Nucl. Fusion 59 (2019) 065002 (21pp) https://doi.org/10.1088/1741-4326/ab0d57

Special Topic

The European approach to the fusion-like neutron source: the IFMIF-DONES project

A. Ibarra[1,a], F. Arbeiter[2], D. Bernardi[3], W. Krolas[4], M. Cappelli[6], U. Fischer[2], R. Heidinger[5], F. Martin-Fuertes[1], G. Micciché[3], A. Muñoz[6], F.S. Nitti[3], T. Pinna[7], A. Aiello[3], N. Bazin[8], N. Chauvin[8], S. Chel[8], G. Devanz[8], S. Gordeev[2], D. Regidor[1], F. Schwab[2] and the full IFMIF-DONES team

[1] CIEMAT, Madrid, Spain
[2] KIT, Karlsruhe, Germany
[3] ENEA, Brasimone, Italy
[4] IFJ PAN, Krakow, Poland
[5] F4E, Garching, Germany
[6] Empresarios Agrupados, Madrid, Spain
[7] ENEA, Frascati, Italy
[8] CEA, IRFU, Université Paris-Saclay, Saclay, France

E-mail: angel.ibarra@ciemat.es

Received 5 January 2019, revised 21 February 2019
Accepted for publication 6 March 2019
Published 9 May 2019

Abstract

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

These activities and R&D 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 the underlying technology basis in order to be ready for IFMIF-DONES construction as early as possible.

The paper presents the main engineering results for a generic site obtained during the first years of design work, as indicated in the recently released IFMIF-DONES Preliminary Engineering Design Report, making emphasis on the design evolution from previous phases and on the critical issues to be further developed in the near future. The proposed European site to host the facility (Granada, Spain) is briefly introduced as well.

Keywords: fusion-like neutron source, materials irradiation, facilities engineering

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

[a] Author to whom any correspondence should be addressed.

1. Introduction

A fusion relevant neutron source is a more than three decades long pending step for the successful development of fusion energy. The need of a neutron source for the qualification of materials to be used in future fusion power reactors have been recognized in the European (EU) fusion program since many years [1]. Safe design, construction and licensing of a nuclear fusion facility by the corresponding nuclear regulatory agency will demand the understanding of the materials degradation under the neutron bombardment during the life-time of the fusion reactor. This needs to be demonstrated through material irradiations in a suitable neutron source facility under fusion relevant conditions. The construction and exploitation of this facility is presently considered to be in the critical path of DEMO [2].

This issue prompted the EU to launch activities for the design and engineering of the IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source) facility based on, and taking profit of the results obtained in the IFMIF/EVEDA (Engineering Validation and Engineering Design Activities) project, presently conducted in the framework of the EU-Japan Bilateral Agreement on the Broader Approach to Fusion [3]. The main objective of these activities is to consolidate the design and the underlying technology basis in order to be ready for the IFMIF-DONES construction early in the next decade. DONES will be the relevant neutron source that can provide such conditions as anticipated for DEMO [4]. 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 taking place in a liquid Li target when bombarded by a deuteron beam with a beam footprint between 200 mm × 50 mm and 100 mm × 50 mm. The energy of the deuterons (40 MeV) and the current of the accelerator (125 mA) have been tuned to maximize the neutrons flux (up to ~5×10^{18} m^{-2} s^{-1}) to get irradiation conditions comparable to those in the first wall of a fusion power reactor in a volume of around 0.5 l that can house around 1000 small specimens.

This paper presents the main engineering results for a generic site obtained during the first years of design work in the framework of the EUROfusion Consortium—as indicated in the recently released IFMIF-DONES preliminary engineering design report [5], making emphasis on the design evolution from previous phases and on the critical issues to be further developed in the near future.

2. IFMIF-DONES plant configuration

The DONES facility will be a plant containing all the necessary buildings and systems to house and run 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 facility 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 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 materials samples located immediately behind the lithium target, in the test modules. Figure 1 shows a 3D model of the DONES facility.

The facility (the DONES plant) is breakdown in five major areas. The systems devoted to produce the high power beam are grouped under the accelerator systems (AS); the systems related to the lithium target management constitute the lithium systems (LS); the systems in charge of the irradiation test module(s), the test cell (TC) and their support systems compose the test systems (TS); the systems in charge of performing the global control of the plant are grouped under the central instrumentation and control systems (CICS) and finally the site, building and plant systems (PS) include the buildings and the systems providing power, cooling, ventilation, remote handling of components and services to the other systems. In the following a more detailed description of the different systems is given.

2.1. Accelerator systems (AS)

The AS include the systems and components which form the DONES accelerator, their corresponding diagnostics and auxiliary systems. Its main function is to generate and accelerate D+ ions in continuous wave (cw) mode and direct them to the lithium target to produce fusion neutrons by nuclear stripping reactions. For this purpose, a high power beam (40 MeV/125 mA/cw) is to be formed, transported and shaped to match the specified footprint geometry at the target. The DONES accelerator is a sequence of acceleration and beam transport stages:

- The injector system produces and extracts a CW 140 mA deuteron beam at 100 keV by its electron cyclotron resonance ion source. A low energy beam transport section guides the deuteron beam from the source to a radio frequency quadrupole (RFQ) accelerator.
- The RFQ system bunches the beam and accelerates 125 mA to 5 MeV. The RFQ output beam is injected through a medium energy beam transport (MEBT) system which conditions it in transverse mode with quadrupoles and in longitudinal mode with rebuncher cavities in order to properly match it to the:
- Superconducting radio frequency linear accelerator (SRF linac) system where it is accelerated to a final energy of 40 MeV.
- All the accelerating radio-frequency (RF) cavities are powered by an RF system based on 175 MHz RF stations with a cw output power level of up to 200 kW. Additionally, the MEBT is powered by two smaller amplifiers rated at lower power of 20 kW cw. A total of 56 such stations are needed (eight for RFQ, two for MEBT and 46 for SRF linac).
- The SRF linac output beam is directed to the neutron production target by a high energy beam transport line (HEBT). The HEBT, which consists of a series of magnetic optics elements, is required to tailor the beam to

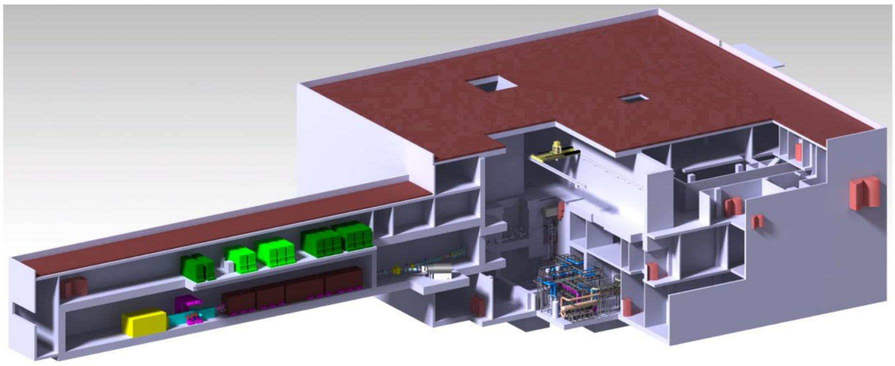

Figure 1. 3D model of the DONES facility.

provide a flat rectangular beam profile on the flowing lithium target. The DONES accelerator will have a beam dump (BD) devoted to stop the pulsed beam at low duty cycle during accelerator commissioning and start up phases after a shutdown, allowing its tuning and characterization. The BD consists basically of a cartridge, which stops the beam, and a local shielding to attenuate the resulting radiation.

– Accelerator systems ancillaries will provide all utilities, equipment and means for covering all the needs of the AS, all along its life cycle (preparation and tests of components, installation, tuning, operation, maintenance and repair, etc), which also act as interface with the plant systems. They are the following: water primary cooling loops, electrical power distribution, vacuum systems, gas distribution systems, LHe cryogenic system, etc.

An overall goal in the design strategy is to achieve hands-on conditions for the maintenance operation of both the RFQ and the SRF linac systems. Choosing the relatively low frequency of the RF power system is a conservative element in the design to facilitate an overall maintenance without a minimum of remote handling tools.

Beam diagnostics and instrumentation is distributed all along the accelerator. More specifically and sorted by system, there are diagnostics along the LEBT (beam current, profile and emittance), RFQ (beam losses), MEBT (beam current, beam position and phase), the SRF linac (beam position and phase, micro losses, beam loss) and HEBT (beam position and phase, beam transverse profile -interceptive and non-interceptive-, beam current, bunch length, emittance measurements (interceptive and non-interceptive), energy spread (interceptive), beam losses, mean energy and finally beam halo as an option). More details about about the IFMIF-DONES AS can be found in [5].

2.2. Lithium systems (LS)

The main function of the LS is to provide a neutron flux for the irradiation of the materials of interest, throughout an injection of 125 mA D+ beam under an angle of 9° into a liquid lithium target, with a footprint of rectangular shape. The LS include:

– The target system which consists basically of the components of the lithium loop (LL) located inside the TC (see next section) and the beam ducts. The main component is the target assembly which includes the concave shaped open channel (backplate) exposed to the accelerator vacuum, where the beam impinges on the liquid metal. The stability of the liquid lithium target, as requested from stringent requirements, has been widely demonstrated both by numerical simulations and experimental tests on the facility EVEDA lithium test loop (ELTL) in Oarai, Japan, [6, 7].

– Other components of the target system are the target assembly (TA) support structure, the lithium inlet and outlet pipes and their shielding plugs, the beam ducts and their shielding plugs, and the quench tank (QT).

– Heat removal system including the main Li loop and its dump tank (DT), re-circulating the lithium between the target system and the primary heat exchanger and the secondary loops transferring the heat to the plant general heat rejection system (HRS). The system is designed to evacuate the heat deposited in the target and control and maintain a constant lithium temperature at the target assembly inlet irrespective of the beam power.

– Impurity control system (ICS) which consists of a branch line to the main Li loop, which extracts a fraction of the lithium and re-injects it after purification and impurity analysis. The system is designed to condition the lithium after maintenance prior to start-up and control and maintain a defined level of purity.

– Lithium systems ancillaries, such as vacuum, heating, cooling, power, gas supply and exhaust system and the lithium and oil recovery system, which also act as interface with the plant systems.

More details about the IFMIF-DONES LS can be found in [8, 9].

2.3. Test systems (TS)

The TS cover:

– The TC which is the cell where the deuteron beam from the accelerator meets the lithium at the place of the lithium target and the irradiation module. The TC accommodates

the irradiation module(s) under controlled environment and conditions for irradiation. The TC is a blind hot cell with an opening at the top, closed by shielding plugs and a top cover which provide a vacuum tight environment. Pipe and cable penetrations connecting the inside with the outside the TC are accommodated in the pipe and cable plugs.
- The high flux test module (HFTM) which is the device where the samples of structural materials to be irradiated are installed.
- The start-up monitoring module, equipped with a wide set of instrumentation, is foreseen to be used during the commissioning phase of DONES to characterize the neutron/gamma flux and spectrum, and to validate neutronic calculation models.
- The TS ancillaries including the dedicated equipment to supply energy, heat sinks (through helium gas or water flows) and control infrastructure to the TC, test modules and other client systems of the TS, acting also as interface with the plant systems.

More detailed information on these systems can be found in [10, 11].

Facilities for complementary experiments are also planned to allow for installation of complementary physics experiments, independent of materials irradiation. Possible areas of these experiments can be nuclear physics, radio isotope production and medicine. These experiments will be using the remaining neutron flux behind the HFTM and/or a fraction of the deuteron beam deflected at 5 or 40 MeV energy [12]. A collimated neutron beam facility which takes advantage of the neutron-flux behind the HFTM has been incorporated into the DONES layout at this stage of the design. A dedicated experimental area has been planned behind the TC with dimensions of around 30 $\times$ 11 m. The complementary experiments area must be allowed to be open and accessible for maintenance and setting up of equipment while the irradiation of samples in the HFTM is ongoing.

2.4. Buildings and plant systems

The buildings and plant systems comprise:

- The main building.
- The auxiliary buildings and administrative buildings of the site.
- Several plant systems that support the operation of the entire plant. the services considered herein are heating, ventilation and air conditioning; electrical power system; HRS; service water system; service gas system, radioactive waste treatment system (gas, liquid and solid waste treatment systems and fire protection system.
- The remote handling system (RHS), which includes the equipment devoted to the remote handling operations required during plant operation, maintenance and decommissioning in the TS, LS, AS and PS. The DONES project consists of complex and heavy systems and components that need to be assembled and maintained on site. For several of them it is required to perform maintenance, inspection and monitoring tasks over many years in a hostile environment and in efficient, safe and reliable manner. According to this, the RHS for DONES, comprises the whole remote handling equipment (RHE) and tooling for the execution of maintenance tasks [14].

