OVERVIEW OF ACHEVEMENTS AND OUTLOOK OF THE IFMIF/EVEDA PROJECT

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Abstract

The Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA) project is underway as one of the three projects (IFMIF/EVEDA, IFERC and JT60SA) of the Broader Approach (BA) agreement between EURATOM and the Japanese government since 2007. The IFMIF is to provide accelerator-based D-Li neutrons at appropriate energy and sufficient intensity to test samples for candidate materials in fusion energy reactors such as DEMO. The mission of the IFMIF/EVEDA project is to produce detailed engineering design of the IFMIF and to validate on major components: Accelerator Facility, Lithium Target Facility and Test Facility. In the first phase of the BA which ended by March 2020, the Engineering Validation Activity (EVA) of the Lithium Target Facility and Test Facility was completed by constructing prototypes, while the EVA of Accelerator Facility with the Linear IFMIF Prototype Accelerator (LIPAc) is still on-going. In the new phase (II), the activities are focused on the continuing the commissioning of the LIPAc and enhancement of some sub-systems for fusion neutron source design (FNSD). This article overviews the achievements and outlook of the LIPAc commissioning and FNSD activities.

1. INTRODUCTION

One of the main challenges of the fusion energy is related to the availability of suitable and reliable materials capable to withstand severe operational conditions with respect to the flux of neutrons generated by the deuterium-tritium reaction (14.1 MeV). Fission reactor (<2 MeV) material databases are substantial, because several materials testing facilities worldwide contributed to the enhancement of the databases. Unfortunately, a similar facility for testing fusion materials under high neutron flux does not exist yet and it is considered as essential in the path to fusion energy in particular to ensure a safe operation, including the operational license by the corresponding Nuclear Regulatory Agency [1].

With the decision to build ITER (International Thermonuclear Experimental Reactor), and considering the fusion road map toward the next nuclear fusion power reactor DEMO, the need to complement the existing material databases reached a consensus. In February 2007, the International Fusion Materials Irradiation Facility (IFMIF)/ Engineering Design and Engineering Validation Activities (EVEDA), one of the three projects defined in the Broader Approach (BA) Agreement between EURATOM and Japan, 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.

Hence the IFMIF/EVEDA project [2-3] is implemented, pursuing the Engineering Design Activities (EDA) and the Engineering Validation Activities (EVA) in parallel. The IFMIF Neutron source concept considered (FIG. 1) is based on an accelerator-driven neutron source using the Deuterium Lithium nuclear stripping reaction to produce high energy neutrons flux (> 10^{18} $m^{-2}.s^{-1}$), at sufficient intensity and irradiation volume to replicate as closely as possible the first wall neutron spectrum of the future nuclear fusion reactors [4]. In order to implement this concept, two high intensity deuteron accelerators are required. Their beams need to hit a flowing lithium target, and the proximity area behind the target is the area of interest for material testing in severe neutron flux. Thus, the validation activities consist of the three main facilities defined by:

- Accelerator Facility: engineering validation of the low energy section up to 9 MeV of the linear accelerator generating a deuteron beam with a current of 125 mA in Continuous Wave (CW),
- Lithium Facility: engineering validation of the Lithium Loop with a 25-mm thick liquid lithium target flowing at about 15 m/s,
- Test Facility: engineering validation of independently cooled capsules housing small test material specimens for a total of around 1000 specimens (> 20 dpa per year of operation).

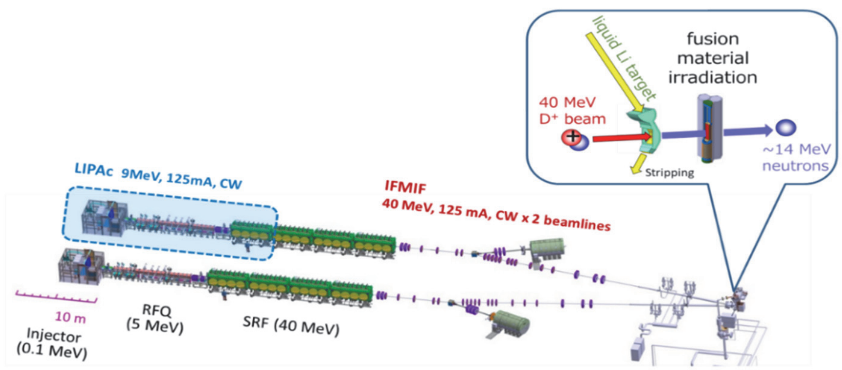

FIG. 1. IFMIF neutron source concept.

The IFMIF/EVEDA Project aims to deliver a comprehensive engineering design of the IFMIF facility, along with all necessary data for future decisions on its construction, operation, maintenance, and decommissioning. In the EDA, the Intermediate IFMIF Engineering Design Report was delivered and approved by the stakeholders in December 2013. The EVA focuses on validating three key technologies -LIPAc accelerator, lithium target, and test facilities- to ensure readiness for IFMIF or similar facilities like DONES (EU) and A-FNS (Japan).

