OVERVIEW OF ACHIEVEMENTS OF THE IFMIF/EVEDA PROJECT

Y. CARIN
Fusion For Energy
Rokkasho, Japan
Email: yann.carin@f4e.europa.eu

S. CHEL
CEA, Université Paris-Saclay
Saclay, France

P. CARA, H. DZITKO, G. PHILLIPS
Fusion For Energy
Garching, Germany

A. FACCO
Istituto Nazionale di Fisica Nucleare
Legnaro, Italy

D. GEX
Fusion For Energy
Rokkasho, Japan

K. HASEGAWA, A. KASUGAI, K. KONDO, S. SATO, M. SUGIMOTO
National Institutes for Quantum Science and Technology
Rokkasho, Japan

G. MICCICHE
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA)
Brasimone, Italy

J. MOLLA, D. JIMENEZ
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)
Madrid, Spain

D. RADLOFF
Karlsruher Institut für Technologie (KIT)
Karlsruhe, Germany

D. TERENTYEV
SCK CEN
Mol, Belgium

Abstract

The International Fusion Materials Irradiation Facility (IFMIF) is conceived to generate fusion relevant neutrons with a broad peak at 14.1 MeV through Li(d,xn) nuclear reactions. IFMIF will enable high intensity neutrons to irradiate materials at above 20 dpa/fpy (displacement per atom per full power year) of a volume around 500 cm^3 in the high flux test module. IFMIF is presently in its Engineering Validation and Engineering Design Activities (EVEDA) phase under the Broader Approach (BA) Agreement signed between EURATOM and Japanese Government in 2007. This agreement mandates to validate the design of the different systems of IFMIF and to produce an integrated engineering design of IFMIF, together with the data necessary for future decisions on the construction and operation of the plant. While the Engineering Validation Activity (EVA) of the Lithium Target Facility and the Test Facility was completed by constructing prototypes, the EVA of the Accelerator Prototype Facility with the Linear IFMIF Prototype Accelerator (LIPAc) is still on-going. This article overviews the achievements in the previous phase ended on 31 March 2020 and the progress in a new phase to complete the commissioning of the LIPAc and to enhance the sub-systems in order to prepare for the design of the future Fusion Neutron Source facility.

1. FUSION NEUTRON SOURCE

In the Tokamak of a fusion reactor, a plasma of Tritium and Deuterium is created thanks to the magnetic confinement and at high temperature. The reaction of these two isotopes of hydrogen gives one helium nucleus and 14.1 MeV neutrons. While the thermal energy could be recovered for electricity production, these high energy neutrons interact with the plasma facing components such as the first wall of the blankets. This interaction leads to the damage of the materials constituent of these components and consequently changes the properties of these materials. As an example, the ductility of the structural material (e.g. EURIFER97 or F82H) drops drastically making the material very brittle. Thus, it is essential to study and to understand these changes in particular to ensure the structural integrity of the components.

On the other hand, a fusion power plant should be capable to operate during several years in order to be economically viable. The first concept of such a facility like DEMO [1] foresaw a damage rate of more than 15 displacement per atom (dpa) per year of operation. Considering 20 years of operation or 6 full power years, the cumulated damage will be rather significant.

Unfortunately, the fission reactor used for the irradiation of materials provides a spectrum of neutron flux with a peak not more than 3 MeV. So, the data generated by irradiating material specimens in these types of reactors are not representative of a deuterium-tritium fusion reaction inside the Tokamak.

Therefore, it is crucial to have a dedicated facility for studying the effects of fusion-like neutrons on both functional and structural candidate materials for DEMO. Following on a review by the International Energy Agency [2], it was concluded that the concept of a D-Li stripping source is the preferred neutron source because of its relatively lower neutron source energy tail and its more mature technology base. Whereas, the feasibility of beam-plasma-based source was still in question despite providing better simulation of the fusion reaction and the material community was not in favour of a spallation source because of its cost. This was the basis for the International Fusion Material Irradiation Facility (IFMIF).

The IFMIF architecture (see below FIG. 1) is an accelerator-based intense neutron source with a deuteron beam of 125 mA in Continuous Wave (CW) accelerated at 40 MeV to interact with a liquid lithium free surface at 250°C and flowing at 15 m/s generating fusion-like neutrons. In the full IFMIF concept, even 2 accelerators are considered to reach a beam intensity of 250 mA on the lithium target. The candidate materials for fusion reactors are placed in a test module just after the lithium target so that they are subjected to similar conditions expected to be experienced inside a future fusion power plant or a demonstrator (DEMO).

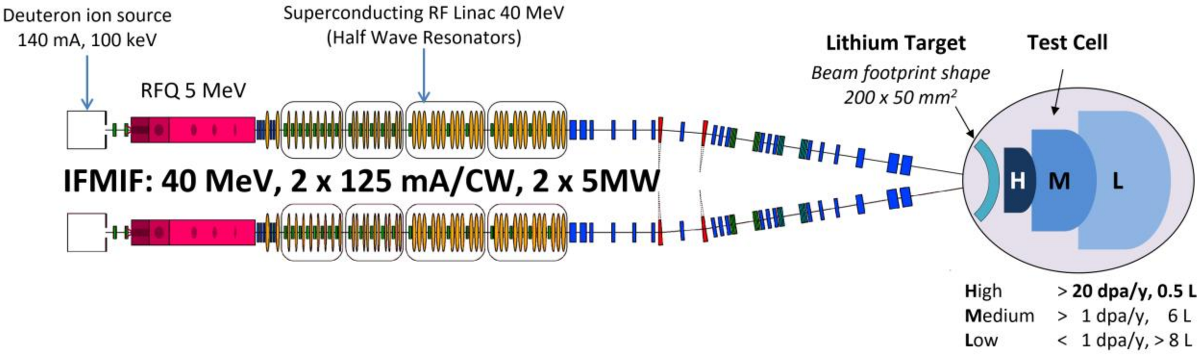

FIG. 1. IFMIF architecture including the accelerator, lithium target loop and the test cells.