More detailed information on these systems can be found in [13, 14].

2.5. Central instrumentation and control systems (CICS)

The DONES instrumentation and control system, is in charge of the global control of the DONES plant. It is designed with a hierarchical structure: from the top level, the CICS, down to the local instrumentation and control subsystems level.

At the top level, the CICS is composed of the following systems:

- The control, data access and communication system, which coordinates DONES plant systems, orchestrating their operation and gathering and archiving the data that DONES will produce.
- The machine protection system, which is in charge of implementing all the investment protection strategies at the different plant levels, ensuring plant protection against failures of the facilities, system or equipment components, failures of the CICS/LICS or incorrect operation.
- The safety control system, which is a dedicated safety grade system devoted to the implementation of all the identified protection functions regarding the personnel or the environment.

More detailed information on these systems can be found in [15].

3. From IFMIF/EVEDA to IFMIF-DONES

As previously mentioned, the presently available IFMIF-DONES baseline engineering design is based on the IFMIF engineering design developed in the framework of the IFMIF/EVEDA project [16] updated to take into account obtained validation results and updated modeling calculations and simplified as much as possible (in order to reduce cost) according to the following criteria.

- The facility will include only one full energy (40 MeV) accelerator, maintaining the planned angular incidence in order to allow a possible upgrade in a later moment.
- The TC and LL should be of the same size although only half cooling will be required.
- Only one irradiation module will be included in the first irradiation campaigns giving rise to a significant simplification of the auxiliary systems of the TS.

Table 1. Cryomodule parameters as defined in IFMIF design [16].

Cryomodule	#1	#2	#3	#4
HWR beta	Low	Low	High	High
Geometrical/optimum	0.094/0.116	0.094/0.116	0.158/0.181	0.158/0.181
Elementary sequence	1 solenoid + 1 cavity	1 solenoid + 2 cavities	1 solenoid + 3 cavities	1 solenoid + 3 cavities
Number of elementary sequence	8	5	4	4
Output energy (MeV)	9	14.5	26	40

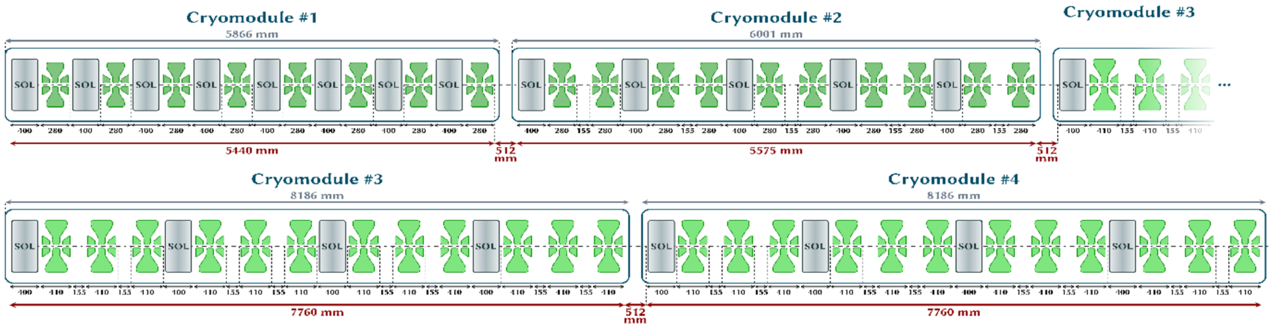

Figure 2. IFMIF SRF-linac layout with consolidated dimensions and four cryomodules.

- Irradiation modules will not foresee reirradiation of samples (extraction of samples from the irradiated module and included them in a new one) giving rise to a significant simplification of irradiated samples management needs.
- Minimum irradiated materials (modules, target,…) manipulation in the plant (irradiated materials will be transfer to external facilities, if possible).

This approach gives rise to a significant design evolution as compared with the IFMIF one. The most relevant ones are summarized in the following sections in which they are described in some more detail.

3.1. SRF linac design

The IFMIF accelerator facility comprises two identical linacs, each accelerating a CW 125 mA deuteron beam at the final energy of 40 MeV, the total beam power of 2 × 5 MW is required to produce the high flux of neutrons [17]. This accelerator comprises the D+ injector, the RFQ, the matching section, the SRF linac and the 40 MeV transport line directing the beam to the Li target. In the frame of the IFMIF/EVEDA project, the accelerator has been designed in order to master the high intensity deuteron beam subject to strong space charge forces [18].

In order to minimize the beam losses to meet the 'hands-on maintenance' machine requirement, all the components of the linear accelerator as well as the distances between adjacent components are made as short as possible. This led to a very compact design of the accelerator, in particular of the SRF linac where the 125 mA 175 MHz cw deuteron beam is accelerated from 5 MeV to 40 MeV. This 24.2 m long SRF linac was split into four cryomodules, each consisting of a chain of superconducting cavities and solenoids for respectively acceleration and focusing purposes (see table 1). The Intermediate IFMIF Engineering Design Report [16] released in 2013 was based on this initial layout.

Because the IFMIF accelerator facility has to reach unprecedented performances, a prototype of the low energy part of the machine is under installation at Rokkasho (Japan). This Linear IFMIF Prototype Accelerator (LIPAc) comprises the D+ injector, the RFQ, the matching section, the first cryomodule of the SRF linac and the 9 MeV transport line ending with the beam dump. With regards to the SRF linac, distances between the successive components are subject to different constraints related to the RF coupler footprint, the amplitude of frequency tuner displacements, the flexible elements interleaved between the superconducting components, the room needed for the assembly, etc. Thanks to the developments already performed in the IFMIF/EVEDA project, as-built dimensions of the SRF linac components (low beta cavities, solenoids, RF couplers, cold-warm transitions, etc) are available [19]. Consequently, dimensions of the second cryomodule (equipped with low-beta cavities too) can be precisely defined, and those of the cryomodules #3 & #4 (equipped with high-beta cavities) may be easily extrapolated. Moreover, distances from MEBT to first cryomodule, from last cryomodule to HEBT, and between subsequent cryomodules (including the tubes ensuring a good thermal insulation, the valves and flexible elements) are updated.

From all the realistic dimensions derived from LIPAc components already built, a longitudinal layout of the SRF linac is defined without modifying the number of cryomodules (see figure 2). Considering the interfaces to the MEBT and the HEBT, the overall length is 28.1 m.

In order to get a reasonable longitudinal acceptance, the synchronous phase is evolving from −50° up to −30°. Beam

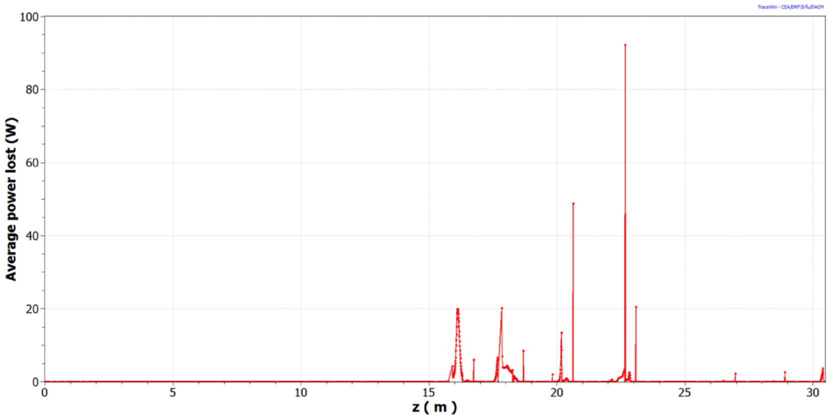

Figure 3. Average power lost over 10 000 linacs with static and dynamic errors.

Table 2. Cryomodule parameters of the optimized design of DONES SRF linac.

Cryomodule	#1	#2	#3	#4	#5
HWR beta	Low	Low	High	High	High
Optimum	0.116	0.116	0.179	0.179	0.179
elementary sequence	1 solenoid + 1 cavity	1 solenoid + 2 cavities	1 solenoid + 2 cavities	1 solenoid + 2 cavities	1 solenoid + 2 cavities
Number of sequence	8	5	4	4	4
Cryomodule end	None	1 solenoid + 1 cavity	1 solenoid + 1 cavity	1 solenoid + 1 cavity	1 solenoid + 1 cavity
Output energy (MeV)	8.3	13.9	21.3	30.3	40

dynamics simulations (performed with TraceWin [20]) show that all the particles in the longitudinal plane should remain inside the bunch, only the beam final energy is 36.7 MeV when 40 MeV are required. To cope with this issue, one can apply a more aggressive synchronous phase law or increase the accelerating field of the cavities above 4.5 MV m^{-1}. Both options have serious drawbacks, such as a smaller longitudinal acceptance with potential beam losses in the longitudinal plane or higher RF power handled by the couplers with smaller margin before quenching the cavity.

The conclusion is even worse when considering the calculations in the transverse plane: only a very small margin, in the mm range in third and fourth cryomodules, remains between the external beam envelope extent and the beam pipe. For this reason, the tuning of the SRF linac in the numerous simulations was quite tricky. These results have been confirmed by errors (static and dynamic) studies: the average power deposited (over 10000 runs) is in the range of a few hundred watts with several 'hot spots' in the linac (see figure 3), and in more than 40% of the runs the beam losses remain above 10 W along the whole SRF linac [21]. It is concluded that transverse focusing is difficult to optimize and it is very unlikely that a much better SRF linac transverse tuning is achievable.

In order to master more efficiently the beam losses and to recover some margin, an alternate design addressing the two major issues (less aggressive synchronous phase law and a higher transverse phase advance per meter in the high-β cryomodules) has been defined. It consists in adding accelerating cavities operating at 4.5 MV m^{-1} to reach a final energy of 40 MeV while applying a smooth synchronous phase law. The higher transverse phase advance per meter is achieved with a shorter focusing lattice in the high-β section i.e. with elementary sequences of 1 solenoid + 2 cavities instead of 1 solenoid + 3 cavities. Finally, to ensure a correct focusing in the inter-cryomodule drift tube, all cryomodules but the first end by one cavity preceded by a solenoid.

Due to these changes, most of the cryomodules are significantly longer. To avoid extra difficulties and risks, the

Table 3. Values of static and dynamic errors used in the beam dynamics calculations.

Element	Static error range	Dynamic error range
Resonators displacement (x, y)	±2 mm	±0.2 mm
Resonators ratation (φ_x, φ_y)	±20 mrad	±2 mrad
Resonators field amplitude	±1%	±0.1%
Resonators field phase	±1°	±0.1°
Solenoids displacement (x, y)	±1 mm	±0.1 mm
Solenoids ratation (φ_x, φ_y)	±10 mrad	±1 mrad
Solenoids magnetic field	±1%	±0.1%
BPMs measurement accuracy	±0.25 mm	/

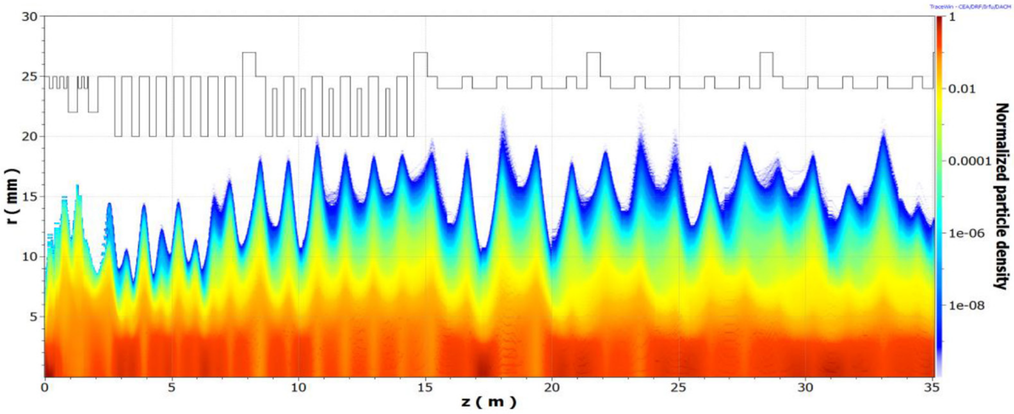

Figure 4. Cumulated density in the *r* plane for 10 000 linacs with static and dynamic errors.