The Lithium Test Loop (ELTL, Oarai, Japan) operated continuously for 25 days under nominal conditions, confirming flow stability and thickness control. The LiFus 6 loop (ENEA, Brasimone) enabled erosion/corrosion studies with F82H and EUROFER, validating RAFMS (Reduced Activation Ferritic Martensitic Steel) corrosion limits under IFMIF-relevant conditions. In the Test Facility Validation, HFTM-DC prototype tested at HELOKA-LP (KIT) achieved <3% isothermal variation in 97% of capsule volume. Capsules irradiated at BR2 (Belgium) provided data for geometry optimization and neutron flux validation. Further details are given in the related reference documents [5].

In 2020, Europe and Japan took stock of the progress made, recognized this highly successful collaboration and reaffirmed their commitment to continue 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.

2. COMMISSIONING OF THE ACCELERATOR FACILITY: LIPAC

2.1. Accelerator Facility

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 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 pi.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 (D-Plate) 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 (8 for RFQ, 2 for the matching section and 8 for SRF). The LIPAc commissioning is currently on-going at Rokkasho Institute for Fusion Energy, QST, Japan.

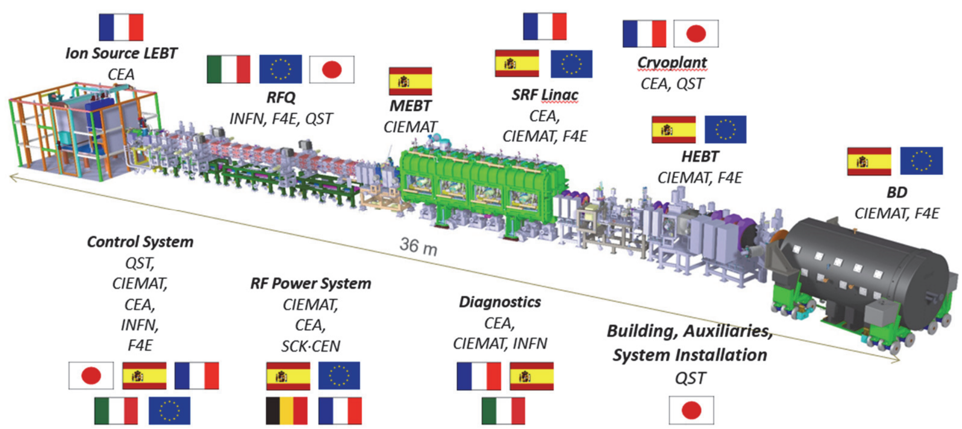

FIG. 2. LIPAc architecture and the contributors per sub-system.

2.2. Staged Approach Commissioning

The LIPAc presents several significant challenges: it features the world's highest current in Continuous Wave (CW), the world's longest and powerful Radio Frequency Quadrupole (RFQ), the highest hadron current through a Superconducting Radio Frequency (SRF)-Linac, and reaching 1.1 MW of beam power. Therefore, to mitigate risks, a phased approach has been and will continue to be implemented for the installation and beam commissioning as shown in FIG 3. The main requirements and objectives of the different phases are as follows:

Phase A:

— Validation of the Injector design demonstrating a reliable prediction of D^+ beam @ 140 mA at 100 keV at the entrance of the RFQ, meeting the requirements (125 mA D+ Beam, transverse normalized RMS emittance lower than 0.3 pi.mm.mrad, with a target value of 0.25 pi.mm.mrad);

Phase B:

— Validation of the RFQ design, thanks to the transmission measurements and energy measurements through the determination of the time of flight of the particles;
— Determination of the overall transmission through RFQ, MEBT, D-Plate from injector to the Low Power Beam Dump (LPBD);
— Validation of the LIPAc diagnostics at low duty cycle (DC);
— Transverse beam emittances at D-Plate;
— Validation of the RF power system in pulsed mode;

Phase B+:
— Validation of the RFQ performance towards high DC up to CW (100% DC);
— Validation of the buncher cavities with maximum beam loading;
— Pre-validation of the BD at higher power (0.6 MW) with associated diagnostics;
— Validation of the non-interceptive Diagnostics at high DC;
— Validation of the beam operation scenarios for the first beam injection in the Cryomodule.

Phase C:
— Optimization of the beam characterization satisfying beam dynamics model of that section, from which a reliable prediction of beam behavior at low beam power can be established.
— Validation of accelerating a D^+ beam of 125 mA D+ beam to 9 MeV at < 0.1% DC through the all components up to the BD.

Phase D:
— Validation of the capacity of accelerating a 125 mA D+ beam to 9 MeV, for different duty cycles from 0.1 % to 100% through all components up to the BD;
— Validation of all the LIPAc systems thermo mechanical design in CW operation.

