THE IFMIF-DONES FACILITY: A FUSION-ORIENTED 5 MW SUPERCONDUCTING CW LINEAR ACCELERATOR *

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Abstract

IFMIF-DONES (International Fusion Materials Irradiation Facility- DEMO-Oriented Neutron Early Source) – a powerful neutron irradiation facility for irradiation of materials to be used in fusion reactors – is planned as part of the European roadmap to fusion electricity. Its main goal will be to characterize and qualify materials under a neutron field similar to the one faced in a fusion reactor, developing a material database for the future fusion nuclear reactors. The facility is based on an intense neutron source produced by a high current deuteron beam impinging on a liquid lithium curtain, aiming to generate by various Li(d,xn) nuclear reactions neutrons with an energy spectrum and flux similar to those expected to be seen by the first wall of a fusion reactor. The IFMIF-DONES facility has accomplished the preliminary design phase and is currently in its detailed design phase. This contribution presents the status of IFMIF-DONES design developed in the framework of the EUROfusion work programme, integrating the lessons learnt from the IFMIF/EVEDA Project (IFMIF/ Engineering Validation and Engineering Design Activities - Broader Approach (BA) Agreement signed between EURATOM and Japanese Government), through a common program which includes the different commonalties and interfaces of the two projects. An overview of the present design status of the facility is provided, putting emphasis on the design status of the high current superconducting LINAC, responsible for delivering the 5 MW D^+ beam at 40 MeV with very high inherent availability, focusing on the main challenges and the related R&D programme.

INTRODUCTION

Due to the increasing world energy consumption and the efffects of climate change, having the ability of feeding the commercial electricity network by means of fusion reactors is considered as one of the most important challenges of the next decades. The control of the fusion reaction and the development of a fusion plant is one of the main scientific and technological endeavours of our time. In the recent years, the different technical progresses and discoveries have increased the optimism to succeed. However, apart from the challenges represented by the control of the plasma in the reactors based on electromagnetic confinement, or the extraction of the fusion energy to convert it to electricity, one of the main challenge is the validation and the qualification of the materials of which those reactors shall be constructed. The type of irradiation to which those materials will be subjected is different to the one in other facilities (fission reactors, spallation sources,...). As ITER and other experimental fusion reactors will not produce sufficient fluence to be used for material testing, the scientific community has identified several means of experimentally generating a database of the properties of those materials under a fusion-prototypic neutron source. Experts panels endorsed the Deuteron-Lithium neutron source as the most promising option, as implemented in IFMIF with two deuteron accelerators, or the staged European version, IFMIF-DONES, where only one of the IFMIF accelerators is built in a first phase, and an upgrade option to two accelerators. Europe has identified IFMIF-DONES as one of its main priorities, being part of European Fusion Roadmap, and including it since 2018 as one of the

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ESFRI (European Strategy Forum on Reseach Infrastructures) facilities. In March 2023, the construction phase of IFMIF-DONES was launched, by setting up the Steering Committee of the DONES Programme.

IFMIF-DONES

The IFMIF-DONES facility [1–3] will serve as a fusion-like neutron source (10^{18} neutrons/m^2/s) for the assessment of materials damage in future fusion reactors. The neutron flux will be generated by the interaction between the lithium curtain and the deuteron beam from an RF linear accelerator at 40 MeV and nominal CW current of 125 mA. The facility is divided in three major group of systems (Fig. 1):1) the ~100 m long Accelerator Systems (AS), grouping those systems involved in the beam production, acceleration and shaping, 2) the Lithium Systems (LS) where the Li(d,xn) reaction (with a neutron spectrum up to 50 MeV) occurs, and 3) the experimental Test Systems areas (TS), where the main component is the High Flux Test Module where a material damage rate in a range between 20 dpa y^{-1} to 50 dpa y^{-1} (displacement per atom/full power year) can be achieved in a volume of 100 cm^3, over 11.5 dpa y^{-1} in 300 cm^3 [3], and temperature controlled within 250 °C to 500 °C.

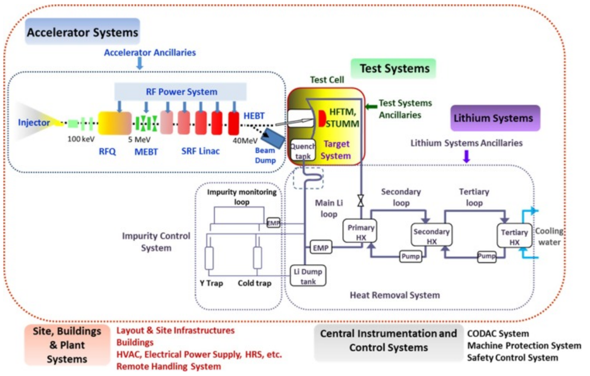

Figure 1: Schematic of the IFMIF-DONES facility.

