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# Overview of achievements and outlook of the IFMIF/EVEDA project

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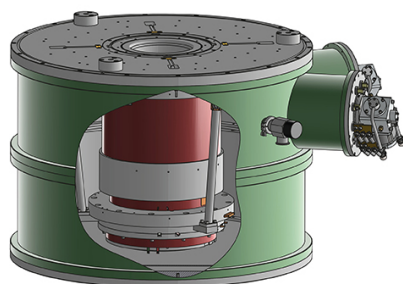


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System pictured with the Karlsruhe  
Institute of Technology (KIT) team

# Overview of achievements 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 have been conducted as one of the three projects (IFMIF/EVEDA, IFERC and JT60SA) within the Broader Approach (BA) agreement between EURATOM and the Japanese government since 2007. The IFMIF is intended to deliver accelerator-based deuterium-lithium (D-Li) neutrons at energies and intensities sufficient to enable the qualification of candidate materials for future fusion energy reactors, such as DEMO. The primary objective of the IFMIF/EVEDA project is twofold: (i) to develop a detailed engineering design of the IFMIF and (ii) to validate its major components, namely the accelerator facility, the lithium target facility and the test facility. During Phase I of the BA, which concluded in March 2020, the engineering validation activity (EVA) for the lithium target facility and the test facility were successfully completed through the construction and testing of prototypes. In contrast, the EVA for the accelerator facility, implemented through the Linear IFMIF prototype accelerator (LIPAc), remains on-going. The current phase (Phase II) focuses on the continued commissioning of the LIPAc and the enhancement of some sub-systems to support the development of the Fusion Neutron Source Design (FNSD). This article presents an overview of the progress achieved in the LIPAc commissioning and FNSD activities and outlines the future directions of the activities.

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**Keywords:** IFMIF/EVEDA, deuteron accelerator, high current, high duty cycle, neutron source, fusion material irradiation, Li target

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

## 1. Introduction

One of the principal challenges in realization of fusion energy lies in the identification and qualification of materials that can endure the extreme operational environment produced by the high-energy neutron flux generated by the deuterium–tritium reactions (14.1 MeV). While extensive material databases exist for fission reactors, where neutron energies are typically below 2 MeV, thanks to decades of work at numerous materials testing facilities worldwide, no comparable facilities are currently available for assessing materials under fusion-relevant neutron flux conditions. The establishment of such a facility is considered essential for the advancement of fusion energy, particular to secure safe operation and obtain licensing approval from the relevant nuclear regulatory authorities [1].

With the decision to construct ITER (International Thermonuclear Experimental Reactor), and in the context of the fusion road map toward the next-generation fusion power reactor, DEMO, the need to supplement existing materials databases became widely recognized. 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 develop an integrated engineering design of IFMIF and to provide the essential data required for future decisions regarding the construction, operation, exploitation and decommissioning of the future fusion neutron source.

Accordingly, the IFMIF/EVEDA project [2, 3] has been implemented to conduct both the engineering design activities (EDA) and the engineering validation activities (EVA) in parallel. The IFMIF neutron source concept considered (figure 1 [4]) is based on an accelerator-driven facility employing the deuterium–lithium stripping reaction to generate a high energy neutron flux ( $>10^{18} \text{ m}^{-2} \cdot \text{s}^{-1}$ ). This neutron field must exhibit both sufficient intensity and irradiation volume to replicate, as closely as possible, the first wall neutron spectrum of the future fusion reactors [5]. To realize this concept, two high intensity deuteron accelerators are required. Their beams are directed onto a flowing liquid lithium target, with the region immediately downstream of the target constituting the primary irradiation volume for testing materials under severe neutron exposure. The validation activities therefore focus on the following three main facilities:

- Accelerator facility: engineering validation of the low energy section of the linear accelerator up to 9 MeV, delivering a continuous-wave (CW) deuteron beam with a current of 125 mA.
- Lithium facility: engineering validation of the Lithium Loop, incorporating a 25 mm thick flowing liquid lithium target operating at approximately  $15 \text{ m s}^{-1}$ .
- Test facility: engineering validation of independently cooled irradiation capsules capable of housing approximately 1000 small material test specimens, achieving irradiation levels exceeding 20 dpa per year of operation.

The IFMIF/EVEDA Project is mandated to deliver a fully integrated engineering design of the IFMIF facility, together with the comprehensive technical data set required to support subsequent decisions regarding its construction, commissioning, operation, maintenance, and decommissioning. Within the framework of the EDA, the intermediate IFMIF engineering design report was completed and formally endorsed by the stakeholders in December 2013. In parallel, the EVA concentrate on validating three key technologies—the linear IFMIF prototype accelerator (LIPAc) accelerator, the liquid lithium target system, and the test facilities—ensuring their technological readiness for IFMIF or similar facilities like DONES (EU) and A-fusion neutron source (FNS) (Japan).