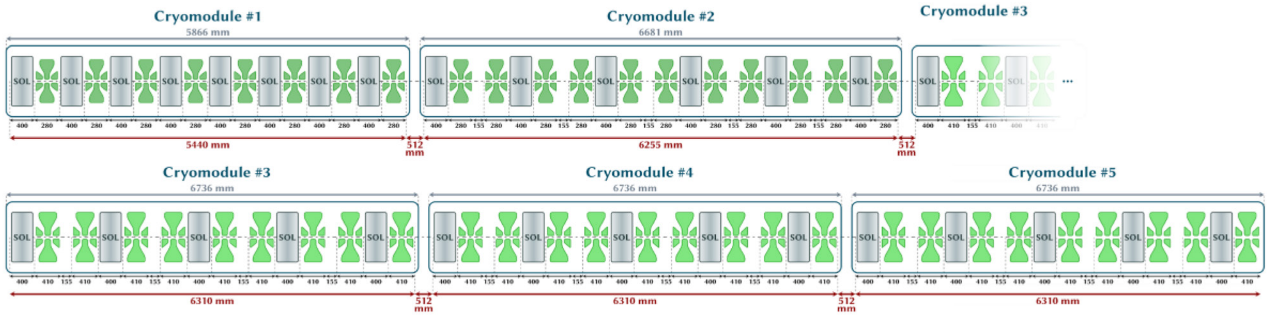

Figure 5. New reference layout of the DONES SRF-linac (split into five cryomodules).

high-beta section of the SRF linac is then split into three cryomodules in order to ease the fabrication, assembly and maintenance. In this optimized configuration (see table 2), the SRF linac is at least 32.7 m long.

At low energy, the synchronous phase starts at $-50°$ and then grows linearly with beam energy up to $-30°$. The related beam dynamics studies show that all the particles remain safely inside the bunch all along the SRF linac, and that the beam extend, without error, is kept below 14 mm (resulting in a margin between the beam outer part and the beam pipe higher than 10 mm) preventing from any beam loss.

In order to validate and test the sensitivity of this promising design, error studies have been carried out. It consists of simulating a large set of different machines, each of them having a different set of static (misalignments and applied fields) and dynamic errors (vibrations, phase and field ripples) as detailed in table 3. Monte-Carlo simulation method is used for tracking 10^6 particles through 10 000 different linacs having different sets of random errors uniformly distributed over typical ranges.

The cumulated particle density is shown on figure 4. The present error studies shows that no beam loss are observed over 10 000 runs with the five cryomodules design, including static and dynamic errors.

These very satisfactory beam dynamics results were considered as a substantial improvement with respect to previous designs. Even if the design where the SRF linac is split into five cryomodules results in a longer machine, with more superconducting cavities (+4) and solenoids (+8), the beam dynamics appears to be much safer (from the beam losses point of view), less sensitive to misalignment or field errors and easier to tune. This SRF linac design with five cryomodules is the new reference for DONES (see figure 5). Further studies and adjustments will be undertaken in the final end-to-end simulations as soon as the real beam distribution measured on LIPAc is available.

3.2. RF source technology

The RF power system proposed for IFMIF was based on the LIPAc RF modules relying on high power tetrode amplifiers. The design was based on 25 RF modules of two amplifying chains up to 200 kW (RFQ and SRF linac) and two solid-state power amplifiers (SSPA) of 20 kW (re-buncher cavities) for each accelerator. To reach up to 200 kW of RF power each amplifying chain was composed of three amplifying stages: a first SSPA stage up to 500 W, a second tetrode stage up to 16 kW and a final tetrode stage up to 230 kW (taking into account losses in the coaxial line and circulator). A high power circulator was used for each chain to protect the amplifiers from the reflected power from the cavity. A typical IFMIF 200 kW RF power module is shown in figure 6.

Although tetrodes are a highly matured technology, the complexity is very high as there are four DC power supplies involved (some of them are high voltage) for each tetrode-based amplifying stage and any problem in managing the

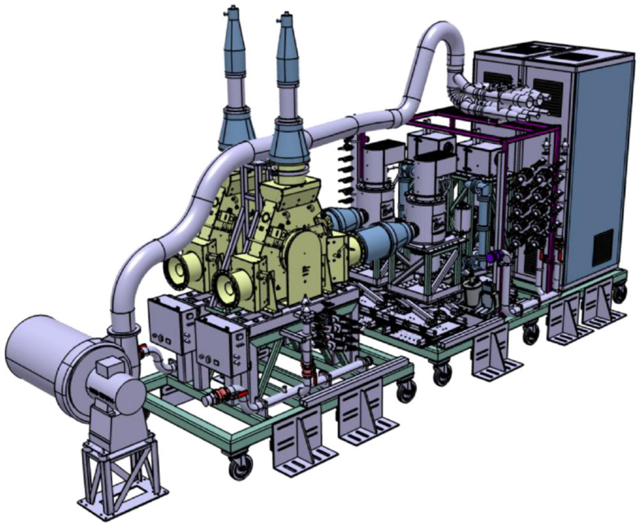

Figure 6. IFMIF tetrode-based RF module.

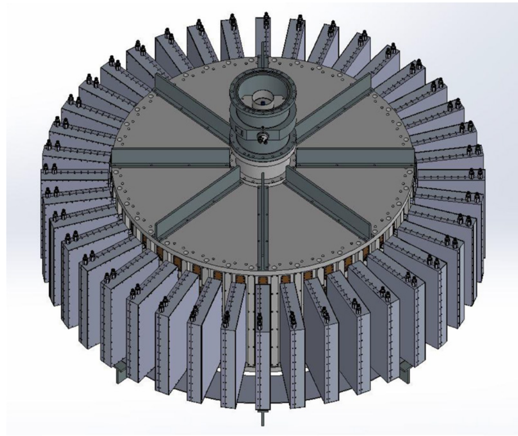

Figure 7. Preliminary design of the RF station (combiner with 40 integrated modules).

biasing of the tetrode may result in catastrophic damage. This biasing requires additional systems that carefully monitor and control the bias of all the tetrode grids at high sampling rates and fast reaction times to avoid damaging the tetrode, as they are a high cost component and its failure directly force the accelerator facility to stop. Additionally, some tetrode models are at their end of commercial lifecycle and if not, they are not mass-produced, so delivery time for spares may be very long or directly impossible. Therefore, as IFMIF facility is a long life operating facility and tetrodes will need to be replaced multiple times due to their relatively short life span, the maintainability due to component obsolescence is compromised with this initial approach. Even if the tetrode manufacturer guarantee the supply of spares for the whole facility operative life, the maintenance cost is very high.

Taking this into account, the IFMIF-DONES RF power system will be based in full solid-state technology amplifiers using the most up to date LDMOS transistors capable of providing 1.5 kW and a planar design of their matching circuit allowing a high repeatability. The transistors will be arranged in integrated modules containing four units sharing the same cooling plate and mechanical structure but with separate outputs. The transistors will be fed from a common DC bus that will be powered by a distributed high efficiency AC/DC power supply system allowing high modularity and redundancy. To achieve the maximum efficiency for the complete amplifier it is proposed to use a combiner based on resonant cavity to combine up to 160 transistor outputs in just a single step (figure 7). All of this innovative technologies together will allow the amplifier to achieve an efficiency of 65% (electric grid consumption to RF power ratio) compared with the 50% to 55% efficiency range of current SSPA amplifiers and the 47% overall efficiency of the IFMIF/EVEDA tetrode-based RF modules. This will allow a significant reduction in the yearly operation cost compared with the original approach based on tetrodes.

Additionally, the use of a fully digital low level RF (LLRF) using White Rabbit for timing synchronization will increase the performance and flexibility of the complete system. The LLRF is being enhanced and adapted to the new amplifier architecture integrating some previously external diagnostics to have a faster and more precise management of the amplifier and associated cavity.

The RF station is being designed with enough redundancy to maintain the performance during the expected operation periods even with some failed transistors or power supplies. During the programmed maintenance stops, the integrated modules will be easily replaced for spares minimizing the repair time so the system availability target can be achieved.

3.3. Lithium quench tank configuration

During operation, liquid Li flows through the TA to receive deuteron beam to generate irradiation neutrons, and then is slowed down in a QT. The QT, which is defined as a permanent component that is maintained or replaced only in case of damage, contains a liquid Li pool to receive the hot Li from the target. The main functions of the QT system can be summarized as:

- transformation of the free surface (versus vacuum) high velocity flow emerging from the target to a confined low velocity pipe flow;
- supply of a Li-surface level with a high enough and stable (low oscillation) pressure head at the electromagnetic pump suction inlet;
- providing of a buffer volume for the Li drained from the part of the loop over the QT during shutdown;
- homogenization of the profiled temperature field of the Li coming from the TA and to dampen step changes in the temperature to reduce thermo-mechanical loads in downstream components.

The position/configuration of the QT in the IFMIF plant has a strong effect on the building design as well as on safety, maintenance and remote handling aspects due to the large size and peculiar interface properties of the QT. In the 2013 IFMIF TC reference design [16], the QT is located in the LL area and below the TC floor (see figure 8). A long Li chute (length ~ 4.0 m) connects the TA and the QT and penetrates the TC floor

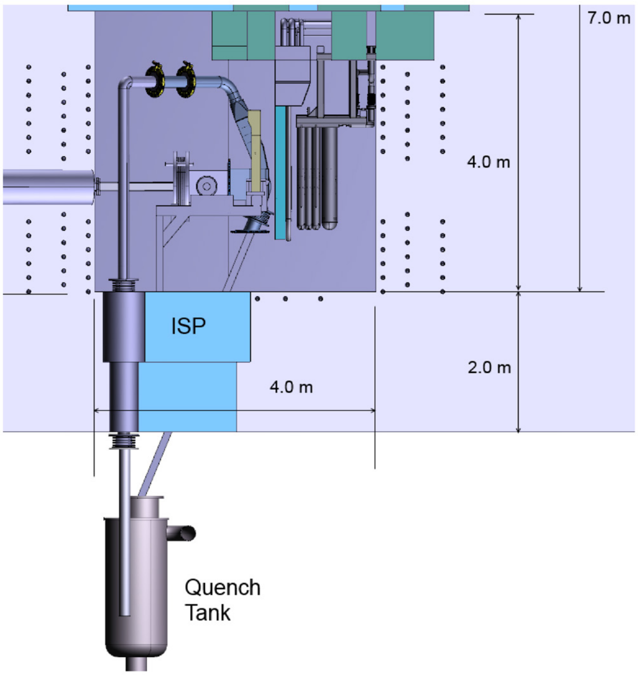

Figure 8. Quench tank configuration in the 2013 IFMIF design.

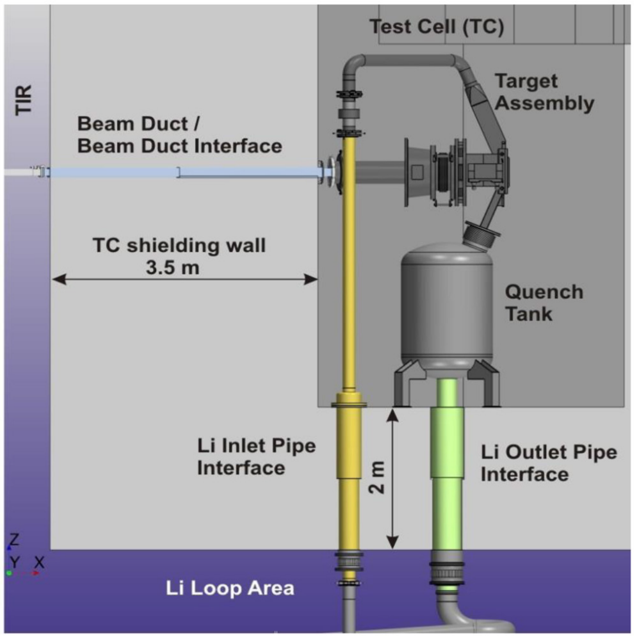

Figure 9. Quench tank configuration in the present IFMIF-DONES configuration.

through a removable interface shielding plug. This configuration was selected with the consideration of lower tritium generation, lower inventory inside the TC and possible convenient maintainability [22, 23]. Several open issues such as the cavitation in the Li flow inside the chute, expansion compensation of the long chute, etc were not fully analyzed at that time [16].

From the point of view of in-TC components, the QT-outside concept provides sufficient space in the TC to conveniently install other in-TC components, such as the TA supporting structure. Another advantage of this layout is minimizing of Li inventory inside the TC. Nevertheless, thermal–mechanical analyses show that the temperature field of the shielding plug interface and Li chute (liquid Li flows at 300 °C and the external concrete should be around 50 °C) causes relevant displacements and thermal stresses. To decrease them, insulation and controlled heating are necessary, which increases the complexity of the design, installation and maintenance. Another open issue in this configuration is the high cavitation risk of the Li flow in the chute. Additionally the neutron streaming due to the void fraction in the chute is so strong that the QT is activated to a level that avoids hands-on handling [24].