IFMIF-DONES (Fig. 2) has been designed for construction in Escúzar, Spain, near the city of Granada. Along the design and constructions phases, because of the complexity of the facility, systems engineering approach has been followed [4, 5]. The facility is then grouped in systems depending on their function:

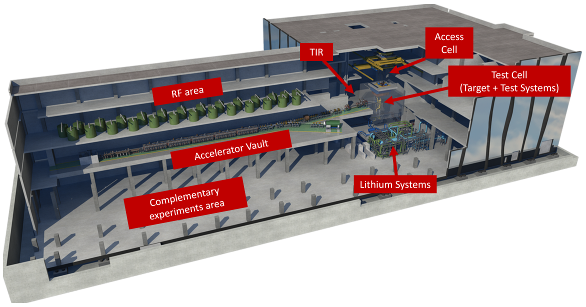

Figure 2: Main areas of the IFMIF-DONES main building.

- The AS (Fig. 3) are the group of systems in charge of generating the deuteron beam, accelerating, shaping and transporting towards the target. They are composed mainly of a high-power RF linear accelerator working at 175 MHz of around 100 m length. The systems are: 1) the Injector [6], with an ECR ion source and a Low Energy Beam Transport line (LEBT), 2) a RFQ [7] of around 10 m length, 3) a Medium Energy Beam Transport line [8], with electromagnets, bunchers and scrapers to transport and match the RFQ output beam to the SRF LINAC acceptance, 4) a SRF LINAC [9] to accelerate the beam up to the nominal energy of 40 MeV using 46 superconducting half-wave resonators grouped in five cryomodules, 5) a High Energy Beam Transport line [10] with electromagnets, collimators, lead shutters and an auxiliary beamline for tuning purposes with a beam dump, 7) a RF Power System [11] based on Solid State Power Amplifiers, with 56 modules to feed the proper 175 MHz field to each of the 49 resonant cavities, and 8) the ancillaries (water cooling, electric, vacuum, gas and cryogenics) to support the other systems. A full set of beam diagnostics is designed for each system [12, 13].

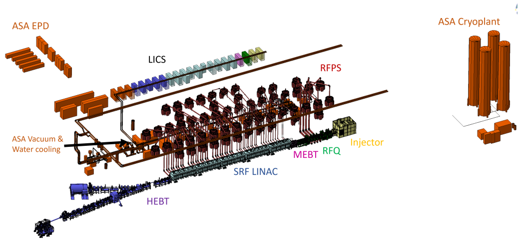

Figure 3: Mockup of the Accelerator Systems.

- The deuteron beam impinges on a liquid lithium target flowing at high speeed (15 m s^{-1}) and high temperature (300 °C). This serves to absorb the 5 MW beam power, as well as permitting an upgrade to a second accelerator, with a total maximum power of 10 MW. The main lithium loop evacuates the heat and a purification system controls the impurities and corrosion in the loop (Fig. 4). In order to avoid the potential direct contact between lithium and water, the heat is transferred outside by a series combination of three isolated cooling loops: a lithium-oil heat exchanger, an oil-oil heat exchanger, and finally an oil-water one.
- The main experimental area of the facility is located in the high neutron flux area just behind the lithium target (Fig. 5). There, a High Flux Test Module (HFTM) is placed, containing several types of material specimen under test with a fusion-prototypic neutron field. Both the HFTM and the liquid lithium target are enclosed within the so-called Test Cell, which provides shielding and a confinement barrier, interfacing with the building. Both target and modules are to be removed periodically. In addition, other test modules are presently under consideration, either for other fusion or

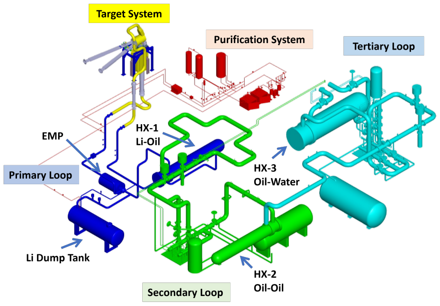

Figure 4: Mockup of the Lithium Systems.

non-fusion applications. In addition to the test cell area, some of those could be located in a room downstream the main neutron flux, or in an area in the floor below the accelerator, using a parasitic fraction of less than 0.1 % of the HEBT beam.