With the decision to build the International Thermonuclear Experimental Reactor (ITER), shortly after in February 2007, Japan and Europe (via EURATOM) seized the opportunity of the Broader Approach agreement to set up a project to define the IFMIF Engineering Design and Engineering Validation Activities (EVEDA). Consequently, this project [3] received the mandate to produce an integrated engineering design of IFMIF and the data necessary for future decisions on the construction, operation, exploitation and decommissioning of the future Fusion Neutron Source (FNS), such as the Advanced Fusion Neutron Source (A-FNS) [4] and the DEMO oriented NEutron Source (DONES) [5].

2. IFMIF/EVEDA PHASE I

The phase I of the IFMIF/EVEDA spanned from February 2007 to March 2020 encompassing the Engineering Design Activity (EDA) with the aim to provide the design description of the complete plant and the Engineering Validation Activities (EVA) with the aim to construct an accelerator facility, a lithium target facility and a complete test module. Further details about the Phase I of the IFMIF/EVEDA project are given in the related reference document [6].

2.1. Engineering Design Activity

The Engineering Design Activity was accomplished in this first phase with the IFMIF Intermediate Engineering Design Report (IIEDR) released in December 2013 [7]. It encompasses an IFMIF Plant Design Description (PDD) document including interfaces based on a 3D-model of the full plant, licensing scenarios and nuclear safety aspects. A careful cost and schedule report was also prepared based on the experience gained with the construction of previous prototypes. The PDD is supported by 35 different Design Description Documents of all plant sub-systems that are the accelerator facility, the lithium target facility, the test facility, the post-irradiation facility and the conventional facility (buildings and infrastructure).

2.2. Engineering Validation Activities (EVA)

2.2.1. Accelerator Facility in phase I

The validation of the accelerator facility is carried out with the development of the Linear IFMIF Prototype Accelerator (LIPAc), which is the first acceleration segment of IFMIF, the most challenging part. The below FIG. 2 shows the architecture and the contributions to the LIPAc. So, the Accelerator Facility validation activities with the LIPAc aim at demonstrating the acceleration of 125 mA deuteron (D^+) beam up to 9 MeV and in Continuous Wave (CW) while keeping the beam losses under 1 W/m. For this purpose, a 140 mA and 100 keV D^+ beam with an emittance below 0.3 π.mm.mrad is generated in an Electron Cyclotron Resonance ion source to be injected in a Radio-Frequency Quadrupole (RFQ) through Low Energy Beam Transport (LEBT) line and accelerated to 5 MeV with less than 10% losses. This 125-mA beam at 5 MeV will be injected in a Superconducting Radio-Frequency (SRF) linac after transfer through the Medium Energy Beam Transport (MEBT) line to reach the value of 9 MeV. It is then transported through the High Energy Beam Transport (HEBT) line, which includes a Diagnostics Plate (DP) for beam characterization and a bending magnet toward the 1.125-MW Beam Dump (BD), where the beam is finally stopped. In parallel, the Radio-Frequency Power System feeds the accelerator with 18 power sources at 175 MHz distributed as follows:

— 8x 200kW inputs for the RFQ cavity,
— 2x 18kW inputs for the Matching Section cavities (bunchers) that are Solid State Power Amplifiers,
— 8x 105kW inputs for the Superconducting RF Linac.

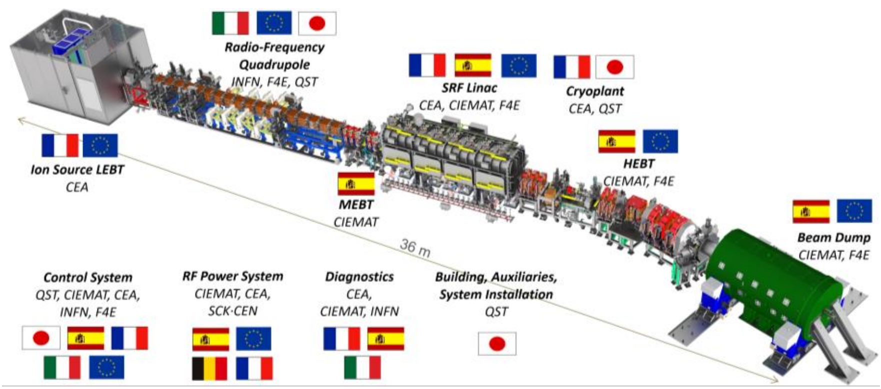

FIG. 2. LIPAc architecture and the contributors per sub-system.

The LIPAc commissioning is currently on-going at Rokkasho Fusion Institute, Japan. During the phase I, the progressive commissioning was carried out reaching the 1st deuteron beam in July 2015 with the injector (ion source and LEBT) at 100 keV and the 1st proton beam accelerated in the RFQ at 2.5 MeV in June 2018. The nominal beam current of 125 mA deuteron was achieved in July 2019 and accelerated at 5 MeV with 0.1% duty cycle (1 ms pulse) and a total transmission of 90%.

2.2.2. Lithium Target Facility in phase I

In the first phase, for the validation purpose of the lithium facility, the construction of the world largest Li loop was completed on 19 November 2010 in Japan (Oarai). The experimental plan of this EVEDA Lithium Test Loop (ELTL) started to be implemented on 31 March 2015 operating the facility for 571 hours in stable manner. This demonstrates the long-term stability of a lithium flow under IFMIF nominal operational conditions with 25 days continuous operation [3]. Following on this success, the ELTL facility was dismantled in March 2017.

Meanwhile, the Lithium Target Assembly, where the deuteron beam meets the lithium surface, was being studying in ENEA (Brasimone, Italy). Using the "Lithium for Fusion 6" loop (LIFUS6) test bench, the erosion/corrosion of the structural material candidates, namely F82H and EUROFER97 steels, was studied while subjected to the flow of the lithium. This enabled to assess the erosion/corrosion rate as well as to monitor the non-metallic impurities in the lithium. After operating LIFUS6 for more than 4000 hours, it was possible to demonstrate the acceptable level of erosion rate (below 1 μm/y). Additionally, the concept of the Lithium Target Assembly was fabricated without welding operations, hence enabling its removal every year thus validating also its remote handling.