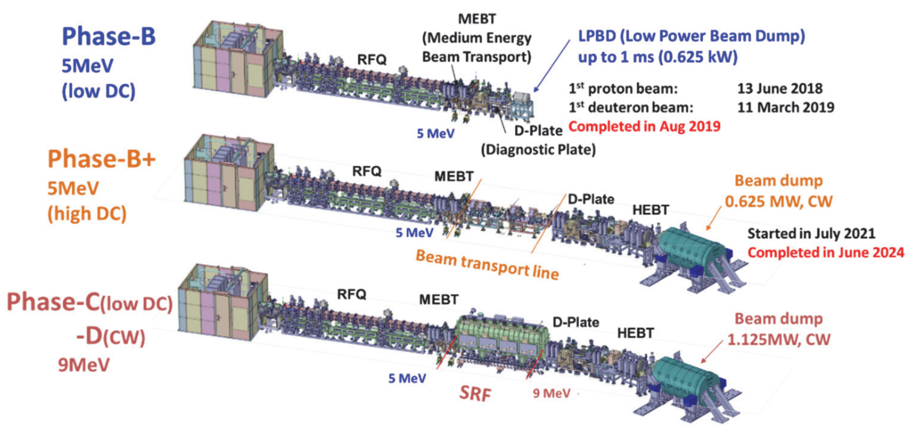

FIG. 3. Phased installation and commissioning of LIPAc.

2.3. LIPAc achievements: Phase A and Phase B

The LIPAc activities are shared in-kind among different institutions involved in the project. Scientists and engineers from Europe and Japan participate in the commissioning.

The commissioning of the Injector (Phase A) started in November 2014 with the proton beam and followed by the deuteron beam. The designed performance was confirmed in the experimental campaigns in 2015-16. The Phase A was completed in August 2017. The optimization of the operation in CW was continuing in parallel to the Phase B, and the performance in CW mode for 7 hours in stable conditions at 100 mA was demonstrated in June 2019 [6].

In the beam commissioning of the Phase B, a dedicated Low Power Beam Dump (LPBD) was installed after the MEBT and Diagnostic Plate (D-Plate). In July 2019, significant achievement was obtained with a 125 mA deuteron beam accelerated at 5 MeV with 0.1% duty cycle and transported to the LPBD without unexpected significant beam losses. Confirmation of the designed beam dynamics was conducted successfully in terms of the beam transmission through the RFQ [7].

During the shift from Phase B to B+, due to the COVID-19 pandemic since February 2020, visit schedule to Japan by European experts was cancelled. Experts who were staying in Rokkasho in charge of the HEBT and BD integration test, were forced to return to Europe earlier. That made significant delay of the schedule.

It became urgent to develop a system for joint team to participate remotely to the integrated commissioning. One solution was a Remote Computer Access (RCA) system to access LIPAc data from Europe. Connecting the accelerator control system network to the Internet posed great security concern. Therefore, a data relay server was placed in a DMZ accessible from the Internet and allowing only one-way access so-called data-diode. In October 2020, data was successfully transferred to the receiving server in the Fusion for Energy (F4E) in Barcelona, Spain. This system enabled to transfer the LIPAc data in real time and European experts could access the data with OPIs. By using this system as well as a video conference system, European experts could participate in the commissioning under the similar conditions as if they were on-site. High duty cycle RFQ conditioning and beam commissioning could be jointly performed, and we had overcame the COVID-19 restrictions. The RCA system faced issues with maintenance and time delays. To resolve this, similar to the RCA, a Remote Data Access (RDA) option was developed. Tests were conducted by June 2023 to compare these solutions. Both solutions (RCA and RDA) with servers in Rokkasho were made available during the operation phase B+ stages 2 and 3.

2.4. LIPAc achievements: Phase B+

To implement the Phase B+ configuration, the HEBT line and high power beam dump (BD) were installed in addition to the systems in the previous phase B (Injector, RFQ and MEBT). The D-plate was moved to its final position. Instead of the SRF-Linac, the MEBT extension line (MEL) between the MEBT and the HEBT was designed and installed [8]. In the MEL, several components, such as beam ducts, Q magnets, diagnostics, and vacuum systems, were on the same stage. The MEL were to be easily removed to make efficient work and avoid risks of pollution at the SRF-Linac installation. Commissioning was proceeded by remote connection and video conference between European Institutes and QST.

The main goal of Phase B+, as mentioned in the previous chapter, is to demonstrate high duty cycle operation of the RFQ. To reach this goal, following three stages of beam commissioning were planned in the Phase B+,

- Stage 1: smaller currents of 10mA H+ and 20mA D+ at low duty cycle (< 0.05 %) (we call them pilot beams). The purposes are to check the injector chop-per, newly installed transport elements and diagnostics in the MEL, the HEBT and the BD.
- Stage 2: nominal current of 125mA D+ at low duty cycle (< 0.1%). The purposes are to confirm operation and tuning of all the elements at high beam current, to check diagnostics (especially non-interceptive devices), etc.
- Stage 3: nominal current of 125 mA D+ at higher duty cycle operation toward CW to confirm the performance.

The Stage 1 beam commissioning was focused on safe, stable operation and system validation, and initiated with proton beam in July 2021. The beam was transitioned to deuteron. A low D+ beam current of 20 mA at the exit of the RFQ was targeted, which was expected and confirmed to be visible in all the beam diagnostics located along the beam line to the BD. These pilot beams were transported to the BD successfully without significant beam losses. The beams were characterized by use of interceptive diagnostics devices at the D-Plate. The Stage 1 of Phase B+ was successfully ended in December 2021 [9].

