are proposed in coherence with a radiological classification of rooms and in support of occupational radiation exposure optimization, which is estimated and reviewed in iterative efforts. Efforts are being made to reasonably minimize exposure to radiation even when it falls below prescribed dose limits.
- Structures, systems, and components potentially involved in accidents are identified and then classified according to 'safety class' degrees depending on their impact on accident initiation, limitation, or progression. System requirements are then adopted and demonstrated to apply in support of licensing studies.
- The environmental impact is considered under application of the prevention and minimization principles in processes concerning waste generation, management, processing, and disposal, as well as in operational and decommissioning phases, including the objective of a negligible impact of effluents.
- Additional well-established safety principles such as 'defense in depth', several layers of confinement barriers, and ALARA optimization are generally applied in design activities.

2.2. Reliability, availability, maintainability, and inspectability (RAMI)

IFMIF-DONES is conceived as an irradiation facility with the final objective of producing the material database in due time according to DEMO needs. In that sense, IFMIF-DONES will be a damage (dpa) production facility with a very demanding operation schedule. Therefore, proper performance in terms of reliability and availability is essential for the IFMIF-DONES mission. As a user's facility, IFMIF-DONES is designed to be flexible, and the final performances will depend also on the definition of the irradiation program. Moreover, the availability needs of IFMIF-DONES are fully linked to the fusion roadmap and may vary according to the definition of the fusion program.

In particular, the facility has to be designed for high availability, and 70% (over the calendar year) is established as the horizon requirement for its engineering design. This requirement is established for the normal operation phase and no specific requirements have been established for other different

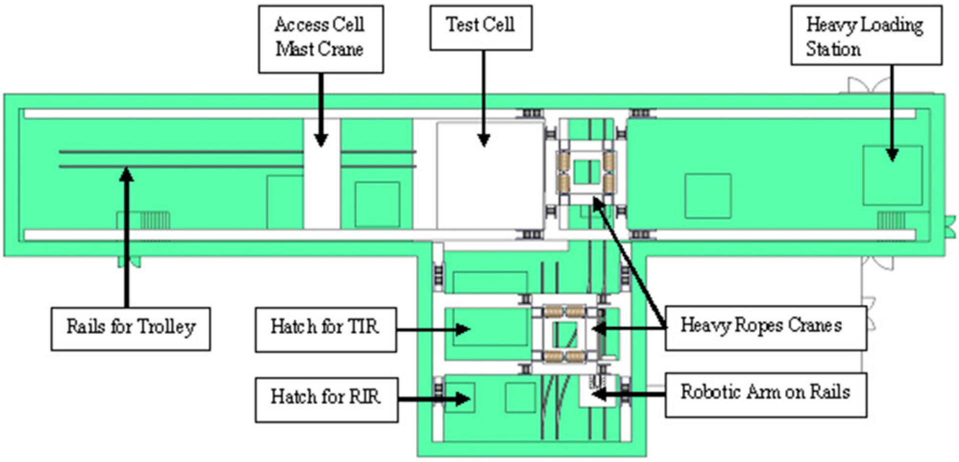

Figure 9. Top view of the access cell of IFMIF-DONES.

possible phases of IFMIF-DONES. Assuming a conservative approach, this availability goal is translated into a maximum inherent availability requirement[8] of 75% over the scheduled operation time. This imposes higher inherent availability requirements on the different IFMIF-DONES systems, such as 87% for the accelerator systems, 94% for the lithium systems, 96% for the test systems, 98% for the plant systems, and 98% for the central control systems based on the results obtained in IFMIF RAMI studies [31, 32].

The plant will operate on the basis of a 24 hours per day, 7 days per week cycle. Regardless of the detailed operation schedule, several principles can already be assumed:

- The DONES operation schedule will be determined taking into account that it is part of the fusion roadmap, being directly coupled to the DEMO schedule. A minimum operational life (irradiation) of 20 years is assumed.
- Irradiation periods are limited by mechanical properties degradation in materials used in irradiation modules and target assembly, and the maintenance scenario. The IFMIF-DONES operation schedule will be created according to these constraints.
- A basic assumption of the maintenance strategy of the IFMIF-DONES plant is that the materials irradiated in a given period of time will not be required to be reirradiated.

The reference maintenance scheme is based on a yearly cycle with two scheduled maintenance periods: one short and one long preventive maintenance period. The long maintenance period (20 days) will be devoted to general maintenance of IFMIF-DONES, mainly for maintenance in the lithium systems and test systems, and for long-term accelerator maintenance. The short-term maintenance period (3 days) will be devoted to activities in the accelerator and other ancillary and conventional systems. This maintenance period includes also the replacement of ceramic disks of the ion source.

[8] The inherent availability is the probability that the system will operate satisfactorily for a given time defined without considering preventive maintenance downtime, logistics time, waiting, or administrative downtime; only corrective maintenance downtime is included.

The RAMI studies being conducted on the lithium and test systems have identified as the main sources of uncertainties the assumptions taken on the lifetime of the systems under analysis, maintenance strategy, failure rates database, Li loop process boundary, main electromagnetic pump, electromagnetic flow meter, impurity control system, and degraded operating mode assumptions.

In the case of the accelerator and plant systems, the main sources of uncertainties are: failure rates, the ventilation and decontamination systems, loss of power supply events, human factors, erratic alarms, fire, and other external hazards.