2.2.3. Test Facility in phase I

During the first phase, many activities were carried out to validate completely the test facility that is the module where the material specimens are irradiated. The Helium Loop Karlsruhe (HELOKA) located in KIT (Karlsruhe, Germany) enables to test the components under relevant high heat flux while using high-pressure and high-temperature helium as a coolant. A full-scale prototype of the high flux test module housing the material specimens to be irradiated with the highest neutron dose (above 20dpa/year) was built and successfully tested in the HELOKA loop [4]. The implementation of the experimental plan demonstrated the technical feasibility of the uniformity in the temperature field selected for the specimen set to be irradiated in each capsule of the test module.

In parallel, three capsules of small specimens with their heaters and thermocouples were irradiated at the fission reactor BR2 in SCK-CEN (Mol, Belgium). This campaign was used to detect possible design and fabrication problems, but also to identify the cooling, retrieval and disassembling difficulties.

All these activities were completed in April 2015 validating the High Flux Test Module (HFTM) and the Medium Flux Test Module (MFTM) at EPFL (Lausanne, Switzerland), as well as the use of Small Specimen Testing Technologies for specimens to be irradiated.

3. IFMIF/EVEDA PHASE II

In 2020, Europe and Japan took stock of the progress made, recognized this highly successful collaboration and reaffirmed their commitment to continuing their joint activities. Consequently, EURATOM and Japan signed a joint declaration on 2 March 2020 in this perspective. This phase II has no end date, but the objectives and financial contributions are set annually by both parties. This second phase focuses on exploiting the facilities that have been built already in the phase I that is continuing the commissioning of LIPAc. Moreover, complementary activities will also be carried out specifically on the lithium target facility and some engineering design activities on a fusion neutron source.

3.1. Accelerator Facility in phase II

After the success of the injector commissioning (phase A) and the RFQ commissioning (phase B) at nominal current and low duty cycle [8] in the first phase of the IFMIF/EVEDA, the accelerator facility validation is continuing with the phase B+ of the beam commissioning. In this latter phase B+, the MEBT Extension Line (MEL) is temporarily placed in the position of SRF Linac, whereas the HEBT and the BD were installed at their definitive locations, see below FIG. 3. This configuration gives the opportunity to continue the commissioning waiting for the finalization of the SRF Linac assembly.

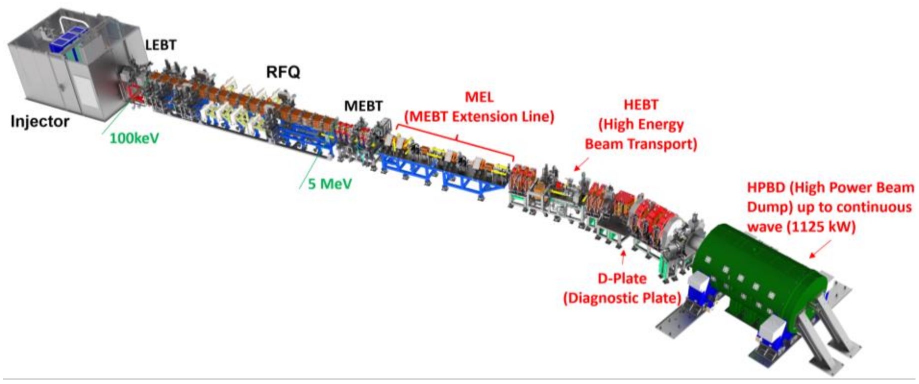

FIG. 3. LIPAc architecture in its configuration phase B+ with the MEL replacing the SRF Linac.

During the first stage the phase B+, a deuteron beam of around 20 mA at 0.01 % duty cycle was successfully transported up to the BD in December 2021 enabling the validation of most of the beam diagnostics instrumentations distributed along the beam line [9]. The beam characterized during this experimental campaign validated also the modelling developed in support of the beam physic simulation activities.

In parallel, the conditioning activities of the injector and the RF/RFQ were on-going toward the commissioning at high duty cycles [10]. They are essential to proceed with the commissioning of LIPAc at nominal current and CW. The conditioning of the RF/RFQ reached CW at around 106 kV (80% of the nominal) for 1 hour on 17 December 2021. Unfortunately, the conditioning had to stop on 2 February 2022 because of the circulator 1B which was damaged due to numerous arcing, see FIG. 4. Despite some satisfactory onsite repairs, it was decided to ship it for a complete repair to the manufacturer in November 2022 in order to avoid potential impact on the commissioning schedule in case of further unidentified failure. Indeed, the inspection made at the premises of the manufacturer showed further damages. After the repairs, the factory acceptance tests were passed on 7/8 February 2023. The onsite acceptance tests were finalized only in June 2023 because of many concurrent onsite activities.

FIG. 4. Circulator 1B inner conductor after onsite inspection and after repair (last right).

Waiting for the circulator to come back, the conditioning of the RF/RFQ has proceeded with 7 RF chains instead of the 8 original ones. On 30 March 2022, it had to stop again because of a problem with the RFQ couplers. Actually, their rising temperature and the vacuum leaks tiggered several interlock events. The couplers were unmounted to go through a visual inspection and the leak testing. They revealed the melted joints at the level of the ceramic windows, the metallisation of the ceramic windows and the overheating of the coupler inner conductor anchors, see FIG. 5. These observations lead us to suspect the thermo-mechanical behaviour of the anchor which needs to be improved with a redesign.

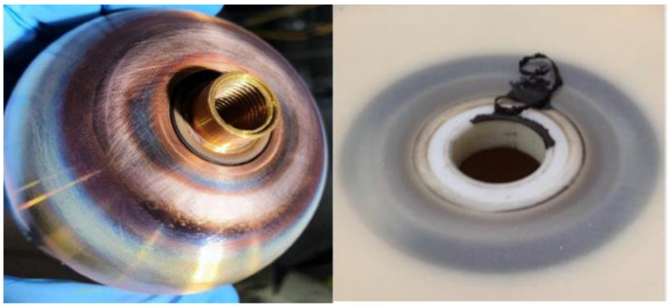

FIG. 5. Overheated inner conductor anchor (left), metallisation of ceramic windows with melted joint (right).