Stage 2 began with a low duty cycle, and the deuteron beam current was initially set to around 70 mA at the RFQ exit by adjusting the ion source. After fine-tuning, the current was increased to approximately 115 mA. With the beam operating near its target current, the buncher was optimized, and detailed measurements of the beam shape and emittance were taken using interceptive diagnostics (which physically interact with the beam). In addition, non-interceptive diagnostics—like the Fluorescence Profile Monitor and beam loss monitors—were successfully tested to confirm their functionality [10]. Final beam characterization using interceptive diagnostics was completed at low duty cycle, marking the end of Stage 2 in November 2023.

While optimizing the beam transport system, unexpected particle losses were detected, especially around the MEL (Medium Energy Beam Transport Line). The simulated particle densities from the RFQ exit (MEBT) to the beam dump in the horizontal plane is shown in FIG. 4 [11]. To investigate, beam simulations were performed using two models: the hard edge (HE) model (FIG. 4 top) and the fringe field (FF) model (field map), which accounts for magnetic field gradients at the edges of quadrupole magnets. The initial simulation used a HE model and there were no beam losses, but beam losses were observed at the arrow positions. Further calibration tests were performed to measure the magnetic field gradients and to refine the conversion coefficients between excitation current and magnetic strength (GtoI calibration) using the 5 MeV D+ beam. The results from the FF model with these updated coefficients (FIG. 4 bottom) show larger beam size than the HE model. FIG.5 shows the simulated and measured rms beam sizes. The field map with GtoI calibration data matched well with actual measurements. Based on these findings, the beam optics were reconfigured to minimize particle loss—and follow-up measurements confirmed the improvement.

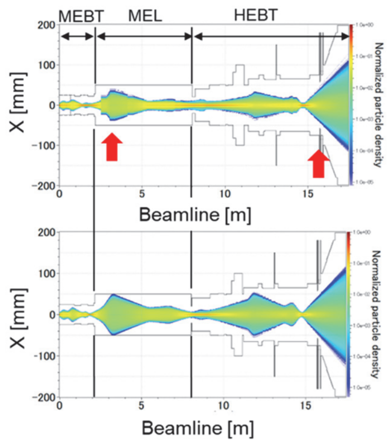

FIG. 4. The simulated particle densities from the RFQ exit to the beam dump in the horizontal-direction (top: HE model, bottom: FF model).

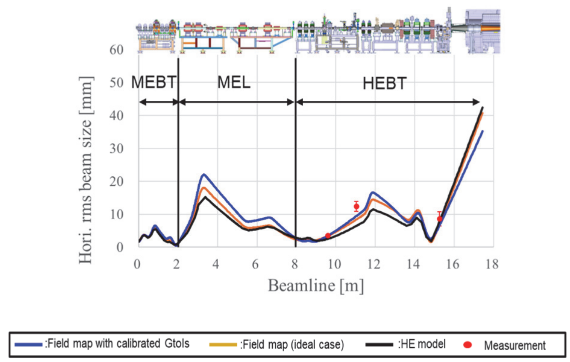

FIG. 5. The simulated and measured rms beam sizes from the RFQ exit to the beam dump in the horizontal-direction.

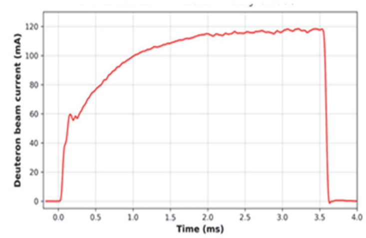

FIG. 6. Beam current waveform at the HEBT at 8.75% duty cycle.

Stage 3 was started in March 2024 after the winter maintenance. Further details are described in the reference documents [12-13]. The chopper in the LEBT was removed to allow direct beam from the injector into the RFQ and to increase the duty cycle. The duty cycle was increased by adjusting the pulse width and repetition rate. It was started from 1msec x 1Hz. The Low-Level Radio Frequency optimization due to the slower rising time without chopper was performed to reach a longer (>2msec) pulse operation. The final and maximum configuration was 3.5 msec pulse width and 25 Hz, that deduces a duty cycle of 8.75%. The beam current was about 119 mA at HEBT (FIG. 6), and the RFQ transmission was about 90%, as expected.

A lot of valuable data were collected such as for beam diagnostics validation and further improvement, beam characterization and modelling, understanding beam losses along the MEBT extension line where the SRF linac will be installed. The improvement in the LLRF control for both the RFQ and the bunchers were performed, which was essential in preparation to the following Phase C operation.

2.5. Challenges to the high duty cycle operation

After completing Stage 1 of Phase B+, conditioning of the RFQ to prepare for continuous wave (CW) operation was started. The goal was to reach a cavity voltage of 132 kV, which was necessary to accelerate deuterons. By December 2021, RF power in CW mode at 105 kV was successfully injected, about 80% of the target voltage, marking the first time the system operated steadily under high thermal load [14].