In order to solve the problem of Li flow cavitation, removing the complete chute and arranging the QT as close as possible to the TA, the QT should be placed inside the TC (see figure 9). In this concept, the QT is anchored on the TC floor and has free thermal extension upward. The Li loop is connected to the QT with an outlet pipe, which vertically penetrates the TC floor. The outlet pipe is fixed to the TC floor and extends downward. Both QT and the lithium pipes are surrounded with thermal insulation materials. Because the QT is directly located below the TA, Li injects directly into the QT without flowing through a long path.

Without the long chute, thermal compensation components can be much easier defined and configured around the QT and Li outlet pipe. The cavitation risk that is found in the reference design is minimized. And finally, the lower neutron streaming allows reducing the activation of LS components below the TC. On the contrary, due to the intensive neutron irradiations inside the TC, the QT will be activated. Therefore hands-on operation on the QT is not possible. Under this circumstance, the QT can be removed from the TC to the access cell (AC) above the TC, which is already designed for transporting highly activated components, such as HFTM and TA. The disconnecting of the QT from the TC will have to be performed using RHE below the TC floor.

The QT in-TC option will also bring additional tritium generation due to the neutron irradiation on the large amount of Li in the QT. An estimation of the tritium generation in the QT located at different positions showed that the in-TC case will produce around 0.33 g/fpy more than in the out-TC case (around 10% of the total tritium generation [24].

Finally, the other issue of this configuration, the limited spaces inside the TC due to the existence of the QT, has also been considered. The TC space analysis does not show the need of a downsizing of the QT. Detailed thermal–hydraulic analyses show that appropriate lithium behaviour can be achieved by modification of the QT shape. The QT design with a flat shape [25] has a good mixing quality and ensures smooth and stable lithium-jet inflow.

3.4. HFTM design improvements

The IFMIF-DONES design improvements of the HFTM are either direct outcomes of the validation experiments with the IFMIF/EVEDA HFTM or a consequence of the new design assumptions of IFMIF-DONES (presently it is foreseen to install only one irradiation module—the HFTM). The experiments in the IFMIF/EVEDA phase had shown a large deflection

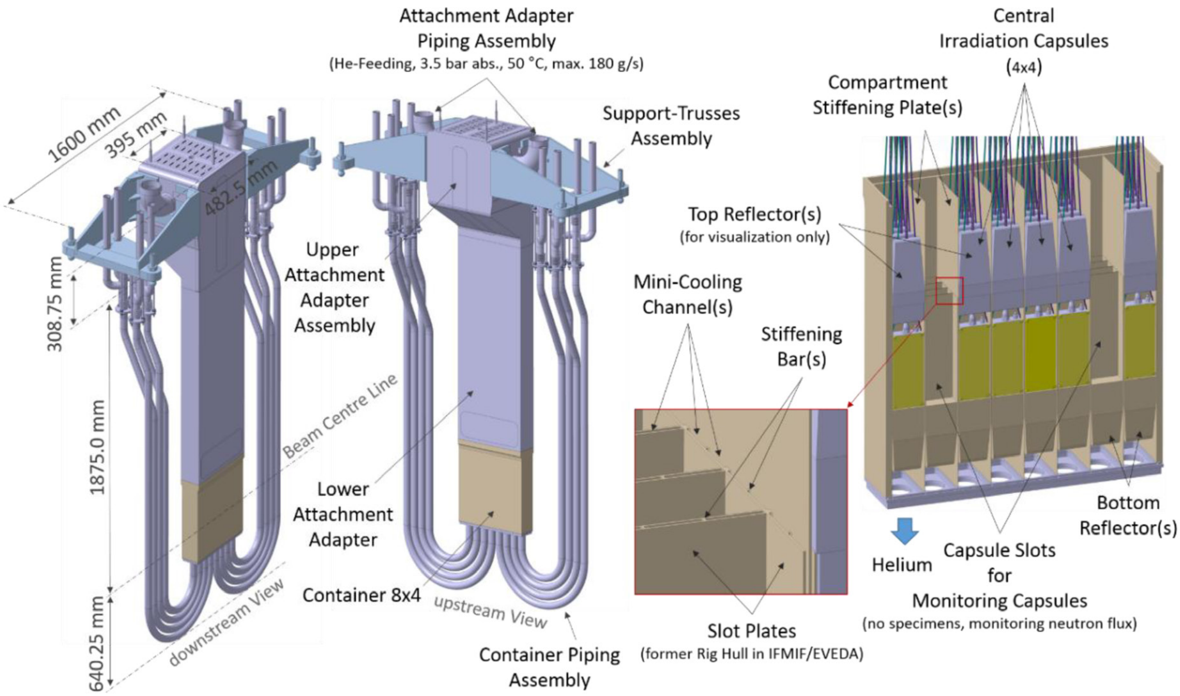

Figure 10. Left: overall structure of the IFMIF-DONES HFTM. Right: cut-open container 8 × 4, showing the eight compartments, each with four slots.

during operation of the HFTM, which was led back onto the huge temperature differences and by this to a highly different thermal expansion of the container structure. Additionally, the high deflection of the HFTM was supported by hot coolant streams from the container into the lower attachment adapter. These streams caused as well an in-homogeneous temperature-field on the lower attachment adapter and by this, different thermal expansion of the structure. To avoid the different thermal expansion of the lower attachment adapter, the coolant flow direction in IFMIF-DONES is reversed. The coolant will now be fed from the attachment adapter piping assembly through the attachment adapter assembly towards the container. This guarantees now a homogeneous temperature-field of the attachment adapter assembly with nearly no thermal induced deflection. Figure 10 shows the IFMIF-DONES HFTM present configuration including the naming of the different components for clarification.

Furthermore, the insertion of the irradiation rigs into the HFTM container of the IFMIF/EVEDA HFTM was identified as critical as well. To organize an easier installation of the specimen-equipped irradiation capsules into the container compartments, the rig-hulls and their bottom reflectors are merged with the container structure. Now, each capsule have its own slot in the container compartments (see figure 10 right side). This lowers massively the risk of mutual canting with neighboring capsules during installation. Furthermore, the integrated slots in the container thereby acts also as additionally safety barrier if any alkali metal is leaking out of any irradiation capsule. Another benefit of this integration is the increase of structural stiffness of the whole container structure, which results mainly in a higher pressure-resistance with lower deformation. The general shape of the mini-cooling-channels in the IFMIF-DONES container are similar to those in IFMIF/EVEDA, which were formed between rig-hulls and the container compartment walls.

The IFMIF-DONES design, with only one irradiation module installed, allows in addition a twice as thick module container (now 102.2 mm) as compared to the IFMIF/EVEDA one, because the nuclear heating of the HFTM container is much lower (half). By this, it is also possible to double the thickness of the specimen-equipped irradiation capsules. This is especially beneficial for the lifetime of the heater-wires of the irradiation capsules, since the bending radii are no longer based on the minimum permissible size. Moreover, of course the specimen payload increases too. It allows also an additional row of capsules in beam direction. The IFMIF-DONES HFTM container has eight compartments now with four integrated slots per compartment in the beam direction. In summary, the IFMIF-DONES container 8 × 4 has 32 slots for 32 capsules.

Another issue during the manufacture of the HFTM in the IFMIF/EVEDA phase was the manufacturing accuracy of the attachment adapter assembly—especially of the lower attachment adapter. In IFMIF/EVEDA, the lower attachment adapter was designed with asymmetric welding seams, which causes many inaccuracies. Now, the lower attachment adapter is produced by wire electrical discharge machining (EDM), out of one solid block of AISI 316 LN and X2CrNiMo17-12-2(N), respectively. The lower attachment adapter also has symmetric inspection openings on up- and downstream side with now symmetric welding seams and an organic optimized stiffening wall in the middle, to increase its stiffness. The upper attachment adapter assembly is re-designed as well and has a stiffening-plate in the middle too, like the lower attachment adapter.

The feedthroughs of the IFMIF/EVEDA phase on top of the upper attachment adapter assembly for the capsules are working solutions, but their very long, metal shielded cables will be susceptible to cable breakages and unintentional damages due to remote handling. To keep installation time of the HFTM in the TC as short as possible and to make the remote handling of the HFTM in the AC as safe as possible for the instrumented HFTM and capsules inside, connectors on top of the HFTM will be foreseen. These connectors thereby will be embedded in a quick and fail-safe multi-coupling solution—all connectors will be connected in one remote handling action step. As insulation between the chromel, alumel and copper pins of the connectors, Macor or Al_2O_3 would be good candidates. These insulation materials are used normally for high temperature vacuum applications. The connection between the HFTM and the TC will be a cable bridge, which of course is also be mounted by remote handling.

In regard to the controllability of the irradiation capsule temperatures, the experiments of the IFMIF/EVEDA phase had shown that the capsule temperatures were within the expected range and worked excellent. The temperature spread was less than ±3%, referred to absolute temperature in Kelvin, in 97% of the specimen payload volume [26, 27]. The capsule design with three heater and six thermocouples are convincing. Each heater is thereby monitored by two thermocouples [26, 28]. However, shortcomings were also identified. The BR2 irradiation experiments [26] showed deficits in heater lifetime of the capsules and a leakage of NaK. In figure 11, the latest design update of the HFTM irradiation capsule assembly of IFMIF-DONES is shown. For the heater-wire lifetime, the heater-wire bending radius is increased from 2.0 mm to 3.0 mm, which is a recommendation of the heater-wire manufacturer Thermocoax. A direct consequence of this is an increase of the specimen bin thickness in beam direction from 9.4 mm to now 19.3 mm. This is uncritical in the case of IFMIF-DONES, because—like already mentioned above—the nuclear heating is only the half of IFMIF/EVEDA. The specimen payload volume in the IFMIF-DONES irradiation capsules assembly results therefore to ~46.22 cm^3, which is double as much as in IFMIF/EVEDA. To lower the risk of leakage of liquid alkali metal (heat moderator) out of the irradiation capsules, as it happened in the BR2 experiments, the specimen bin and its bottom closure are combined now to a single part, see figure 11 bottom right. The new specimen bin is manufactured by sinker-EDM.

Furthermore, NaK-78 (eutectic mixture), used as heat-moderator in BR2 capsules and also foreseen in IFMIF/EVEDA, is replaced by sodium (Na). Neutronic analyses have shown, that under high-energy fusion-like neutron irradiation, NaK produces argon isotopes (Ar), which would massively increase the internal capsule pressure and higher by this the risk of structural failure. Additionally, Ar bubbles would be trapped in the gaps between the specimens and would act there as insulators, which can cause unsteadiness in temperature distribution, what is to avoid.

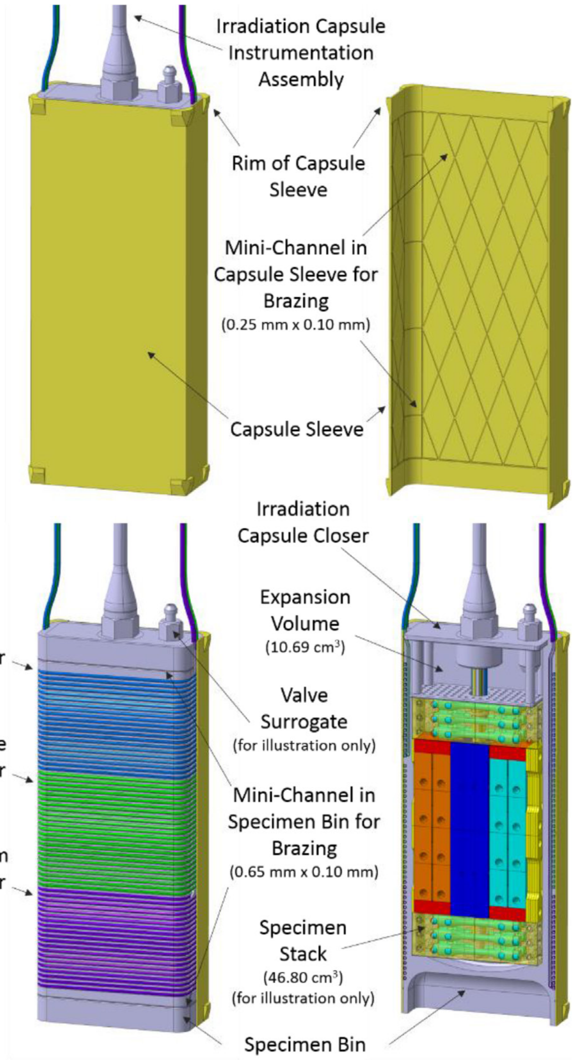

Figure 11. HFTM irradiation capsule assembly of IFMIF-DONES.