Significant progress has been achieved through dedicated experimental infrastructure. The Lithium Test Loop (ELTL, Oarai, Japan) successfully demonstrated continuous operation for 25 days under nominal conditions, confirming both flow stability and precise control of lithium-jet control. The LiFus 6 loop (ENEA, Brasimone) enabled detailed erosion/corrosion studies of RAFMS (reduced activation ferritic martensitic steel), including F82H and EUROFER, thereby validating corrosion performance limits under IFMIF-relevant conditions. Within the test facility validation framework, HFTM-DC (High Flux Test Module Double Compartment) prototype underwent qualification testing at HELOKA-LP (KIT), achieving stringent thermal hydraulic performance targets, with isothermal variation below 3% across 97% of the capsule volume. Irradiation campaigns at BR2 (Belgium) provided essential data for capsule geometry optimization and for numerical validation of neutron flux distribution. Additional details are available in the correspondence reference documents [6].

In 2020, Europe and Japan jointly reviewed the substantial progress realized under the BA collaboration, acknowledged the success of partnership, and reaffirmed their commitment to continue the joint activities. This resulted in the signing of a new EURATOM and Japan Joint Declaration on 2 March 2020. This second phase (II) has no predefined end date, is governed by annually agreed objectives and financial contributions. This second phase focuses primarily on the scientific and technical exploitation of the facilities established during Phase I, including the continued commissioning of LIPAc. In addition, targeted complementary activities are being pursued

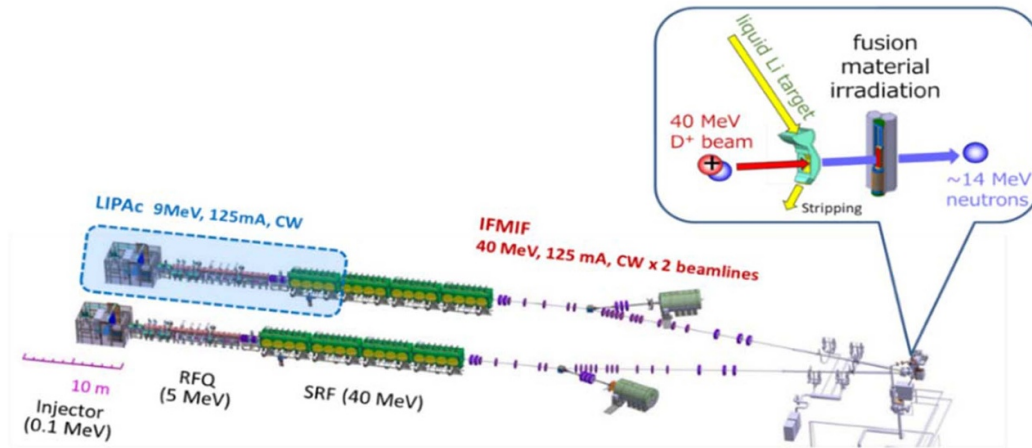


Figure 1. IFMIF neutron source concept. Reproduced from [4]. CC BY 4.0.

on the lithium target facility and selected EDA related to future fusion neutron source facilities.

The results obtained by 2023 have been reported in the corresponding publications [3, 7], and the present article primarily addresses the progress achieved thereafter.

## 2. Commissioning of the accelerator facility: LIPAc

### 2.1. Accelerator facility

The validation of the IFMIF accelerator facility is being carried out through the development of the LIPAc, which constitutes the low-energy and most challenging accelerating stage of IFMIF. The overall layout and main subsystems of LIPAc are shown in figure 2 [4]. As described in the reference document [7], LIPAc is designed to demonstrate the acceleration of a 125 mA deuteron ( $D^+$ ) beam up to 9 MeV and in CW operation, while maintaining beam losses below  $1 \text{ W m}^{-1}$ . A deuteron beam of 140 mA at 100 keV, with an emittance below  $0.3 \pi \cdot \text{mm} \cdot \text{mrad}$ , is produced by an electron cyclotron resonance ion source. The beam is transported through the low energy beam transport (LEBT) line to the radio-frequency quadrupole (RFQ), where it is accelerated to 5 MeV with losses of less than 10%. This 125 mA beam is then transferred through the medium energy beam transport (MEBT) line to the superconducting radio frequency (SRF) Linac, where it reaches the final energy of 9 MeV. Subsequently, the beam is transported through the high energy beam transport (HEBT) line, which includes a Diagnostics Plate (D-Plate) for beam characterization and a bending magnet directing the beam toward the 1.125-MW Beam Dump (BD), where it is finally stopped. The Radio-Frequency Power System supplies the accelerator with 18 power sources (8 for the RFQ, 2 for the matching section and 8 for the SRF). The commissioning of LIPAc is currently ongoing at Rokkasho Institute for Fusion Energy, QST, Japan.