There are 8 chains of RF sources and 8 couplers to feed to the RFQ. The cross-sectional view of the present coupler is shown in FIG. 7 (top). In March 2022, a vacuum leak was discovered in one of the RF couplers. Upon inspection, it was found that the O-ring on the vacuum side had melted, likely due to excessive heating caused by either RF power dissipation or a phenomenon of multipacting (where electrons bounce and build up in RF fields, generating heat).

To prevent similar issues in the high-duty cycle operations, two solutions were pursued:
- Improving the existing RF coupler design, especially the cooling system.

- Developing a new coupler with its inner conductor brazed directly to the vacuum window for better thermal management as shown in FIG. 7 (bottom).

We focused on the first solution. Engineers redesigned the coupler's anchor, which connected the RF window to the cooled inner conductor. The original design had a small contact area, limiting heat transfer. The new anchor increased this contact surface to improve cooling. By March 2023, the upgraded coupler was assembled, installed, and passed the leak test. RFQ conditioning resumed in June, and by August, the system reached the required voltage for deuteron acceleration, allowing Stage 2 to begin.

Meanwhile, conditioning continued to push for higher duty cycles. By December 2023, they reached 27% duty cycle at nominal voltage. But again, heat buildup in the couplers became a problem, and signs of vacuum leakage reappeared. The arc sensors in the couplers detected light emissions that didn't match typical arc discharges. These signals appeared in all five couplers that had overheated, pointing to multipacting as the root cause of the O-ring failures. As a result, the decision was made to halt further high-duty conditioning and capped the operation at 10% duty cycle for the Stage 3 of Phase B+.

At the stage 3, we tried to increase to 10% duty cycle, but it was unstable because of time-varying power reflection. This resulted in an unbalance in each RF chain as shown in FIG. 8. As a result, the interlock from RF signals stopped before the cavity temperature and vacuum level reached a steady state level.

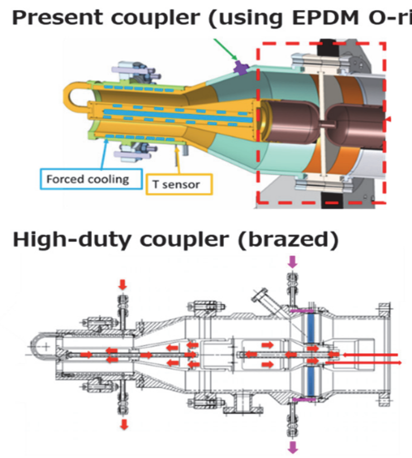

FIG.7. Cross-sectional views of the present (O-ring-type) coupler (top) and high-duty (brazed-type) coupler (bottom).Red arrows indicate cooling water flow.

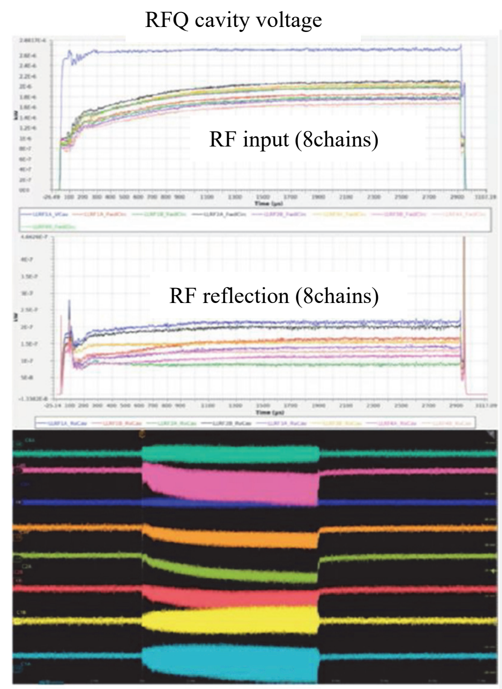

FIG. 8. RFQ cavity voltage and RF input power for 8 chains (top), RF reflection power for 8 chains (middle), and Arc sensor signals on the 8 RF couplers (bottom) at the duty cycle of 8.75%.

2.6. Preparation of next stage: Phase C and D

The next phase of LIPAc commissioning—Phase C/D—implies replacing the temporary MEL with the SRF Linac. This upgrade will complete the final configuration of LIPAc and allow the deuteron beam to be accelerated from 5 MeV to 9 MeV.

Preparations for Phase C/D have been already underway. The first major task is assembling and testing the SRF Linac's Radio-Frequency Power System, which will supply power to the eight accelerating cavities using four modules, each delivering 2 × 105 kW.

Assembly of the SRF Linac began in early 2019 but faced delays due to manufacturing issues with the focusing solenoids and necessary measure for repairs. The assembly contractor from Europe was paused by the entry restriction to Japan due to the COVID outbreak.

In August 2022, assembly work resumed after the COVID outbreak. In the initial stage, the assembly work proceeded with all cavity coupler assemblies and mounted on the cold mass support frame. One solenoid could not get its Beam Position Monitor leak tight and additional rework were needed. The assembly was paused from November 2022 to March 2024.