The thermal properties of liquid Na are comparable to the ones of NaK except the thermal conductivity and the respective melting liquidus temperature. The thermal conductivity in the relevant temperature range from 100 °C to 550 °C of liquid Na is in between 86.9 and 64.9 W $(m\ K)^{-1}$, the one of NaK is in between 23.2 and 26.2 W $(m\ K)^{-1}$. The higher thermal conductivity of Na is an advantage because it supports the temperature homogenization of the specimens. The melting temperature of Na is 97.72 °C whereas the one of NaK is −12.6 °C. This is the main disadvantage of Na compared to NaK, because at room temperature Na is solid. This makes the alkali metal filling process of the specimen-equipped capsules with (Na a little bit more complicated compared to NaK. The specific heat capacity in the relevant temperature range (100 °C–500 °C) of liquid Na is in between 1382.7 to 1256.8 J $(kg\ K)^{-1}$, the one of NaK is in between 937.2 and 870.3 J $(kg\ K)^{-1}$. The mean volumetric thermal expansion coefficient in the relevant temperature range (100 °C–500 °C) of liquid Na is with $0.24 \times 10^{-3}\ K^{-1}$ a little bit smaller than the one of NaK with $0.28 \times 10^{-3}\ K^{-1}$. Because of this, the thermal expansion of Na in the IFMIF-DONES irradiation capsules

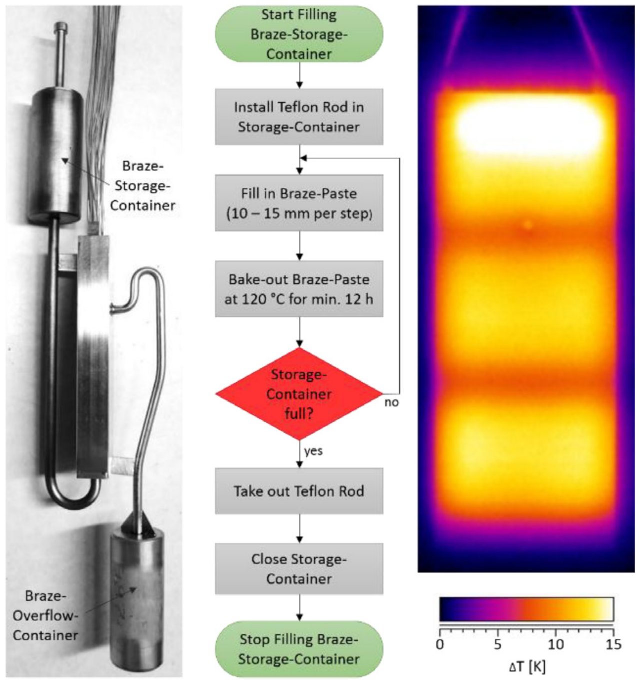

Figure 12. Principle of re-designed brazing process. Left: storage-container arrangement. Middle: filling procedure of braze-storage-container with braze paste. Right: infrared photo of a perfect brazed capsule.

is not critical. For thermal expansion of heat moderator, the expansion volume in the capsule top is foreseen. For more information about sodium and NaK-78 (eutectic mixture), see [29]. Furthermore, the compatibility of pure liquid Na with steels is very good. Liquid Na also features good wetting characteristics. An effective wetting of Eurofer and AISI 316L stainless steel specimens can be assured when the temperature of the steel-sodium system is 430 °C or higher [30]. This temperature level of the Na filling process is not critical.

However, in case of any gas production inside the capsules during irradiation, an expansion volume is inserted to collect it. As well, a 'one-time use' valve system will be foreseen in the capsule closer to evacuate the Na-filled and hermetically sealed irradiation capsules before irradiation. In contrast to IFMIF/EVEDA, a separation of function will take place in filling the capsule with alkali metal and the temperature measuring during operation. To fill the capsules with Na, a special tool and procedure will be developed, respectively.

In addition, the brazing process for the capsules is re-designed as well. Figure 12 shows the used brazing principle and its validation. These results has been obtained using a baked braze paste (Ni 710, DIN EN ISO 17672:2017-01) as brazing material. However, some embrittlement has been observed in the metal shielded wires due to the presence of phosphorus in the base braze. In the future, it will be replaced by a copper based braze (Cu 925, DIN EN ISO 17672:2017-01) which have a much lower content of phosphorus. For a good liquid braze distribution, mini-channels are integrated now into the irradiation capsule sleeve, see figure 10 top right. This will guarantee a good braze distribution and wettability and a cavity free connection between heater-wires, the specimen bin and the capsule sleeve.

3.5. Lithium purification strategy

It is known that the major impurities in the Li loop are the hydrogen isotopes and ^{7}Be (coming from the interaction of the deuteron beam with the lithium), some metallic components like Fe or Cr (coming from the limited corrosion of steels by the lithium jet) and other non metals like N, C, and O (coming from the atmospheric contamination during the maintenance periods) [31]. The impurities content of the LL must be controlled under strict limits in order to maintain the corrosion rate low enough (it is a strong function of some impurities content) and to limit the radioactive inventory. As a consequence, the presently allowed impurity content in the liquid Li loop is different for each impurity type. In the case of tritium it must be below 0.3 wppm (during the IFMIF/EVEDA phase it was 1 wppm and it has been reduced in IFMIF-DONES in order to limit the radioactive inventory); in the case of N, it must be below 30 wppm (during the IFMIF/EVEDA phase it was 10 wppm and it has been relaxed taking into account recently obtained experimental results [32]). No specific limits have been defined for metallic impurities, neither C or O but they should be reduced as much as possible in anycase to the range of tens of ppm.

A cold trap is used to extract oxygen, carbon and corrosion products as binary or ternary compounds based on their solubility (this assures a low enough content of these ions in the Li flow). The getter material is stainless steel wire mesh on which solid impurities will be deposited. On the other side, nitrogen has a very high solubility in Li and cannot be reduced to the required concentration level by cold trapping [33], therefore a hot trap is utilized, filled by a solid material (getter) able to entirely remove N. A different hot trap is also used to extract hydrogen isotopes, which are continuously produced in the target during beam operation. The getter material is yttrium, which shows a higher affinity to hydrogen than Li [34].

The DONES system in charge of controlling and monitoring the liquid Li quality is the ICS and it consists, see section 2.2, in a dedicated loop connected to the main Li loop. A few percent of the Li flow is deviate thought the purification traps. The systems also include a monitoring section. The DONES configuration, in terms of P&ID, of the ICS is given in figure 13, while in figure 14 the one of IFMIF ICS is reported.

Comparing the schemes shown in figures 12 and 13, the main differences are described.

(1) The N trap in IFMIF was foreseen in-line. This solution was abandoned for two main reasons:

  (a) there is no experience on the operation of a N trap in line, and it is extremely difficult to determine the optimum resident time and operational temperature, that are the key parameters for the design;
  (b) the Lifus 6 experience demonstrated that the contamination by N during operation is a remote possibility, also considering that the loop is operated in Ar atmosphere. The only possibility is during maintenance, and a specific purification strategy will be adopted after each maintenance operation.

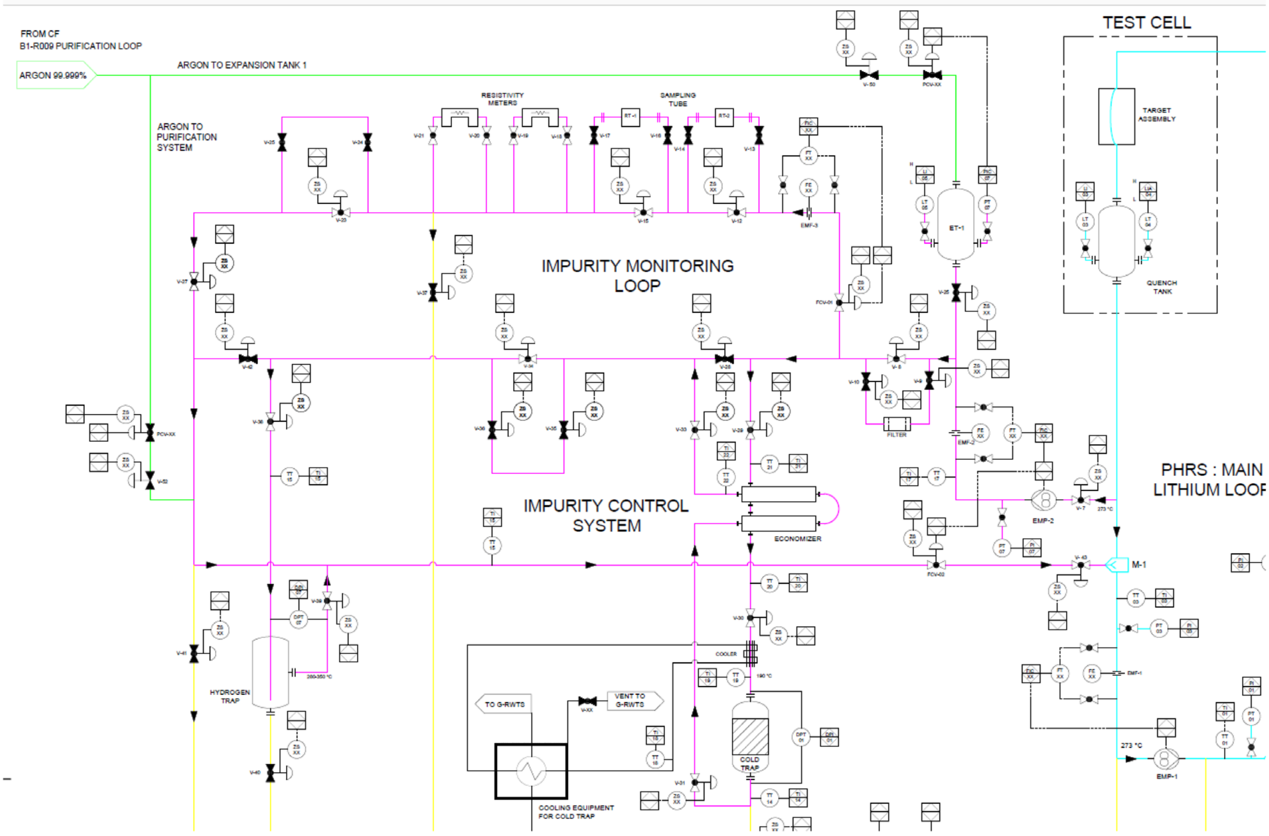

Figure 13. DONES ICS.

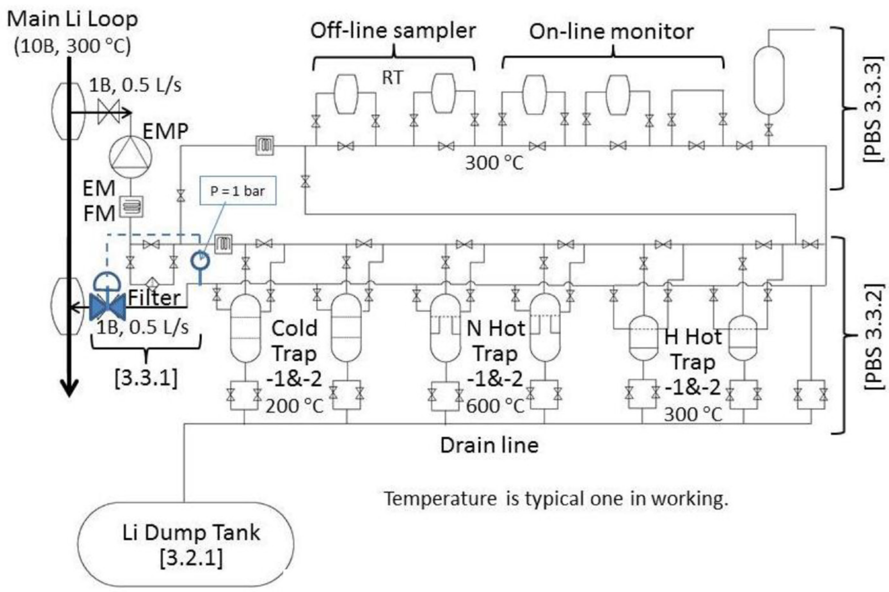

Figure 14. IFMIF ICS.