Considering these conclusions, it was decided to use the original couplers that were designed with brazed (i.e. no elastomeric joints) and water-cooled ceramic windows in addition to the water-cooled inner conductor anchors, see FIG. 6. These couplers were designed to be used at the first place but they failed the zero-power test because of a too thick titanium nitride coating. Despite their redesign to fix the problem and passing both the zero-power tests and the tests with high Q-load circuit, they were never tested at high power again because by the time they were ready, a temporary solution (the current ones used so far) was designed and manufactured but with elastomeric joints, and already available for installation after their validation tests.

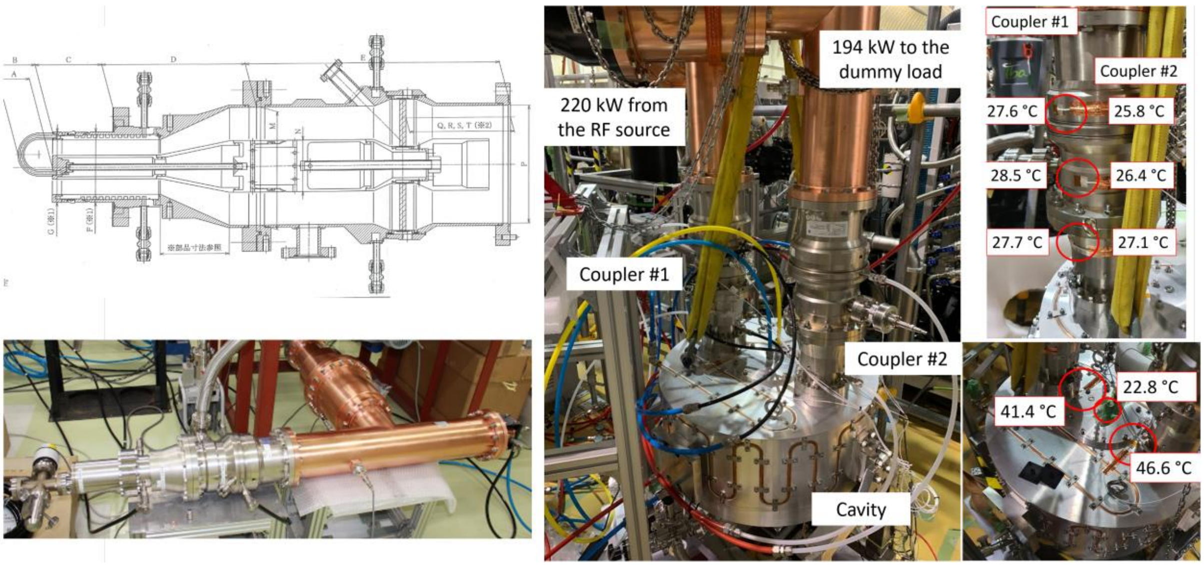

FIG. 6. Design drawing of the coupler with brazed ceramic window and cooled inner conductor anchor (left top), brazed coupler during high Q-load circuit testing (left bottom), high-power test bench for the brazed couplers (right).

Before using these original couplers, it was necessary to validate them at high power up to 200kW and high duty cycle up to CW, to condition their surfaces, and to check the integrity (i.e. no defects) of their ceramic windows. To do so, a dedicated high-power test bench was set up with a RF source and a bridge cavity to connect 2 couplers. Assuming the bridge cavity was working properly without too much dissipation, this setup enabled to test 2 couplers at the same time simulating the conditions and the environment of operation. As RF source, one RF chain of the RFQ was used, while the bridge cavity used initially had to be refurbished improving its cooling capacity but also adapting its flanges for this new RF source. Given the increase of temperature of the current couplers, the test bench was complemented with a thermal camera and several thermocouples in order to monitor also the temperature field of the 2 couplers and the bridge cavity. With this setup, multipacting phenomena occurred at all frequencies with a high forward power above 5kW. The situation did not improve by increasing the conditioning time. The analysis of the collected data led us to suspect the location of the multipacting to be in the bridge cavity rather than the couplers. Indeed, it was observed that: 1) the cavity temperature field increased with duty cycle but not couplers, see FIG. 6 right, 2) the cavity tuning was changing the pulse shape, 3) no light was observed at couplers view port by arc detection system, and 4) the bridge cavity is made of aluminium prompt to the high secondary electron yield. With these observations, it was not possible to condition the 2 couplers at the same time. Nevertheless, the first one reached a duty cycle of 96.3% after almost 3 months of effort, but it was preferable to stop the conditioning to avoid damage of the circulator or the tetrode, and also not to delay the restart of phase B+. Instead, the complete refurbishment of the bridge cavity was launched and the conditioning of these brazed couplers postponed to a later stage after the completion of the phase B+.

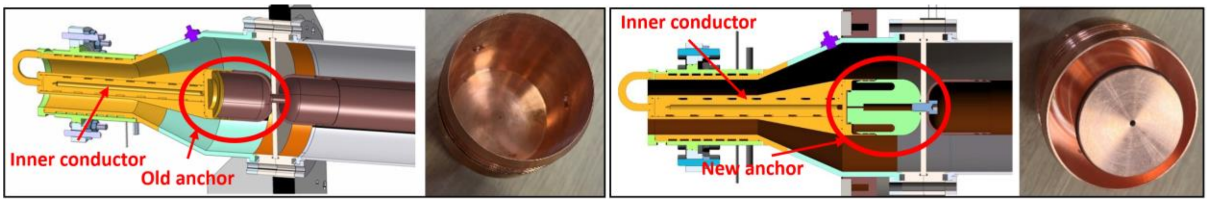

FIG. 7: Coupler with original anchor (left) and thermal-improved one (right).

Meanwhile, as mentioned above, the circulator 1B was back onsite after its factory acceptance tests. So, in order to resume the phase B+ as soon as possible, it was decided to design a new anchor for the couplers with a direct contact to the water-cooled inner conductor to improve the thermal dissipation, see FIG. 7. A thermal paste is applied between the 2 surfaces to ensure the contact and the heat transfer. This design and its related procurement were performed as a backup solution in parallel to the conditioning of the brazed couplers. After the successful test of a prototype to check in particular the proper mounting with the rest of the coupler assembly, the complete set of 8 final new anchors arrived onsite on January 2023. They were leak tested and assembled in parallel to the onsite acceptance tests for the validation of the repaired circulator 1B.