In September 2024, the string assembly as in FIG. 9 (connection work of cavities and solenoid coils) was completed and extracted from the clean room. The resonant frequency of each cavity was measured. The data were shared with CEA and measured data at room temperature in Japan were correlated with those done at 4K at CEA Saclay. The beamline was aligned with a laser tracker. The assembly of the cold mass continued with the addition of the tuning systems of the cavities, the piping connection, leak tests, etc. Then, in January 2025, cold mass insertion into the cryomodule was completed.

In March 2025, the cryomodule was transported from the assembly building to the accelerator vault in the IFMIF building. The 12-ton cryomodule was pulled out the assembly building using an air caster system, then lifted by a crane and loaded to the articulated lorry. The unloaded cryomodule was transferred to the accelerator vault. Two shock detectors were attached but no events were recorded during the transport [15]. The assembly was continued in the vault. The current leads, which supply the superconducting solenoids, was expected to be inserted, but an interference was detected between the current lead jackets and the chimney elements of the magnetic shield. Manufacturing of new current lead jackets is underway, and in the meantime, assembly and alignment work is on-going in the vault as shown in FIG. 10 [16].

FIG. 9. Installation of the component of the beam line in the clean room.

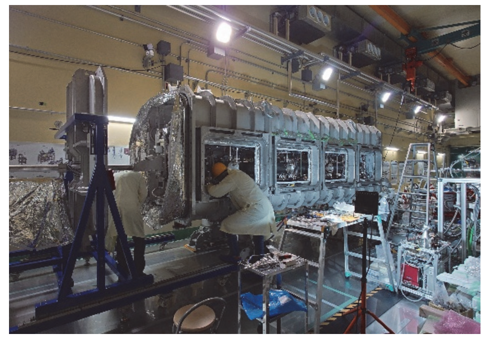

FIG. 10. Cryomodule assembly work in the accelerator vault.

3. FUSION NEUTRON SOURCE DESIGN ACTIVITIES

The Broader Approach (BA) activities are focused on laying the groundwork for building a future Fusion Neutron Source (FNS) facility. As part of the Fusion Neutron Source Development (FNSD) program, several shared tasks have been identified and are being carried out in both Europe and Japan. The new activities were started since November 2021 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.

3.7. Lithium Target Facility Activities

The Lithium Target facility encompasses a wide range of R&D efforts, including the design of liquid lithium purity control pilot plants in both the EU and Japan, development and validation of lithium target diagnostics, erosion-corrosion modeling, stabilization methods for used or leaked lithium, experimental analysis of lithium fire risks, and technologies for impurity detection in lithium.

FIG. 11 shows the lithium loop pilot plants constructed in Japan (1:10 scale) and Europe (1:1 scale) to validate technologies for impurity retention and monitoring in liquid lithium. The construction of the plant in Japan was completed in December 2024. The operation campaigns were carried out in January-February, May-June, and September-October, 2025. The operation was successful and the impurity trap performance was tentatively confirmed and the results are being analyzed. On the EU plant, the assembly was finished and the commissioning is expected to start [17].

Diagnostics must be designed to monitor the lithium target under facility-specific conditions such as radiation fields. FIG. 12 (left) shows a lithium loop diagnostic method at Osaka University [18]. The flow diagnostics were carried out at a distance of 10 m between the laser head and the Li target with flow velocities of 15 m/s. The wave hight of Li target flow could be measured with acceptable accuracy of sub-millimeter, but longer focal length should be used in order to improve the signal/noise ratio. FIG. 12 right shows the EU-side diagnostics [19]. The similar to the ITER IVVS (In-Vessel Viewing System) sensor had been used. The assembly of the prototype was

FIG. 11. Lithium loop pilot plants in Japan (left) and in Europe (right)

completed. The experiments were carried out up to 8m away from the target of the Galistan (Alloy of Ga-In-Sn) liquid metal. Good vertical resolution was obtained within the required <0.3 mm.

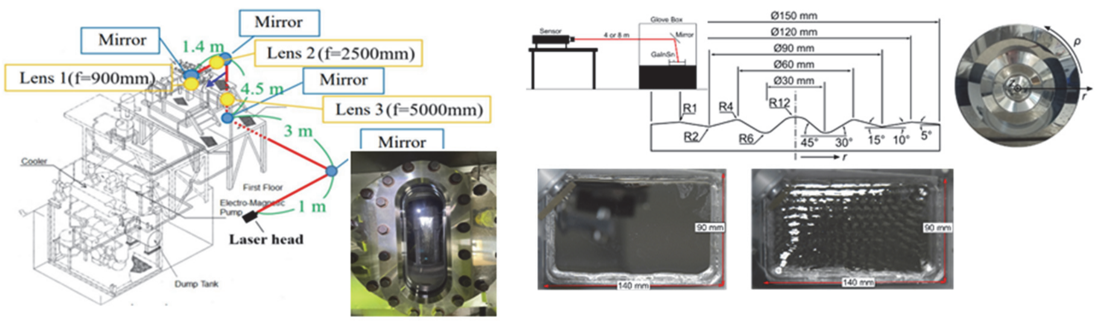

FIG. 12. Lithium target diagnostics in Japan (left) and in Europe (right)

The activities related to the Erosion/corrosion analysis on ELTL materials were completed. The surface and cross-sectional observations were performed using Scanning Electron Microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS/X) of the base material and the welded joints of ELTL pipe at the cavitation location. The observed cracks were characteristic of fatigue fracture, reducing nitrogen impurities could limit the corrosion.