(2) To reduce the thermal losses in DONES an economizer is installed on the lithium line going to the cold trap.
(3) The cold trap is not duplicated assuming that its substitution will be necessary only after the commissioning phase and each 15 years of operation, but it will be possible also during loop operation in a relatively short time.

The ICS components, including the N trap that is now not part of the purification loop (PL), are dimensioned on the basis of the design parameters shown in table 4.

The N hot trap, allocated in the lithium storage tank, DT, will be operated in static condition on the whole Li inventory, before the first start-up of the plant and after the stops for

Table 4. Design parameters of the DONES lithium main loop (included in the heat rejection system) and the purification and monitoring loops (included in the ICS).

Fluid	Liquid lithium
Design temperature	350 °C
Design pressure	0.45 MPa (g)
Maximum flow rate:	
Li main loop	104 l s^{-1} (16 m s^{-1} in the Li jet)
ICS	0.65 l s^{-1}
Purification loop	90% 0.65 = 0.585 l s^{-1}
Monitoring loop	10% 0.65 = 0. 065 l s^{-1}
Li flow velocity	<6 m s^{-1}
Material	316 l

maintenance. The getter material has not been surely defined yet, but it will be chosen among titanium, titanium alloys or niobium. In order to provide sufficient reactivity, the trap is operated at 500 °C–600 °C nominal temperature: because of this high value, the trap will be realized in SA-240 316H. The amount of nitrogen is calculated assuming a maximum initial content of ~3150 g (700 wppm) and an annual recontamination of ~9 g (2 wppm) during the maintenance procedure of the loop: the trap, dimensioned to cover the DONES lifetime, is then asked to manage up to ~3500 g of nitrogen.

The hydrogen isotopes and other impurities (O, C, ^{7}Be, etc) will be instead removed online in the purification branch through, as previously mentioned, two types of traps [35].

- A cold trap to extract oxygen, carbon and corrosion products as binary or ternary compounds based on their solubility. The getter material is stainless steel wire mesh on which solid impurities will be deposited. The trap is operated at 200 °C. To reduce thermal losses in the room, that as explained is filled with a controlled Ar atmosphere, the reduction of lithium temperature before the cold trap follows a two step process: Li with a temperature of 280 °C passes first through an economizer and is cooled along the trap by an external Ar cooling circuit. The trap is sized based on the oxygen source term assuming the estimated initial content and the possible annual recontamination due to the maintenance. The trap is dimensioned to cover the DONES lifetime. In the current design it is still under evaluation the possibility to integrate the cooler in the cold trap or to have a separate cooler. In any case the second step of cooling will be performed using forced convection with the Ar present in the room. The resident time fixed for the cold trap is 10 min, with a flow of 0.585 l s^{-1}.
- A hot trap to extract hydrogen isotopes, which are continuously produced in the target during beam operation. The trap operates in the temperature range of 280 °C–300 °C. The traps are sized to extract the annual production of hydrogen isotopes (83.3 moles, 93% deuterium and 4% tritium), and is scheduled to be replaced by remote handling during operation as frequently as needed (typically on a monthly basis) in order to maintain the tritium inventory below a given limit.The initial content of hydrogen assumed as design basis is 720 g, which is to be removed during the commissioning phase. The hydrogen trap serves not only a technical function, but also a strong safety function, because in case of an accident it should be the major source of tritium released in the environment. For this reason a double trap configuration is the final choice. In such a way, it will be possible to reduce the tritium inventory in the loop, removing the trap when the tritium confined inside it reaches a fixed value.

The ICS holds also a monitoring branch, which in turn contains:

– Li samplers, to collect Li samples for off-line analysis. The unit is arranged to allow sampling and extraction of the sampler during operation;
– online monitoring systems: a resistivity meter to measure the electric resistance of the Li, which is indicative of the integral non-metallic impurities content, with a higher sensitivity to nitrogen and hydrogen [36];
– an electrochemical hydrogen sensor [37]. The development and the qualification of an electrochemically based H-sensor, which can be operated in liquid lithium under online measurement conditions, is an important issue, due to the fact that hydrogen isotopes can not only have a strong impact on the use of structural and functional materials but also on safety. The measurement of the dissolved hydrogen content in the melt under given test and process conditions will be essential. Thus, the H concentration has to be monitored and controlled, preferably by a fast response and reliable on-line technique. The dimension of the H-sensor, its shape and the finish as single-rod measuring cell, are already as close as possible harmonised to an easy use for external liquid lithium applications (outside of inert gas containments). Possible variations might evolve by updated requirements and will refer to length and width or external heating elements.

3.6. The remote handling approach in DONES

Remote handling maintenance of DONES' systems and components is very a challenging activity involving almost all areas of the plant. Each system of DONES is designed to guarantee an availability of 70% of DONES plant and then systems and components must be monitored, inspected and maintained so that they function as per design. To fulfill this stringent requirement of plant availability, the annual preventive maintenance of components has to be completed within 20 d, counted between the beam off and beam on phases. According to this, a proper maintenance strategy has been implemented that relies, among the other things, on the possibility to parallelize all maintenance operations in each area of the DONES plant. The systems and components of DONES requiring regular and scheduled maintenance have been already identified and the most critical ones are in the TC of the TS, since they are located in the most severe region

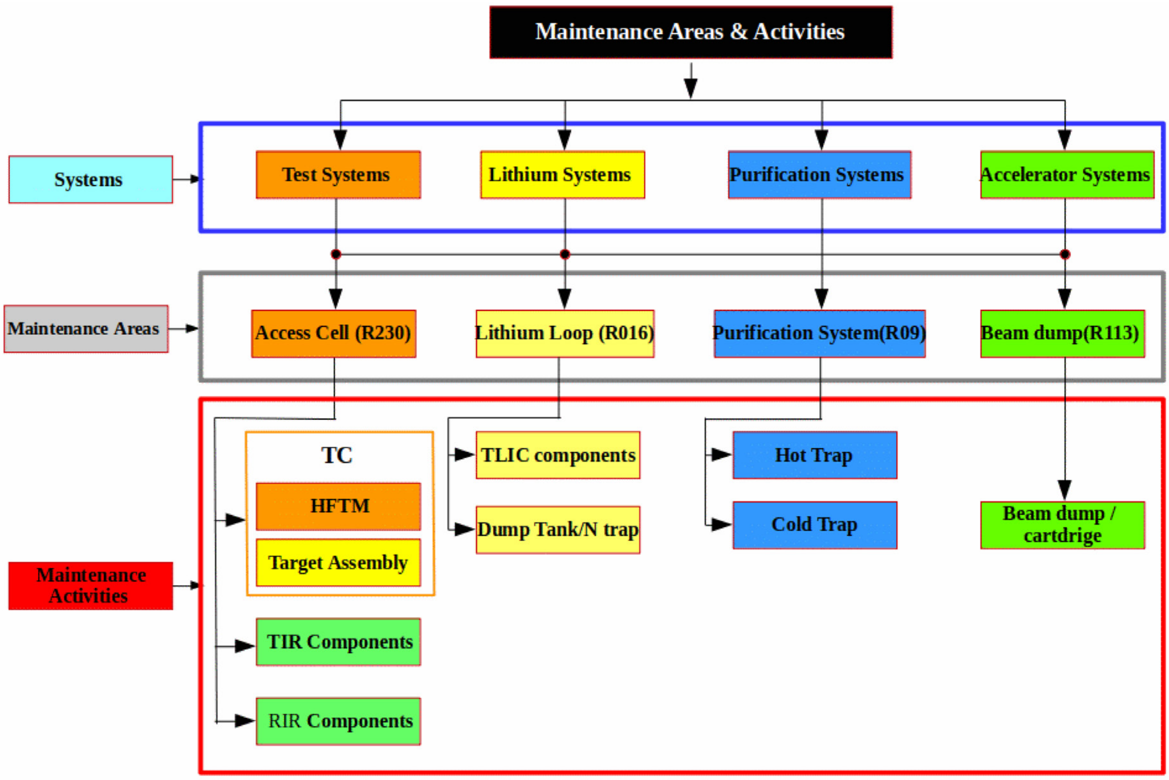

Figure 15. DONES maintenance areas and activities.

of neutron irradiation. All these maintenance operations have to be performed remotely in dedicated areas equipped with special RHE.

There are four main areas in DONES for the maintenance of critical components via RH: the AC, the LL, the PL and the beam dump area (BD). These are independent areas provided with suitable RHE and tooling for the execution of the maintenance tasks. The graph in figure 15 gives an overview of the main maintenance activities to be performed in each of these areas for first class components. In addition, there is another maintenance area, not included in this figure, namely the irradiating waste treatment cell (IWTC). This latter area is devoted at the handling of the solid irradiated waste components and at dismantling critical components, such as the TA and the HFTM, to minimize its size and weight so that samples of these components can be transported out of DONES facility for the post irradiation examination (PIE) activities.

The most critical area, from the RH maintenance point of view, is the AC, because it covers the maintenance of components belonging to different systems. The possibility to parallelize, as much as possible, the maintenance operations in that area is the main effort carried out to stay within the window period for the preventive maintenance. Here a general description of the AC arrangement is given together an overview of the main maintenance process.

The AC is located just above the TC, the transfer irradiation room (TIR) and radiation interface room (RIR) areas, and it is sized to accommodate all the RHE and tooling for the execution of the maintenance tasks, as well as for the temporary store of all removable components, such as the test cell cover plate (TCCP) and the two TC shielding plugs, while the TC is open, and the shielding plugs of the hatches. An overview of the AC layout is given in the figures 16 and 17.

The T shape AC consists of two areas: the main and the annex areas. This architecture allows performance of parallel maintenace operations, as follows.

- In the main area:
  - opening and closing of the TC including plugging/unplugging of electrical and cooling pipes;
  - HFTM exchange and its transportation to the IWTC for its dismantling;
  - TA exchange and its transportation to the IWTC for its dismantling;
  - exceptionally, also maintenance on components belonging to the third class of the RH classification could be required, such as the steel liner and the shielding cooled walls of the TC.
- In the annex area:
  - TIR component replacements, such as vacuum pump, collimator, TA diagnostics and beam duct;
  - RIR component replacements.

The maintenance for in-TC components will be performed in a serial sequence, the HFTM is removed first and installed last, while the TA is installed first and removed last. Concerning the AC extension area, where maintenance of the TIR and RIR components is performed, no parallel operations are possible with the present configuration: maintenance will be performed in sequence in the TIR or in the RIR. However, it

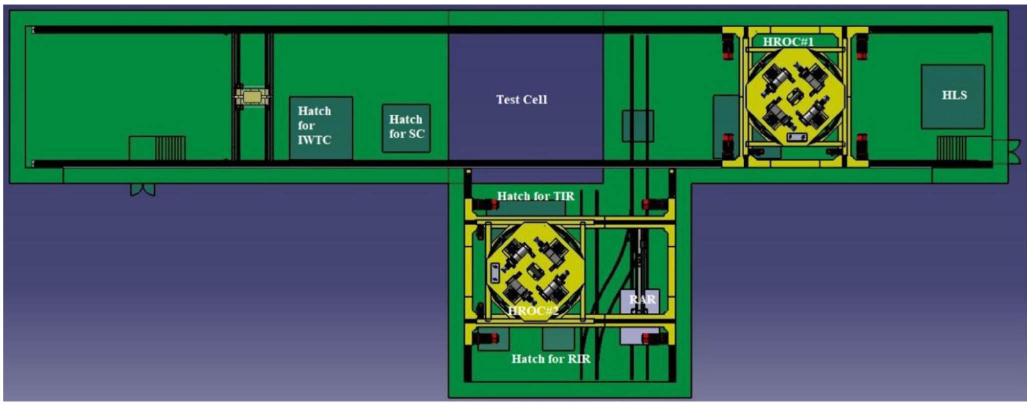

Figure 16. Top view of the AC of DONES.