During the same period, the conditioning of the injector was ongoing to figure out the optimal plasma electrode with the best beam characteristics. After the CW campaigns with the 11mm and 12mm plasma electrodes, it turned out that the best aperture is the intermediate 11.5mm one, for which an extracted current of 155 mA was reached with a satisfactory emittance slightly below 0.2 π.mm.mrad.

The completion of the o-ring coupler improvement and injector preparation could enable us to proceed with the preparation for resuming the beam operation. The re-assembly of the co-axial lines and other preparatory works could be finished in July 2023 leading to resume the phase B+ with the stage 2 on the 1 August 2023. Eventually, the operation procedure to implement the experimental programme of the stage 2 started with the 11.5 mm plasma electrode, the repaired circulator 1B and the RFQ couplers with their new redesigned anchor to improve their thermal dissipation. After the transport through the RFQ of low intensity deuteron beam, the operation continued with the steerer tuning along the MEBT, the MEL and the HEBT to center the beam barycentre which is checked with the help of the Beam Position Monitors. The beam dimensions and its profile were characterized with the slits and the Secondary Emission Monitor grids both in the horizontal and vertical plans. On the 7 August 2023, 113 mA deuteron beam current was transported successfully up to the BD with a total transmission of 90%. This enabled a tuning the bunchers. The operation is ongoing to increase the current to the nominal value that is 125 mA. Once the nominal current is achieved with enough stability, the operation will pursue with the stage 3 increasing the duty cycle progressing aiming at high duty cycle and monitoring carefully the temperature of the RFQ couplers.

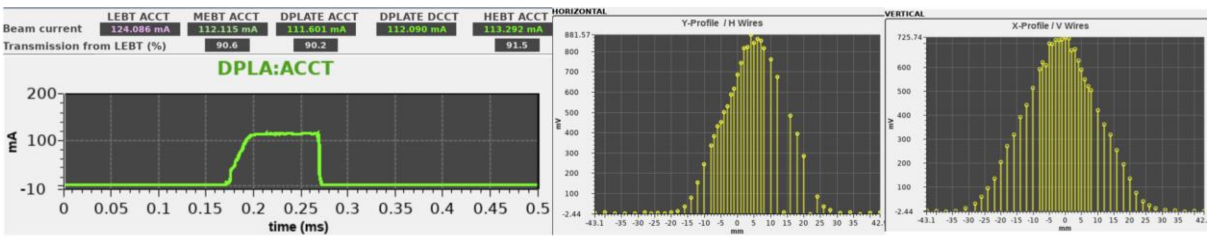

FIG. 8: D+ beam current of 113 mA transported at 0.1% duty cycle to the Beam Dump (left) and the horizontal and vertical beam profiles measured with Secondary Emission Monitor grid (right).

The next step of the commissioning is the Phase C/D with the MEL that is replaced by SRF Linac in order to achieve the final configuration of LIPAc and increase the acceleration of the deuterons from 5 MeV to 9 MeV.

The preparatory works for this phase C/D are ongoing with first the assembly (see FIG. 9) and hardware commissioning of the Radio-Frequency Power System of the SRF Linac to feed its 8 cavities with 4 units of 2x105 kW each [11]. Initially planned to be assembled in Europe, it was eventually decided to assemble the SRF Linac in Japan, at Rokkasho, following a careful risk analysis that identified the transportation risks to high. This analysis also allowed to implement a mitigation plan to mitigate other risks such as the licensing process, magnetic, seismic, cool-down and thermal-hydraulic risks. The assembly of the SRF Linac started in early 2019, but it had to be paused several times due to various quality manufacturing issues discovered in the focusing elements (8 superconducting solenoids) [12]. The last repair is still on-going and it is expected to resume the clean room assembly in the coming months. By mid-2024, it is planned to transfer the SRF Linac to the accelerator room (i.e. the vault) to be integrated to the rest of the beam line by the fourth quarter of 2025. This final configuration will be beam commissioned to demonstrate that all the needed components are working as expected, validating the beam dynamics at low DC, which is a prerequisite, then the DC will be ramped up to validate it at higher DC as well as the thermo-mechanical design of the various subsystems at high duty cycles. The complete validation of the LIPAc as a prototype of the IFMIF will be achieved when 125 mA deuteron beam with be transported up to the BD in continuous wave and at 9 MeV. It is currently planned to be accomplished by the fourth quarter of 2027.

FIG. 9: Vacuum tank of the cryomodule (left), mounting of a cavity in the clean room (middle) and assembly of cavities and solenoids (right).

The objectives of the project are not only to validate that the concept of a fusion neutron source is functional, but that it is also viable for a long-term use during a neutron production period. For this purpose, several enhancements are planned in order to improve the reliability of the injector, the RFPS and the Control System, hence to improve the availability of the complete accelerator beyond 2027. Regarding the injector, the primary goals of its enhancements are the plasma chamber with a better stability and reproducibility in the extraction of the particles, its accelerator column with an improved alignment feature and enhanced breakdown resistance, its diagnostics such as the Emittance Measure Unit capable to perform measurements at high duty cycle, a new local control system to tackle its obsolescence, and a vacuum system standardized to use similar hardware. Concerning the RFPS, the current tetrode-based technology is planned to be replaced by a Solid-State Power Amplifier based technology which is known to be more reliable with so-called hot redundancy maintenance, and an updated local control system. Finally, the control system with be also updated with more centralized and integrated system starting with its Machine Protection System. All these upgrades aim at a better availability of the overall machine validating also new technologies for a future neutron source.

3.2. Fusion neutron source design

The new activities were started since November 2021 until 2026 to prepare for the construction of the future Fusion Neutron Source facility (FNS). They encompass the Lithium Target Facility (LF) activities and Engineering Design (ED) activities. The LF framework comprises engineering validation activities performing additional R&D in order to improve the reliability of the individual systems from the viewpoints of maintenance and long-term operation. While, the ED activities are a set of tasks aiming to obtain relevant information for the design of an IFMIF-like Neutron Source carried out in an independent way.