Due to lithium's high chemical reactivity, stabilization was critical for safety operation. The Li stabilization test set-up was developed in a collaboration research between QST and Shizuoka University. A Fourier-transform infrared spectroscopy was added to the lithium vapor deposition and in-situ reaction system enabling 4 types of experiments with Li-CO_2-D_2, Li -D_2-CO_2, Li-D_2-H_2O-CO_2, and Li-H_2-D_2O(purge)-CO_2 (LHDC) of Li vapor deposition and gas exposures. These experiments demonstrated that direct CO_2 exposure to lithium would not be suitable for the stabilization of tritium included in lithium.

To enhance safety, fire scenarios were studied to understand ignition risks and mitigation strategies. The experimental study on lithium fire protection was performed in QST. Characterization of high temperature lithium has been investigated with an experimental apparatus. The condition on the lithium ignition was clarified. The suppression and extinguishment of the Li fires were successfully achieved by supplying argon gas.

Monitoring impurities was essential for safe plant operation. Hydrogen concentration in lithium was measurable via the heavy water dissolution method. To improve accuracy, D_2 gas (with 0.2 at.% H) diluted by carrier gas was tested to determine optimal sample volume. Nitrogen concentration was assessed using the Kjeldahl method. Preliminary tests with lithium nitride (Li_3N) and up to four sequential filters showed ammonia trapping decreases geometrically. Separately, the plugging gauge for the lithium purification validation system was successfully designed, fabricated, and commissioned. A plugging temperature of ~267°C was observed, aligning with following 250°C cold trap operation. The plugging gauge validation plan was integrated into the system's operational schedule.

3.8. Engineering Design Activities

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.

To ensure safety in fusion facilities like DONES and A-FNS, it's important to estimate how much tritium was released and how it migrated during normal and abnormal operations. On the JA side, tritium migration modeling led to defining detritiation system requirements under normal operation [20]. Maintenance analysis identified the primary heat exchanger (HX1) as the key permeation source, requiring replacement every 5 years. A redesign showed reduced tritium levels below threshold. On the EU side, a full Impurity Control System model was developed using EcosimPro to assess: Tritium inventory in residual lithium post-drainage, Desorption during accidental trap exposure, and Desorption from Quench Tank leakage.

Models simulating erosion and deposition processes in the target systems of FNS facilities (DONES and A-FNS) were developed and analyzed. On the JA side, activation calculations of Li and impurities (from ELTL data) under deuteron and neutron reactions were performed. A transfer model incorporating temperature, flow speed, and magnetic field estimated spatial distribution of activation products, revealing radioisotope inventories in the Li loop for the first time. Installing a Quench Tank (QT) to trap fine particles was identified as an effective measure to reduce radiation dose and flow restriction risks. On the EU side, the model was updated with new neutronic data (including deuteron activation) and DONES-2023 design changes. Neutronics analysis tracked 24 Activated Corrosion Products (ACP) across 120 reactions. Corrosion rate and Beryllium-7 equilibrium were calculated. Erosion and Activated Erosion Products (AEP) estimated a conservative erosion rate of 2 μm/year, based on LIFUS data.

The accident analysis covered FMECA, Safety Control System (SCS), and Materials At Risk (MAR). On the JA side, failure modes and severity were analyzed based on LF (LS) PBS from IFMIF/EVEDA. Rescue measures were defined for high-severity failures, leading to updates in LS P&ID and SCS design, including a startup/operation flowchart and instrument classification. Specifications were finalized for key instruments: flow meters, pressure gauges, level gauges, thermometers, and leak detectors. The Japanese radioactive material diffusion code was enhanced to model diffusion of beryllium-7 and argon-41 other than tritium. On the EU side, FMECA identified 13 accident scenarios for Lithium System, plus events for Test System (10), Accelerator System (4), and Site Building & Plant System (4), informing safety design and requirements.

The optimization of Li-Oil Heat Exchanger was studied. On the JA side, material criteria for Oil1 in HX1 were re-evaluated for radiolytic stability. Dibenzyl-toluene was selected as a candidate, meeting the required radiation resistivity (0.15–5 MGy) and showing similar properties to hydrogenated terphenyl. Thermal calculations led to a redesign of HX1 with ~1.5× larger heat transfer area, while maintaining original dimensions. HX1–HX3 redesigns were complete, and impacts on Secondary and Tertiary Loops were studied. On the EU side, irradiation tests assessed oil stability for the Li Loop. Partially hydrogenated phenyl naphthalene showed good gamma resistance up to 13 MGy with no harmful byproducts. Comparative tests with JA's dibenzyl-toluene revealed stable purity but increased viscosity and density at higher doses, indicating possible compound formation. Polymerization effects may impact heat transfer efficiency. Sensitivity under Strictly Controlled Closed System conditions was noted.