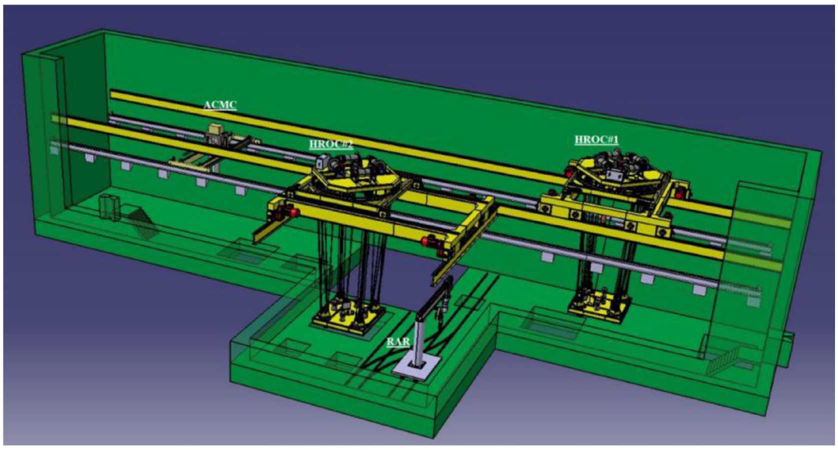

Figure 17. 3D model of the AC (open view).

should be pointed out that the frequencies of maintenance for these latter components are still unknown. Figure 18 shows a flow diagram for the maintenance activities in the AC.

To accomplish all RH maintenance tasks the AC is provided with a RHS consisting of the following main equipment.

- In the main area:
  - **The heavy rope overhead crane (HROC#1):** the HROC is a nuclear grade multi-ropes double beam overhead travelling crane. It is a fully 6 DoF crane having a payload capability up to 140 tons. The HROC is used to perform transfer operations in the AC of massive components, such the upper shielding plug, the lower shielding plug and the TCCP. A 3D model of this equipment is shown in figure 19.
  - **The access cell mast crane (ACMC):** the ACMC is a nuclear grade double beam overhead crane equipped with vertical telescopic boom. It is used for the maintenance of in-TC components. At the lower end of the telescopic boom a mast gripper change system is installed allowing the use of various devices and end effectors: parallel kinematic manipulator, robotic arm, HFTM gripper (a lifting/positioning frame for HFTM installation and removal), mast grapple (for vertical handling of components of mass up to 2 tons). It is also equipped with an auxiliary hoist with a payload up to 3 tons. An overview of the installation of the ACMC in the AC is shown in figure 20 left, while in figure 20 right the main end effectors used by the ACMC are illustrated.
- In the annex area:
  - **The heavy rope overhead crane (HROC#2):** it is a crane such as the HROC#1 covering the TIR and the RIR area. It has a load capability up to 60 tons, and is used to remove and install the TIR and RIR plugs.
  - **Robotic arm on rail:** a Servomanipulator installed on rails, running between the AC annex and main area. It is designed to support normal maintenance operations, as well as the execution of rescue operations, for the TIR, RIR and TC components. It has 6 DoF, plus 2 DoF of the mobile platform, and a payload capability of a few tens of kilograms.
  - **Robotic mast arm (RMA):** a telescopic mast extending down from the AC with the servomanipulator mounted on the bottom on the mast on a horizontal pivot allowing a pitching movement. The top of the mast is mounted on the end of an articulated boom, which in turn is mounted on a linear horizontal rail on the wall of the AC annex. The RMA is the main robotic system employed for the maintenance of the TIR components. In figure 21 the conceptual design of the RMA is illustrated.

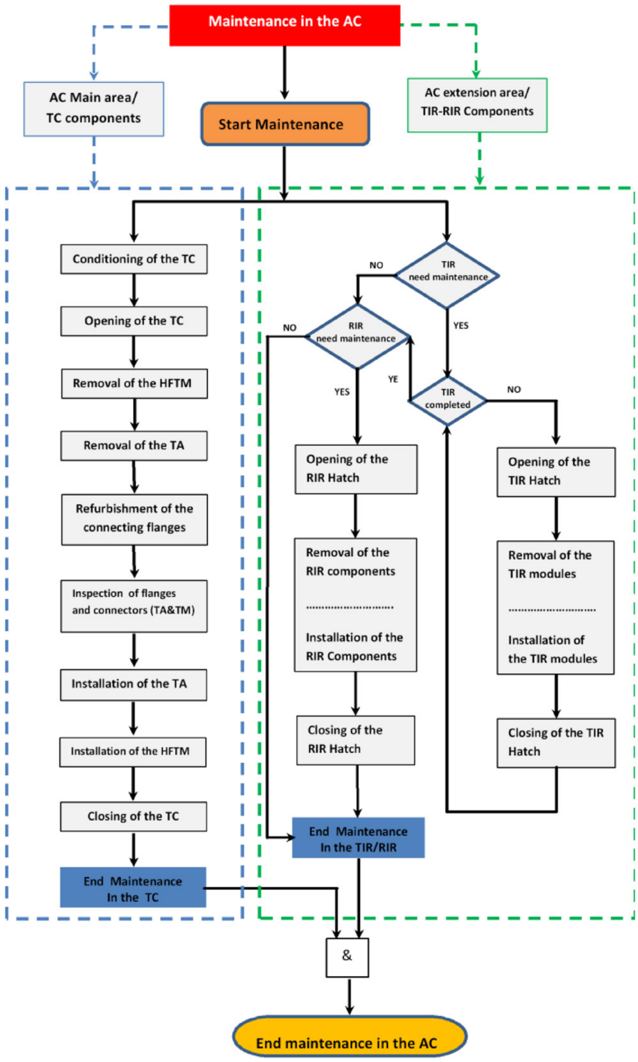

Figure 18. Flow diagram for the maintenance activities in the AC.

3.7. Complementary experiments at DONES

Facilities for complementary experiments have been added to the baseline DONES plant configuration to allow for installation of complementary physics experiments, independent of materials irradiation. The idea of a possible extension of the scientific objectives of the DONES facility was pursued as part of the EUROFusion ENS work package activities in collaboration with the Scientific Council of the Polish ELAMAT Consortium. A White Book report on 'Complementary Scientific Programme at IFMIF-DONES' [12] was prepared by a group of international experts. The collection of science cases for the complementary research can be ordered by domain: (1) applications of medical interest, (2) nuclear physics and radioactive ion beam facility, (3) basic physics studies, and (4) industrial application of neutrons. It has been concluded that many of these research topics can be accommodated into the DONES design and operation without compromising its main role of a material irradiation facility for the fusion program. At the same time, the unique characteristics

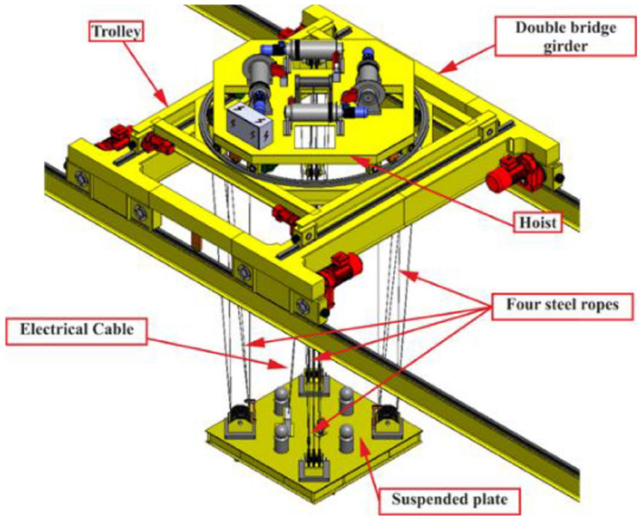

Figure 19. 3D model of the heavy rope overhead crane.

of the DONES facility, its neutron energy spectrum and flux intensity, present to the science community capabilities not offered at other research infrastructures such as fission reactors and spallation neutrons sources.

The present design of DONES includes a dedicated *collimated neutron beam facility* to be placed behind the TC—see the scheme of figure 22. It is foreseen that one or several neutron guides will be used to collimate the neutron flux remaining after passing through the HFTM and send it through the wall of the TC to an adjacent complementary experiments hall. The size of the room (~330 m^2) allows for placement of several experimental setups which can be connected to the neutron guides. The complementary experiments hall will be allowed to be open and accessible for setting up and maintenance of the equipment while the irradiation of samples in the HFTM is ongoing. Thus, the experiments will be operated in a parasite mode without having any effect on the continuous operation of DONES facility.

The layout of experimental equipment and its requirements are roughly estimated and will be determined in detail by the user groups. Below we list a number of complementary experiment topics which have been proposed for implementation using the neutron flux after its passing through the HFTM.

- Irradiation facility for the production of radioisotopes suitable for medical imaging and diagnostics, positron emission tomography (PET) and targeted alpha therapy, such as ^{99}Mo, ^{47}Sc (β emitter suitable for PET) and ^{225}Ac (alpha therapy). The production mechanisms require irradiation with fast neutrons with energies above 10 MeV.
- Studies of reactions induced by fast neutrons, such as (n, n'), (n, xn), production of light charged particles and neutron-induced fission.
- Production and spectroscopic studies of the most exotic neutron-rich nuclei via fast-neutron-induced fission.
- Investigation of the β–ν correlations in light radioisotopes produced by neutron beams.

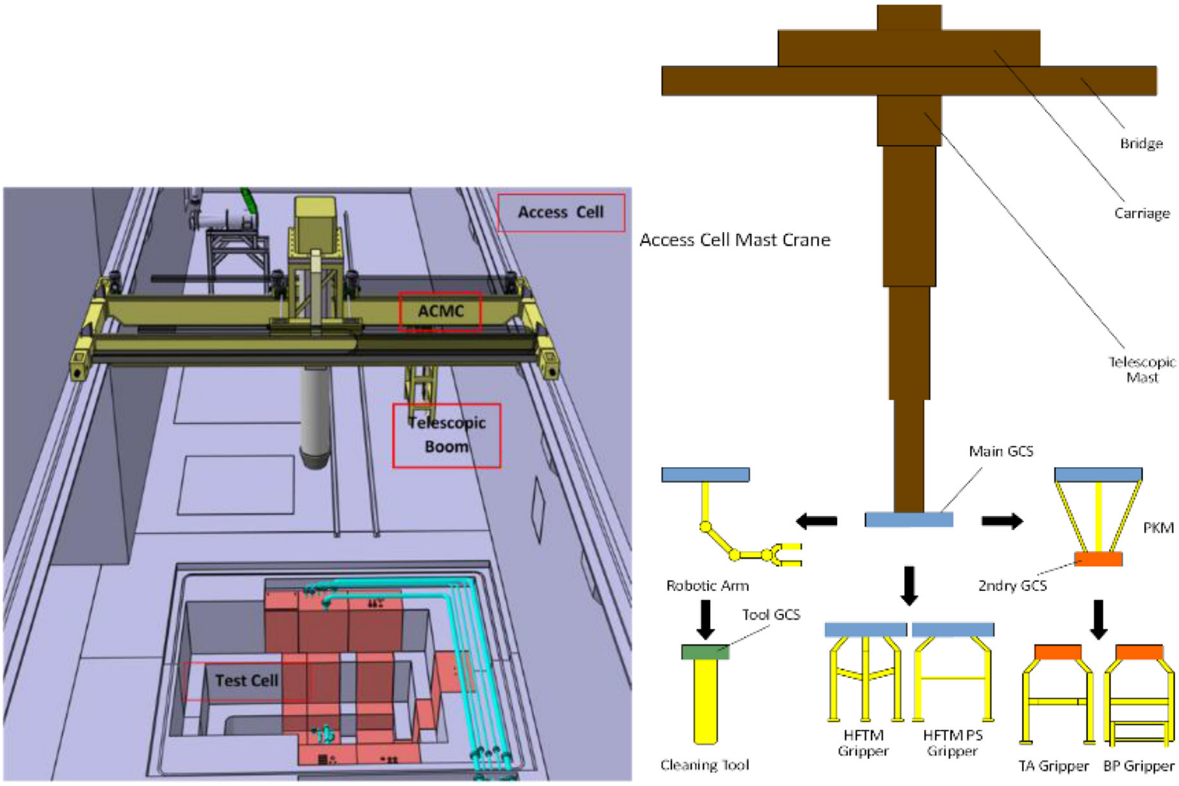

Figure 20. Overview of the ACMC as installed in the AC (left) including a summary of the main end effectors (right).

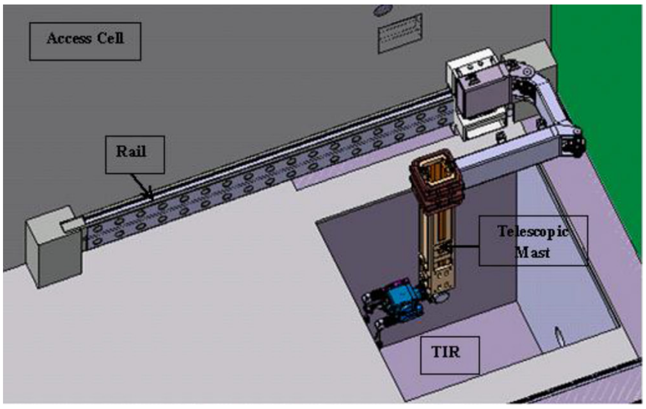

Figure 21. Conceptual design of the RMA.