3.2.4. Lithium Target Facility in phase II

The Lithium Target facility activities encompass the design of liquid Li purity control pilot plants both in EU and in JA, Li target diagnostics design and validation, erosion-corrosion modelling analyses, stabilization method of used/leaked Li, experimental analysis of Li fire risks, and R&D on analysis technologies of impurities in Li. The below paragraphs provide details on the latest achievements.

For the design of liquid Li purity control pilot plants, these pilot plants will be constructed and used for the execution of experimental programmes. The final objective is the validation of technologies for retention and monitoring of impurities in liquid Li. The designs of the pilot plants were completed and their constructions have started both in Japan (1:10 scale) and Europe (1:1 scale). The fabrication of the main components of the pilot Li purification plant is ongoing. Additionally, the experimental plan is also being discussed between the EU and Japanese experts [13].

Li target diagnostics need to be designed and validated in order to monitor the Li target taking into account the environment of the facility (e.g. radiation field and source location). A Li loop is available in Osaka University for testing the possible diagnostics (see FIG.10 left), but also a water loop and a Ga-In-Sn loop in Europe. The experiments have begun for testing a lithium free surface diagnostic method for liquid lithium flow using a laser probe on a lithium flow loop test apparatus at Osaka University. It is planned to measure the wave height of the lithium free surface with an accuracy of less than 1 mm using an optical comb method with a laser from a maximum distance of 10 m from the target assembly considering the harsh radiation environment. A similar ITER In-Vessel Viewing System (IVVS) sensor is also used Ga-In-Sn loop.

The erosion-corrosion evolution of target assembly and ELTL materials are essential to estimate properly their life time. The objective of this activity is to develop a model of erosion-corrosion for the target assembly taking into account the experimental results. Following the experiments, the surface morphology of the ELTL material are analysed by observing the surface and cross-sectional using Scanning Electron Microscope (SEM) of the base material and the welded joints at the outlet of the main electro-magnetic pump, potentially where the erosion-corrosion is the highest. These observations were made on samples after an operation time of 3849 hours. The results show a corrosion layer with a thickness less than 10 µm. The experimental values are being included in the analytical and Finite Element Analysis model developed based on estimated shear-stress, see FIG. 10 right. The analysis of the corelation is ongoing until the end of 2023.

Given the high reactivity of lithium, it can easily be ignited in the Li loop, hence its stabilization set up has to be thoroughly studied. Within this activity, the experimental set-up to stabilize solid lithium will be designed and fabricated to carry out experimental tests on surfaces stabilization. The Li stabilization test set-up was developed in collaboration research with Shizuoka University. Li vapor was produced by the test set-up heating above 523 K. Thereafter, various gas species are introduced into the reaction chamber and produced gas species that can be analysed by a quadruple mass spectrometer. Small SS-316 specimens were also introduced into the reaction chamber for post-mortem surface analysis using X-ray photoelectron spectroscopy. As a preliminary experiment, Li vapor was produced at 523 K for 4 hours and carbon dioxide was introduced into the reaction chamber with the pressure of 0.1 MPa. The reaction of Li with carbon dioxide was performed for one day. The results are being studied and further experiments are planned.

To reinforce safety, several fire scenarios have to be studied in order to prevent and limit the risks of Li fire. For such a purpose, an experimental facility has been designed and built [14]. The experiments are carried to study the ignition under controlled atmosphere, the interactions with the surrounding materials, the durability and stability in contact with Stainless Steel, and finally the influence of changing atmosphere for extinguishing. After building the experimental setup, the atmospheric condition that caused Li fire ignition was investigated by performing Li fire experiments with a variable parameter of humidity in air. The humidity was changed by controlling the amount of the air flowing through a water bubbler. The different level of humidity studied were 0.15, 0.3, and 0.6 vol.%. In order to acquire repeatability data, the experiments were repeated three times under the same conditions. As a first conclusion, it can be noticed that there is no ignition at 0.15 vol% and below. More experiments are ongoing to study the effects of the Li environment.

The monitoring of the impurities in the lithium loop is fundamental for a safe operation of the plant. The monitoring systems can be roughly divided into online and offline devices. Their reliability and the sensitivity still need to be defined. The activities are focus on the design, fabrication, and validation tests of a pilot plug-in monitor using the 1:10 scale pilot plant, and also on the design and setting up of H and N detection systems in Li. In parallel, the online activated impurities will be studied with analytical models. It has been clarified that the hydrogen concentration in Li could be measurable by heavy water dissolution method, while the measurement error obtained by this method was not enough for FNS. To improve the measurement error, D2 gas diluted by carrier gas were measured to reveal appropriate amount of sample gas. The method to measure the hydrogen concentration in Li by using heavy water dissolution method is on-going.

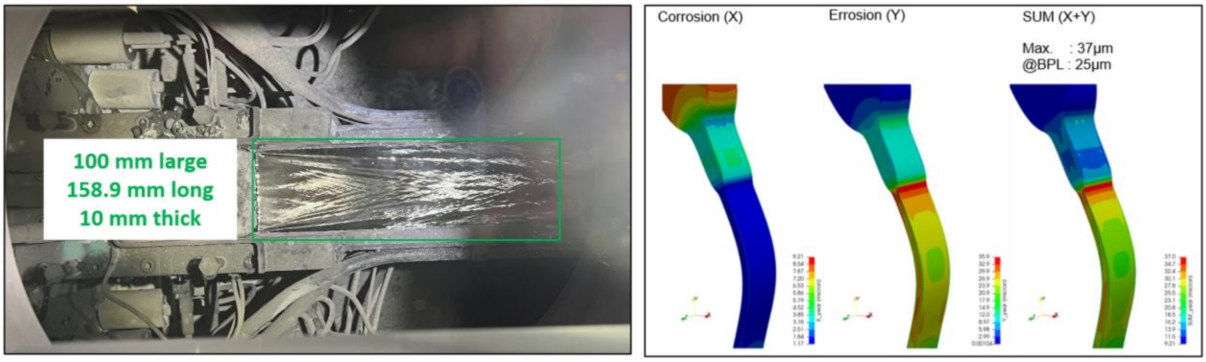

FIG. 10: lithium loop facility in Osaka University (left), Erosion/corrosion simulation of the Target Assembly (right).