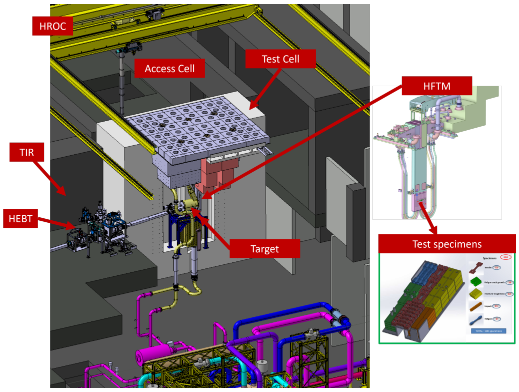

Figure 5: Mockup of the Test Cell (*left*), and the High Flux Test Module (*right*) of the Test Systems.

Other important group of systems are: 1) the Buildings acommodating the requirements of mechanical stability as well as further shielding and confinement to the previous systems; 2) the Plant Systems providing common services such as electrical power, water, gas,...; 3) the Remote Handling systems [14, 15] which deal with the design and operation of the robotic systems in charge of very delicate operations in the facility, such as periodic removal of the lithium target chamber, or the test samples modules; or 4) the Control Systems which integrate the monitoring and controlling of all the systems in the plant, adding dedicate protection layers devoted to the machine protection and the prevention and actuation of safety-related accidental events [16].

THE 40 MeV DEUTERON ACCELERATOR

Accelerator design

The design of the accelerator is based on the IFMIF accelerator [17], whose front end design corresponds to the LIPAc [18]. The main parameters of the accelerator are listed in Tab. 1. Besides the nominal operation of the 40 MeV deuteron beam, during the staged commissioning phases, the AS [19] will be tested with protons at scaled energy of 20 MeV, and peak beam current of 70 mA. The design is driven by two main goals: 1) maximize the neutron irradiation of the proper energy spectra by using a flexible beam footprint (Fig. 6), 2) keep the availability of the AS above 87 % [20]. The availability of the accelerator is linked with the reliability of each system, and to the ability of the accelerator to quickly recover the normal operation after a beam trip or a failure. Hence to minimize the downtime of the machine it is crucial that hands-on maintenance can be applied to most of the components of the accelerator. For this reason, beam losses along all the accelerator should be kept below $1\ \mathrm{W\,m^{-1}}$. This represents 2×10^{-7} of the high energy beam, which is obviously a challenge for the accelerator design.

Table 1: Main beam accelerator systems nominal parameters.

Particle	D^+(p)
Peak current	125 mA
Duty cycle	CW
Beam energy	40 ± 5 MeV FWHM
Beam power	5 MW
RF frequency	175 MHz
Horizontal beam profile @ target	10 cm to 20 cm
Vertical beam profile @ target	5 cm

Several modifications have been performed to the IFMIF-DONES acccelator compared to the initial IFMIF design. Some of the most relevant are:

- The change of the tuning and layout of the accelerator and in particular of the SRF LINAC (Tab. 2). The number of cryomodules has been increased from four to five. The number of Half Wave Resonators is then 46, divided in two types: one optimized for the first two cryomodules (19 cavities) called low-β cavities [21], and a second one for the last three cryomodules (27 cavities) called high-β cavities. The required accelerating field was kept below $4.2\ \mathrm{MV\,m^{-1}}$ for all the cavities. A total of 29 focusing solenoids are considered with an integrated magnetic field below 1.1 T m. The requirement of the steerers integrated field included in the solenoid package has been increased up to 70 G m. On the other hand, the HEBT design has suffered modifications to improve the flexibility of the target footprint which is flexible in the horizontal plane from 10 cm to 20 cm to optimize the irradiation profile, as well as the intensity of horizontal side peaks, while ensuring a lossless transmission along the beamline. The beam evolution along the whole accelerator based on the reference tuning is shown in Fig. 6. Error and accidental studies [22, 23] are presently ongoing to reinforce the most critical parts of the accelerator.
- An alternative design of the RFQ has been proposed as backup solution, based on a theoretical model of the vane degradation, in which the lifetime is enhanced.

Table 2: Updated layout of the superconducting LINAC parameters. *S* represents the solenoids and *C* the superconducting cavities.