– Half-life measurements on long-lived isotopes produced in (n, α) reactions.
– Computed tomographic imaging of small objects using a collimated beam of fast neutrons.
– Neutron-transmutation doping of silicon and testing of radiation effects in electronic devices.

It has also been proposed to be used for complementary experiments a fraction of the deuteron beam. This could be done either at the middle energy beam transport (MEBT) section of the accelerator with the D+ beam of 5 MeV energy, or at the exit of the SRF linac taking advantage of the full beam energy of 40 MeV. The deflection of a 1/100 to 1/1000 fraction of the full beam intensity for complementary experiments would have an insignificant impact of the neutron flux parameters yet offer an interesting opportunity for other experiments requiring relatively high beam intensity such as production of medical isotopes or rare radioactive species. The main difficulty in pursuing this approach is to assure that the deflection mechanism based on an electrostatic beam kicker does not deteriorate the beam parameters—beam dynamics and losses and beam time structure—which are essential for the proper operation of the lithium target. Beam dynamics studies performed up to now show that this may be difficult for the deuteron beam at 5 MeV energy, yet it is considered feasible for the 40 MeV beam energy. Further studies will be made to determine the time structure of the deflected beam and obtain a conceptual design of the beam kicker.

4. Granada (Spain) site

Most of the engineering work carried out up to this moment has been developed for a generic site. In parallel to this development, during the last two years and in the framework of the site selection process launched at the European level by Fusion for Energy, Spain and Croatia (the two countries that initially bid to site the facility) joint forces in an effort to assure the facility is built in Europe as soon as possible and agreed that it should be built in Granada (Spain). This agreement has been welcomed recently by Fusion for Energy and by the EU Council of Ministries. Figure 23 shows the site layout for the IFMIF-DONES facility in the proposed site.

It consists of a usable surface area of around 10 hectares, close to a rectangular shape. The main building is erected at

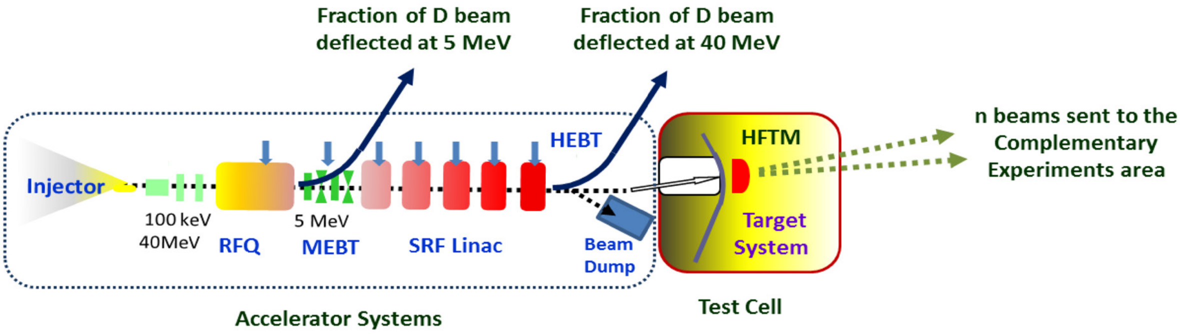

Figure 22. Schematic view of the possible placement of complementary experiments in the DONES facility. Experiments will use either the neutron flux behind the HFTM or a fraction of the D beam deflected in the MEBT (5 MeV energy) or HEBT (40 MeV energy) section of the accelerator.

Figure 23. Preliminary layout of DONES in the Granada site (grey buildings are the ones required for a possible future upgrade to IFMIF performance).

its center, and it is directly connected with the adjacent access control and administration 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 cablings. Connected to the main building through service galleries and distributed all along the perimeter of the site, the different services areas are laid down: transformers 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, another parking area is erected.

The overall dimensions of the main building are 158.5×74.75 m, and externally it is a two-storey building. It has two underground levels of basement (the bottom most basement occupying only a reduced area of the total footprint of the building, and the upper basement level occupying the whole building footprint). It has one elevated floor as well with whole building footprint and other elevated floor with same partial footprint as bottom basement. In general terms, it can be divided into two different parts: accelerator area and irradiation area.

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.

Safety is being integrated in DONES design according to Spanish and international regulations inspired in nuclear facilities, which assure an important degree of robustness of the facility to provide protection to the public, the workers and the environment. Safety activities are challenging due to the first-in-a-kind nature of the facility and the numerous safety functions involved for several dedicated systems. Design basis are being developed in a continuous interaction with design teams and the licensing process is expected to be launched shortly. One of the top level national regulation is the Spanish 'RINR', or 'Regulation for Nuclear and Radioactivity Facilities', as of 1999, modified in 2015, which leads to IFMIF-DONES classification as a 'First Category Radioactive Facility'. The complete set of required documentation to provide to the regulatory body for licensing of facilities is specified according to the RINR classification. In the case of DONES, a single operation permit will be requested. The owner of the facility must have as general objective to protect people of the public and workers as well as the environment from dangerous effects of ionizing radiation. In accomplishment to such objective, important safety principles apply, as limitation, controlling and minimization of radioactive material, limitation of probability of events related to loss of control, minimization of consequences, and minimization of waste production.

5. Conclusions

In this paper, the status of the IFMIF-DONES engineering design is summarized. It is strongly based on the IFMIF engineering design developed in the framework of the IFMIF/EVEDA project and, as a consequence, all the prototyping results obtained in this project can be also applied to IFMIF-DONES. Anyhow, a significant design evolution takes place as compared to the IFMIF engineering design solving some pending issues.

The present baseline engineering design is consolidated, although some minor additional design changes are under discussion (mainly related to the TC configuration) and in order to take into account site specific features.

In summary, the DONES project, based on the present reference baseline engineering design, will be able to provide in short time (around 2 years of irradiation time) a set of around 200 SSTT specimens (following the small specimen-testing-techniques standards) irradiated up to 30 dpa with a neutron spectrum similar to fusion reactor spectra, together with, in a longer timeframe, an additional set of around 1000 samples irradiated up to 40–50 dpa, and a much higher number at lower irradiation doses, that will provide the related set of materials properties data required for DEMO design.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission, Fusion for Energy or of the authors' home institutions or research funders.

ORCID iDs

A. Ibarra https://orcid.org/0000-0002-2420-2497

References

[1] 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

[2] Donné T. and Morris W. 2018 *European Research Roadmap to the Realisation of Fusion Energy* (www.euro-fusion.org/eurofusion/roadmap)

[3] Knaster J. *et al* 2013 IFMIF: overview of the validation activities *Nucl. Fusion* **53** 116001

[4] Ibarra A. *et al* 2014 A stepped approach from IFMIF/EVEDA towards IFMIF *Fusion Sci. Technol.* **66** 252–9

[5] Ibarra A. *et al* 2018 The IFMIF-DONES Project: preliminary engineering design *Nucl. Fusion* **58** 105002

[6] Kondo H. *et al* 2017 Validation of liquid lithium target stability for an intense neutron source *Nucl. Fusion* **57** 066008

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

[8] Arena P. *et al* 2019 The design of the DONES lithium target system *Fusion Eng. Des.* accepted (https://doi.org/10.1016/j.fusengdes.2019.02.024)

[9] Dezsi T. *et al* 2018 Overview of the current status of the IFMIF-DONES secondary heat removal system design *Fusion Eng. Des.* accepted (https://doi.org/10.1016/j.fusengdes.2018.12.084)

[10] Schwab F. *et al* 2019 Thermomechanical analysis and design optimisations of the IFMIF-DONES HFTM *SOFT18 (29 September–3 October, Taormina)* (https://agenda.enea.it/event/60/contributions/698/contribution.pdf)

[11] Tian K. *et al* 2018 Overview of the current status of IFMIF-DONES test cell biological shielding design *Fusion Eng. Des.* **136A** 628–32

[12] Maj A. *et al* 2016 White Book on the complementary scientific programme at IFMIF-DONES *IFJ PAN Report* 2094/PL (Garching: EUROfusion) (https://ifj.edu.pl/badania/publikacje/raporty/2016/2094.pdf)

[13] Barcena J. *et al* 2018 Design of the main building and plant systems of the IFMIF-DONES facility *SOFT18 (29 September–3 October, Taormina)* (https://agenda.enea.it/event/60/contributions/1646/contribution.pdf)

[14] Micciche G. *et al* 2019 The remote handling system of IFMIF-DONES *Fusion Eng. Des.* accepted (https://doi.org/10.1016/j.fusengdes.2019.01.112)

[15] Cappelli M. *et al* 2018 DONES central instrumentation and control systems: general overview *SOFT18 (29 September–3 October, Taormina)* (https://agenda.enea.it/event/60/contributions/1464/contribution.pdf)

[16] Knaster J. *et al* 2015 The accomplishment of the engineering design activities of IFMIF/EVEDA: the european-japanese project toward a Li(*d*, *xn*) fusion relevant neutron source *Nucl. Fusion* **55** 086003

[17] Mosnier A. 2008 The IFMIF 5 MW linacs *Proc. of LINAC 2008 (29 September–3 October, Victoria, Canada)* p FR201 (http://accelconf.web.cern.ch/accelconf/linac08/papers/fr201.pdf)

[18] Nghiem P. *et al* 2011 The IFMIF-EVEDA challenges in beam dynamics and their treatment *Nucl. Instrum. Methods Phys. Res.* A **654** 63–71

[19] Bazin N. *et al* 2017 Manufacturing status of the IFMIF LIPAc SRF-linac *Proc. of IPAC2017 (14–19 May, Copenhagen, Denmark)* (http://accelconf.web.cern.ch/AccelConf/ipac2017/papers/mopva038.pdf)

[20] TraceWin and GenlinWin (http://irfu.cea.fr/Sacm/logiciels/index.php)

[21] Du L. *et al* 2018 Beam dynamics studies for the IFMIF-DONES SRF-linac *Proc. of IPAC 2018 (29 April–4 May, Vancouver, Canada)* p 687

[22] Nitti F.S. *et al* 2015 The design status of the liquid lithium target facility of IFMIF at the end of the engineering design activities *Fusion Eng. Des.* **100** 425–30

[23] Simakov S.P. *et al* 2004 Assessment of the ^{3}H and ^{7}Be generation in the IFMIF lithium loop *J. Nucl. Mater.* **329–33** 213–7

[24] Qiu Y. *et al* 2017 Neutronics assessment of different quench tank location options in IFMIF-DONES *Fusion Eng. Des.* **124** 1059–62

[25] Gordeev S. *et al* 2018 Analyses of the quench tank configuration for DONES liquid-lithium target system *Fusion Eng. Des.* **136** 330–4

[26] 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

[27] Klein C. *et al* 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

[28] Schwab F. *et al* 2017 Manufacturing of the IFMIF HFTM double compartment prototype *Fusion Eng. Des.* **124** 1068–72

[29] Foust O.J. 1972 *Sodium-NaK Engineering Handbook* (*Sodium Chemistry and Physical Properties* vol 1) (London: Gordon and Breach)

[30] Abou-Sena A. *et al* Using sodium as filling and heat-conducting material in the irradiation capsules of the fusion materials irradiation facility IFMIF-DONES *Fusion Eng. Des.* submitted

[31] Knaster J. and Favuzza P. 2017 Assessment of corrosion phenomena in liquid lithium at $T < 873$ K. A Li(d, n) neutron source as case study *Fusion Eng. Des.* **118** 135–41

[32] Favuzza P. *et al* 2018 Erosion-corrosion resistance of reduced activation ferritic-martensitic steels exposed to flowing liquid lithium *Fusion Eng. Des.* **136** 1417–21

[33] Hirakane S *et al* 2005 Gettering of nitrogen in liquid lithium *Fusion Eng. Des.* **75–79** 721–4

[34] Edao J. *et al* 2010 Tritium S. removal by Y hot trap for purification of IFMIF Li target *Fusion Eng. Des.* **85** 53–7

[35] Kato Y. *et al* 1998 Impurity control in liquid lithium loop for IFMIF target facility *J. Nucl. Mater.* **285–63** 394–9

[36] Creffrey G.K. *et al* 1974 Electrical resistivity of liquid and solid lithium *J. Chem. Soc.* **0** 2325–9

[37] Hoilstein N. *et al* 2019 Development of an electrochemical sensor for hydrogen detection in liquid lithium for IFMIF-DONES *Fusion Eng. Des.* accepted (https://doi.org/10.1016/j.fusengdes.2019.02.100)