3.2.5. Engineering Design

The Engineering Design activities comprise tritium migration estimation, erosion/deposition modelling in the target system, accident analysis in safety, study on the optimization of the Li-Oil heat exchanger, and use of LIPAc as testing facility. These activities are ongoing until 2025 and intermediate results are expected by the end of the year 2023.

The tritium release and the tritium migration have to be estimated during normal operation of DONES and A-FNS. This estimation is based on a code simulation which will be followed afterwards by analysis during off-normal scenarios. These estimation in normal and off-normal conditions will be used for the definition of safety-related requirements. The tritium migration estimation has been studied in the maintenance of the lithium target loop to define the requirement for the tritium processing system. From the first estimation, there is concern that each component of the lithium target system will retain from several GBq to several dozen TBq of tritium, most of which will be contained in the attached lithium, during the maintenance. Since metal lithium is a very active hazardous material, it is dangerous to store it as metal. Therefore, the possibility of storing the lithium after stabilization was investigated. Experimental studies on a stabilization treatment are currently underway. Since tritium in lithium is released into the gas phase during lithium stabilization, the tritium release rate was tentatively set up to studying the requirement for lithium treatment system. Meanwhile, after the study of the normal operation, accident scenarios are being studied. The focus is on 2 scenarios: firstly, the leak in Dump Trap, Quench Trap, and H-Trap to define the critical size and characteristics of leak, and secondly the tritium permeation per pipe important during maintenance and accidents. The definition of the model to study these scenarios is ongoing.

Similarly, models of erosion/deposition in the target system for FNS (both DONES and A-FNS) are developed and analysed. These simulations may be followed afterwards by analyses of distribution in the plant (A-FNS and DONES) of beryllium Be-7, activated corrosion products and activated Li impurities. All these impurities may be a source of radioprotection related issues. The activated erosion products are expected to deposit on the liquid lithium loop components depending on the flow condition. One of the candidate components is a heat exchanger, where liquid lithium flow speed is slower than in other parts. The degradation of the primary heat exchanger oil caused by the gamma ray emitted from the activation erosion product in the case of deposition on the heat exchanger is one of the concerns. Thus, the absorbed dose rate of the primary heat exchanger oil due to the activation corrosion/erosion products was evaluated [15]. As a result of this evaluation, the absorbed dose was found to be 2.2 Gy/year for all nuclides in total. The absorbed dose rate in the primary heat exchanger oil due to Be-7 was calculated as 0.12 MGy/year, and the absorbed dose from the activated corrosion/erosion products produced in back plate of the target assembly is 4 to 5 orders of magnitude smaller than that from Be-7. Therefore, it can be concluded that the effect of oil degradation due to activation corrosion/erosion products is negligible compared to that due to Be-7. The modelling activities are now being focused in the corrosion. A model with the update of the neutronic data to take into account the effects of deuteron activation (and not only neutrons) is now considered. This model is being used with the new design modifications of DONES (as the temperature increase of the loop operation), the post-processing of the generated data is currently ongoing.

The accident analysis in safety has the goal to identify and to analyse the failure or accidental scenarios in the plant (A-FNS and DONES) which should be addressed later in safety analysis stages. An environmental impact assessment code, namely PUFF code, for tritium atmospheric release is being developed to evaluate the tritium concentration. The PUFF code uses the Gaussian puff model, which can take into account topographical and meteorological conditions, and includes a function to input actual data on these conditions. It can also take into account re-release and re-deposition effects of tritium. Hence, the use of the PUFF code is found to be more effective in analysing the exact distribution of tritium diffusion in the environment. The first results indicate that the use of actual meteorological and geomorphological data is extremely important for studying the detailed distribution of tritium diffusion in the environment, see FIG. 11 left. In parallel, the Failure Mode Effect and Cause Analysis (FMECA), Safety Control System (SCS) and Materials At Risk (MAR) are also being studied. About FMECA activities, the first draft is available and includes references to the top-level safety regulations. In the case of SCS activities, it is in full development with a first version expected by the end of the year 2023. About MAR, the first activity is to perform the benchmarking of the PUFF-GENII, the first conclusions are expected on later in 2023.

The objective of the study on the optimization of the Li-Oil heat exchanger is to assess the potential degradation of cooling fluid candidates to be used in the in the primary heat exchanger including the study of their radiation resistance. The thermal design has been conducted with the dibenzyl toluene as the Japanese candidate. Thermal calculations for the primary heat exchanger were performed using CC-THERM in the chemical engineering process simulator CHEMCAD SUITE. The radiation resistance of dibenzyl toluene was investigated. The absorbed dose rate for dibenzyl toluene will be 3.6 MGy after 30 years of operation. The results of the literature survey on radiation resistance of dibenzyl toluene showed that the absorbed dose rate for a 25% change in viscosity or acid number was about 10 MGy, and that no significant degradation due to radiation was expected after more than 30 years of operation. Moreover, an experimental irradiation campaign to assess the oil candidates (European and Japanese) stability has been performed using the NAYADE gamma facility in CIEMAT. As main results, a good stability under gamma irradiation has been found up to 13 MGy (dose expected in DONES), see FIG. 11 right. It is remarkable that no new compounds have been detected whose presence could compromise the reactivity of the oil with Li or with other loop components.

Finally, there are a set of activities to use LIPAc as testing facility. The LIPAc facility will be used for the validation of sensor and diagnostics, for real materials activation studies, for Reliability, Availability, Maintainability and Inspectability (RAMI) data from LIPAc exploitation, for neutronics validation calculations and for any other activities deemed necessary for the development of a fusion neutron source. The Neutron Beam Loss Monitors (CEA diagnostics) will be among the first sensors/diagnostics to be tested with LIPAc during the Phase B+ beam campaign. For the moment, their installation in ongoing to be able to validate them possibly during the stage 3 toward high duty cycle. As for the progress of Activation materials and Neutronics, the neutron dose rate was simulated with a Monte Carlo radiation transport calculation code and the nuclear data library FEND-3.2 during operation of 5 MeV deuteron at 125mA injection into the beam dump. The results of the analysis show that the neutron intensity is 3x1013 n/s at the copper in the beam dump, and that the neutron dose rate in the accelerator area is on the order of up to 1x106 micro Sv/h due to neutron back streaming. Regarding the progress of RAMI activity, the injector and the RFPS will be used as cases studied and training purpose. Several inputs on the Event Report Management System and Maintenance Records will be used as input date for this analysis. It was identified that an update of the LIPAc license is necessary to proceed with irradiation of materials.