2.3. Logistics and remote maintenance

The DONES project consists of complex and heavy systems and components that need to be assembled and maintained on site. For several of these systems and components, it is required to perform maintenance, inspection, and monitoring tasks over many years in a hostile environment and in efficient, safe, and reliable manner. A systematic evaluation of the radiation and contamination environment in the different rooms and operational states has been developed in order to identify which activities will require remote handling (RH) during the maintenance tasks. DONES requires the use of advanced RH technologies to prevent human exposure to the high radiological activated environments and accomplish the stringent requirements as to plant availability. Based on the data available today coming from the engineering design, simulation activities, and the validation of some of the RH maintenance tasks to be performed, it is possible to say that both objectives can be achieved. In fact, the RH procedures implemented and the correspondent operations can be fully completed remotely, within the time frame allocated for the preventive maintenance of components. However, there are still experimental activities to be done to validate and prove the suitability of the overall RH procedures and the equipment developed.

Three main areas have been identified for the RH maintenance activities to be performed: the access cell, the lithium loop area, and the beam dump area.

Almost all RH maintenance activities for the IFMIF-DONES components will be performed in the AC. In fact,

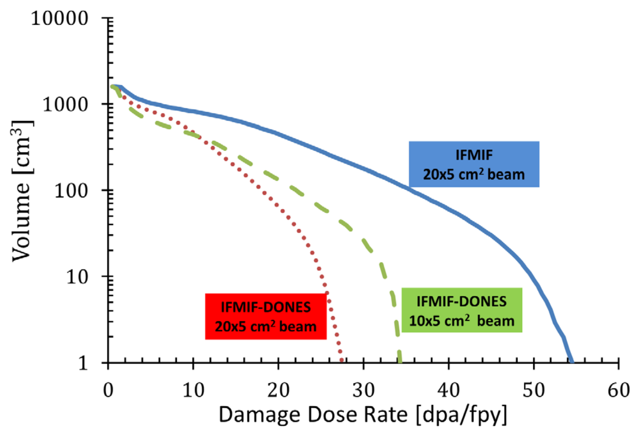

Figure 10. Available integrated irradiation volume versus damage dose rate (dpa fpy-1) for each beam condition considered (IFMIF and different IFMIF-DONES beam shapes).

critical components requiring RH are located inside of the test cell and in the target interface room such as the HFTM, the TA, and ancillary systems such as pipes, plugs, connectors, instrumentations, cooling system, supporting structures, and so on. An overview of the AC is given in figure 9.

The AC is located just above the TC, and above the room that houses the last components of the accelerator beam line (TIR room). It is designed to accommodate all the RH equipment and tools to be used during the RH maintenance tasks, and is sized to temporarily store all removable components, such as the test cell cover plate and the two TC top shielding plugs (USP and LSP) while the TC is open, as well as for the shielding plugs on the AC floor that connect to the rooms in the lower floor.

The main operations to be performed in this area are:

- Opening and closing of the TC including plugging/unplugging of electrical and cooling pipes connections.
- HFTM exchange and its transportation to the irradiating waste treatment cell for storage or dismantling.
- TA exchange and its transportation to the irradiating waste treatment cell for storage or dismantling.
- TIR components replacement such as vacuum pumps, valves, bellow, collimator, and diagnostics.

In addition, as an exception, RH operations on other components could be required, such as the exchange of the following:

- Interface shielding plugs (ISP) for the lithium inlet and outlet pipes.
- Steel liner of the TC.
- Cooled walls of the TC.
- The five PCPs.
- TA support structure.
- Quench tank.

The main RH equipment located in the AC are:

- Two heavy rope overhead cranes (HROCs), one in top of the area where the TC is located and another one on top of the area where the last components of the accelerator line are located. These are nuclear-grade multi-rope double-beam overhead traveling cranes dedicated to performing transfer operations with weights from 10^4 up to 1.4×10^6 N.
  The most critical operation to be performed by the main HROC is the precise positioning of the in-TC components (the interface shielding plugs and the TCCP). The lifting system of the HROCs is based on ropes, each of which are connected with a hoist.
- The access cell mast crane is a nuclear-grade double-beam overhead crane with a telescopic mast equipped with a change gripping system to allow for the connection of different end effectors, including a parallel kinematic manipulator to manage the positioning of the target assembly, a robotic arm to manage the various RH tools for the different connection/disconnection and inspections operations inside the TC, the interface for lifting/lowering the HFTM, and a mast grapple for vertical handling of components with masses up to 1000 kg.

3. Conclusions

Based on the design configuration described in the previous sections (more details can be obtained from [33]), it is concluded that the IFMIF-DONES facility will be able to produce a neutron flux distribution with significant dose rates in the required irradiation volume.

Figure 10 summarizes the capabilities of the facility. This figure depicts the available integrated irradiation volume versus the damage dose rate, comparing the IFMIF and two different beam shapes of the IFMIF-DONES facility developed with the methodology used in [34, 35].

Our results also suggest that a number of topics and questions of today's science in the different active fields of research and technology could be addressed and investigated at IFMIF-DONES without compromising its main role as a material irradiation facility for the fusion program; these include, for example, isotope production, nuclear and basic physics research, and electronics irradiation among others.

Considering the results obtained and the contents of the IFMIF-DONES Preliminary Engineering Design Report [33], the next phase of the project will be focused on the site-specific aspects as well as on a more detailed engineering design of the components and systems on the critical path to the construction phase.

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