Cryomodule	**1**	**2**	**3**	**4**	**5**
Type of cavity	Low-β	Low-β	High-β	High-β	High-β
Geometrical / optimum	0.094/0.116	0.094/0.116	0.158/0.181	0.158/0.181	0.158/0.181
Elementary sequence	1 S + 1 C	1 S + 2 C	1 S + 2 C	1 S+ 2 C	1 S + 2 C
Final sequence	none	1 S + 1 C	1 S + 1 C	1 S + 1	1 S + 1
Number of cavities	8	11	9	9	9
Output energy (MeV)	8.4	14.2	21.8	30.7	40

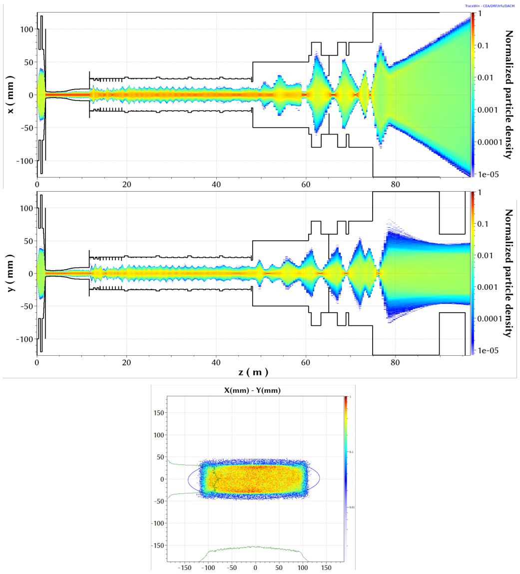

Figure 6: Beam density in horizontal and vertical direction for the nominal tuning of the accelerator from ion source to target (*top*) and nominal beam footprint (*bottom*).

- The SRF LINAC design was modified to facilitate maintenance from side panel to the top one (top loading solution).

- Regarding the HEBT design, the Radiation Isolation Room has been removed, and the collimator embedded in the wall separating that room from the TIR has been moved inside the TIR, in order to better protect the target from beam halo particles. The collimator is now cooled by helium gas instead of water, in order to minimize the consequences of accidental scenarios. Fast valves are located now in the Accelerator Vault instead of Target Interface Room (TIR), in order to better protect the machine and improve the maintanaibility. Most of HEBT beamline is considered to be made of aluminium instead of steel to minimize the activation and reduce the machine downtime. In addition, a possible solution for extraction of a parasitic fraction of the beam (0.1 %) down to the experimental area has been conceptually designed, based on a combination of travelling wave and electrostatic kickers and a septum magnet.

- The RF Power system is now based on 200 kW 175 MHz Solid State Power Amplifiers (SSPA) instead of tetrodes, with the target of having a better availability of the accelerator.

The design of the accelerator has been supported by several simulations: 1) the vacuum pressure profile along the accelerator using Molflow+ [24] (Fig.7) to ensure the requirements along the accelerator are fulfilled, 2) neutronics simulations with MCNP to ensure the fulfillment of the prompt doses and the activation of the accelerator, and the irradiation performance of the beam footprint at the target, 3) safety simulations with MELCOR for the accelerator safety-related events, 4) Reliability and Availability simulations using Blocksim to improve the design performance and 5) Virtual simulations for the analysis of the logistics and maintenance operations. On the other hand, optimization activities are currently ongoing based on the coupling of beam dynamics and neutronics simulations for irradiation optimization, or the use of novel machine learning algorithms.

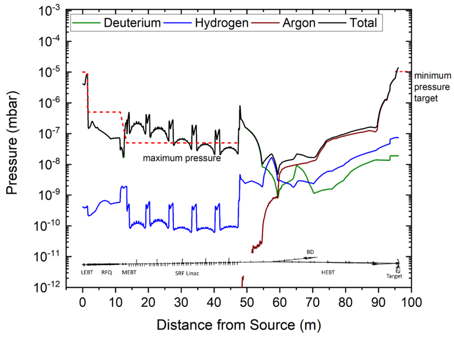

Figure 7: Simulated gas pressure profile for various gas species along the accelerator.