A range of activities was planned to use the LIPAc facility as a testing facility for technologies needed in fusion neutron source development. These include:

- Validating sensors and diagnostic tools (Layout is in FIG. 13)
- Studying how real materials respond to neutron activation (Layout is in FIG. 13)
- Collecting data on Reliability, Availability, Maintainability, and Inspectability (RAMI)
- Performing neutronics validation calculations
- Supporting any other necessary development efforts

On the JA side, neutron and gamma-ray measurements during Phase B+ used various detectors (scintillators, semiconductors, ionization chambers). $LaBr_3$ scintillator results confirmed its suitability as a beam monitor. Neutron activation studies (Au, Ni) were conducted at multiple beam locations, with EU comparison ongoing. Shutdown dose rate analysis via MCNP and measurements identified Cu-64 and Mn-56 as key contributors, with results aligning well [21].

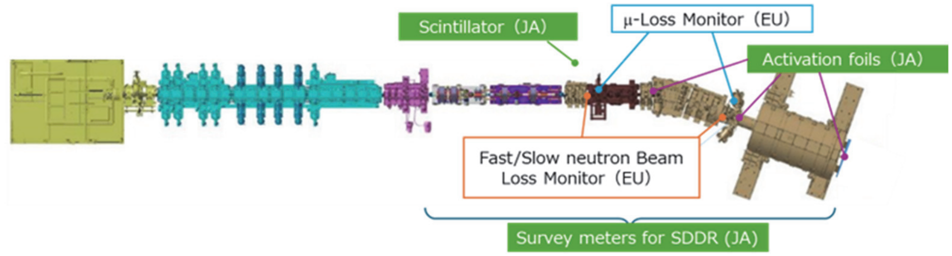

FIG. 13. Quantitative Evaluation of Beam Loss Based on Radiation Detection in High-Duty Beam Commissioning of LIPAc RFQ

RAMI analysis focused on the injector, identifying 48 major risks and initiating reliability block diagrams. Neutron generation from copper under 5 MeV deuteron bombardment was measured at 3.2×10^5 per deuteron, projecting 3×10^{13} neutrons/sec at 125 mA CW. Neutron flux distribution was modeled using MCNP6 and FENDL-3.2. Activities continue into Phases C/D.

On the EU side, diagnostics during Phase B+ included micromegas monitors, MIC, and CVD diamond detectors. MIC performance was validated in pulsed mode (1% duty cycle). Nuclear models and activation estimates were compared with experimental data from July–May 2024, identifying optimal irradiation zones and validating models for DONES. Sensitivity studies explored TENDL-21 and EAF-2010 modifications.

4. OUTLOOK OF THE IFMIF/EVEDA

The project is shifting from phase B+ to C with the completion of the high duty RFQ beam operation and preparing the SRF Linac. The assembled cryomodule was transported to the LIPAc building in March 2025. Helium piping work is being carried out inside the accelerator vault. Then it will be integrated into the LIPAc beam line, and the final configuration will be commissioned to demonstrate the targeted performance. Phase C beam operation is expected to start in 2027.

It has become clear that the current O-ring type RF couplers for the RFQ is a limitation to CW due to the multipacting. Some measures are being taken; another type couplers, brazed type, are under high power test, and new brazed couplers under the framework between F4E and CERN are under manufacturing as a backup option. The CW beam tests will be done in the SRF-Linac beam commissioning in Phase D.

One of the main objectives of the LIPAc is the full validation of the engineering design of the performance towards high duty cycle up to CW at nominal beam intensity. But considering the accelerator for IFMIF-like irradiation facility, such as IFMIF-DONES in Europe and A-FNS in Japan, the next scope after the Phase D is to demonstrate higher reliability and availability. To perform them, the refurbishment and improvement of some key subsystems, called enhancement, are or will be implemented [22]. Tetrodes are being used in the high power RF sources. Based on the recent semiconductor technology along with future supply instability of the tetrode tubes, it is rational to consider solid state RF amplifiers as a replacing solution. The design of the control system was done more than 10 years, some parts are no more available and it takes time to renew and validate some subsystems in view of future facility construction. The injector upgrade is underway not only for its performances like beam current and in CW, but also for its maintainability and availability. The ultimate LIPAc goal will be the demonstration of the high availability operation.

On FNSD, we have many valuable outcomes on the Lithium Target Facility Activities and Engineering Design Activities.

The IFMIF/EVEDA achievements represent a successful EU‑Japan partnership under the Broader Approach Agreement. They directly support the launch of the European Fusion Neutron Source facility IFMIF-DONES in Spain [23] by providing qualified designs, validated technologies, and operational know-how thanks to a close collaboration between the 2 Projects.

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