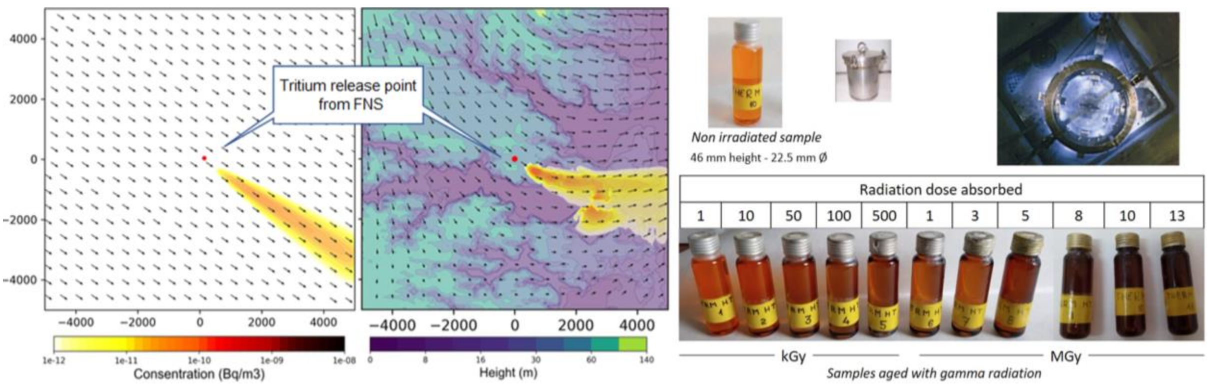

FIG. 11: Distribution of tritium diffusion in the environment (left), irradiation of the oil samples heat exchanger (right),

4. IFMIF/EVEDA LESSONS LEARNED FOR FUSION NEUTRON SOURCE

The commissioning of the LIPAc toward high duty cycle was resumed on 1 August 2023 after having fixed the failures of an RF circulator and the high-power couplers. The operation phase B+ aiming at 5 MeV deuteron beam with a current of 125mA toward high duty cycle and possibly continuous wave will continue until at least the end of 2023. It will be followed by the integration of the SRF Linac to enable the commissioning at 9 MeV in continuous wave. In the meantime, enhancement activities on LIPAc sub-systems will be carried out in order to be ready to complete the full engineering design of the future fusion neutron source. The additional activities on Lithium Target facility and Engineering Design will produce data to improve FNS design.

The LIPAc is potentially expected to be exploited beyond the validation of the concept of the accelerator concept. Therefore, it will be continued to be used as a training platform to train future engineers and scientists, but also to prepare and optimize the commissioning and exploitation phases of the future Fusion Neutron Source (A-FNS and DONES).

ACKNOWLEDGEMENTS

This work was undertaken under the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan. The views and opinions expressed herein do not necessarily state or reflect those of the Parties to this Agreement.

The authors thank all the members of the home institutions and research founders, especially those who have been involved in, or supported, the IFMIF/EVEDA project; the former IFMIF/EVEDA project leaders, P. Garin, H. Matsumoto, J. Knaster and P. Cara; the former home team leaders, R. Heidinger, Y. Okumura, T. Nishitani, and S. O'hira.

REFERENCES

[1] Federici G. et al., An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, Fusion Engineering and Design, Volume 141 (2019), Pages 30-42

[2] Kondo T. et al., The status and prospects of high-energy neutron test facilities for fusion materials development, Journal of Nuclear Materials, Volumes 191–194, Part A (1992), Pages 100-107

[3] Knaster J. et al., Overview of the IFMIF/EVEDA project, Nuclear Fusion (2017), 102016

[4] Ochiai, K. et al., Design Progress of advanced fusion neutron source for JA/DEMO fusion reactor, Nucl. Fusion 61 (2021) 025001

[5] Ibarra, A. et al., The European Approach to the Fusion-like Neutron Source: The IFMIF-DONES Project, Nucl. Fusion 59 (2019) 065002.

[6] Cara P. et al., IFMIF/EVEDA project achievements and outlooks beyond 2020, 28th IAEA Fusion Energy Conference (2021)

[7] Knaster J. et al., The accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The EU-JA project towards a Li(d,xn) fusion relevant neutron source, Nuclear Fusion (2015) 55

[8] Kondo K. et al., Validation of the Linear IFMIF Prototype Accelerator (LIPAc) in Rokkasho, Fusion Engineering and Design, Volume 153 (2020), 111503

[9] Masuda K. et al., Commissioning of IFMIF Prototype Accelerator Towards CW Operation, LINAC (2022)

[10] De Franco A. et al., RF conditioning towards continuous wave of the RFQ of the Linear IFMIF Prototype Accelerator, 14th International Particle Accelerator Conference (2023)

[11] Dzitko H. et al, Technical and logistical challenges for IFMIF-LIPAc cryomodule construction, SRF15 (2015) FRBA01

[12] Chambrillon J.K. et al., Cleanroom assembly of the LIPAc cryomodule, SRF2023 (2023), TUPTB027

[13] Oyaizu M. et al., Design of Lithium Purification Validation System for Fusion Neutron Source with the Test Plan, 32nd Symposium on Fusion Technology (2022)

[14] Kenjo S. et al., Experimental Study on Li fire with the heat insulator employed in the liquid Li target loop of a FNS Atomic Energy Society of Japan (2023)

[15] Kenjo S. et al., Progress on A-FNS design and R&D, Dose rate assessment due to activated depositions in Li loop of A-FNS, Atomic Energy Society of Japan Fall meeting (2022)