Validation activities

During the design phase of IFMIF-DONES one of the main objectives has been to minimize the technological risk by validating the most critical components of the facility. In particular, a broad validation programme was foreseen for the deuteron CW accelerator, including the following prototypes:

- *LIPAc* is an accelerator under commissioning in Japan, which was a constructed as a 1:1 prototype of the frontend of the IFMIF accelerator to validate the critical technologies [25]. It has already achieved major engineering validation activities: the injector at nominal operation, the RFQ accelerated a record beam at nominal deuteron current and low duty cycle, or the handling of high reactive beam loading in the re-buncher cavities of the MEBT. Several validation activities are in progress such as the beam diagnostics, the control systems, the RFQ couplers, the RFQ RF conditioning, the injector long-term stability or the activities related to the SRF LINAC. An effort to enhance the commonalities between both accelerators is under way, in order to ensure the timely integration of the feedback into the IFMIF-DONES facility. The present status is detailed in a separated article [26]. IFMIF-DONES team is supporting the commissioning activities of LIPAc, as the best test stand and support facility to guarantee the success of IFMIF-DONES later on.

- A prototype of the *High-β superconducting resonant cavity* is being designed and tested. Those cavities will be used in the last three cryomodules, and are optimized for a $\beta = 0.18$. A naked cavity (Fig. 8) has been already validated, surpassing experimentally the target requirements of 4.5 MV m^{-1} with a Q_0 of 10^9 [27]. The design and tests of the complete cavity with the helium tank and the tuner is presently under way. In parallel, a re-design of the *RF coupler transition box* (T-box) has been proposed and will be manufactured, incorporating a bias voltage in the conductor to minimize multipacting.

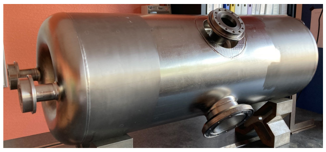

Figure 8: Picture of the naked high beta cavity before cryogenics tests.

- A couple of prototypes of 200 kW *SSPA RF stations* at 175 MHz are under progress, which will replace the tetrodes technology used previously in LIPAc, in order to increase the flexibility and availability of the whole machine. The main difference between both prototypes is the type of RF combination. One is based on traditional combination, focused on the application to the 8-ports RFQ, while the second one is based on a high efficient RF cavity combiner. Both prototypes are now in the commissioning phase. Up to 100 kW in CW have been already obtained with a 160-input cavity combiner [28], and 200 kW have been already obtained in the first tests of the second prototype, with an efficiency (RF/AC_{in}) of around 60 %. R&D activities related to the analysis of alternatives for the high-power LDMOS transistors used in the amplifier modules, and the need of circulators are ongoing.

- An *experimental beamline* with a geometry similar to the last 15 m of the HEBT down to the target is under construction to serve as theoretical and experimental qualification of the protection measures for several accidental scenarios detected in the facility by the safety team related to inrush of water or air into the vacuum chamber (Fig. 9). A detailed description of the status of the construction of this facility is provided in [29].

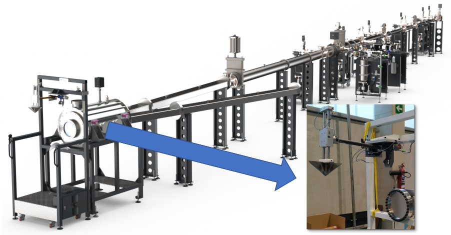

Figure 9: 3D mockup of the MUVACAS facility.

- Characterization and analysis of alternatives of *Beam Loss Monitors* are one of the main areas of R&D at the moment. Two types of prototypes are under development: 1) a neutron beam loss monitors [30] is considered as alternative or complementary to the ionization chambers used along the transport lines in LIPAc. Experiments are planned for LIPAc to test and crosscheck both options with real beam conditions. 2) CVD Diamonds as beam loss detectors along the SRF LINAC are considered in parallel. Their validation will be performed during Phase B+ and C of LIPAc commissioning. Assessment of the charge collection efficiency for neutrons and gamma down to cryogenic temperature, and the discrimination of both type of radiation sources are presently under way in the Croatian RBI ion microbeam facility.

CONCLUSIONS AND OUTLOOK

The design of the IFMIF-DONES, based on a high power RF superconducting linear accelerator, is completed. Validation activities of the most critical parts have been performed in order to provide the necessary feedback to consolidate the design. Recently, a new phase of the IFMIF-DONES facility has been triggered off with the first DONES Steering Committee and the start of the DONES Construction Phase. The design being carried out within the frame of EUROfusion Early Neutron Source workpackage, the DONES Preparatory Phase and other projects will be now gradually transferred to the Construction Phase. It is expected that after a ramp-up phase of the project in Granada, the procurements of the first components will be launched in the forthcoming years.

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