### 2.2. Staged approach commissioning

The LIPAc presents several significant challenges: it features the world's highest current in 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 figure 3 [4]. 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  $0.3 \pi \cdot \text{mm} \cdot \text{mrad}$ , with a target value of  $0.25 \pi \cdot \text{mm} \cdot \text{mrad}$ );

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 the RFQ, the MEBT, the D-Plate from the injector to the Low Power Beam Dump (LPBD);
- Validation of the LIPAc diagnostics at low duty cycle (DC);
- Transverse beam emittances at the 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 SRF.

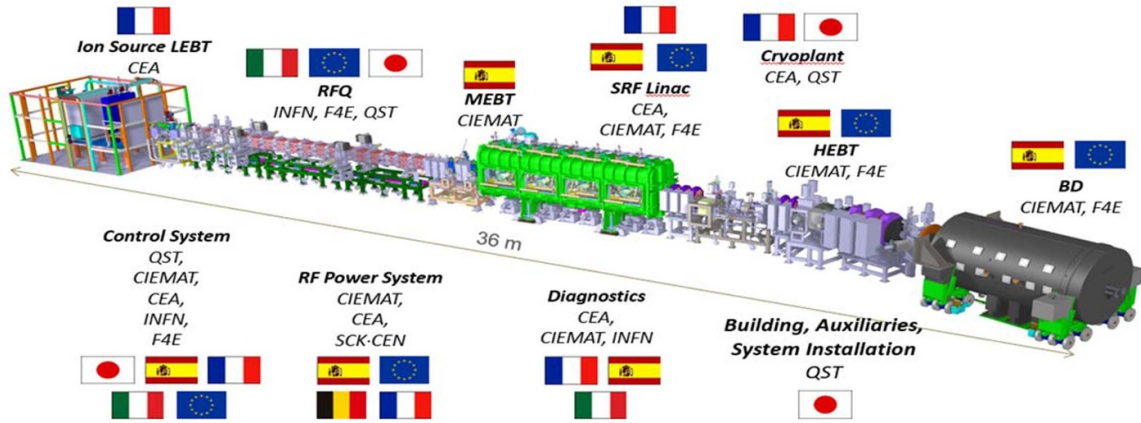


Figure 2. LIPAc architecture and the contributors per sub-system. Reproduced from [4]. CC BY 4.0.

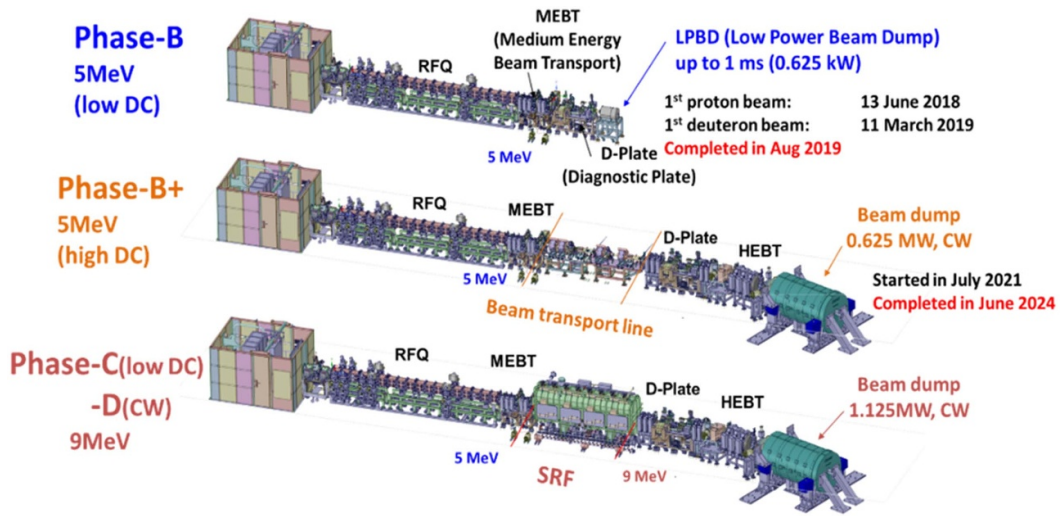


Figure 3. Phased installation and commissioning of LIPAc. Reproduced from [4]. CC BY 4.0.

#### 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 to 9 MeV at  $< 0.1\%$  DC through 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 thermos-mechanical design in CW operation.

#### 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 [8].

In the beam commissioning of the Phase B, a dedicated Low Power Beam Dump (LPBD) was installed after the MEBT and the 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 [9].

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 canceled. Experts who were staying in Rokkasho in charge of the HEBT and the 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 (DeMilitarized Zone) 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 Operational Interfaces (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 overcome 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 the 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 [10]. In the MEL, several components, such as beam ducts, Q magnets, diagnostics, and vacuum systems, were on the same stage. The MEL was designed 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.

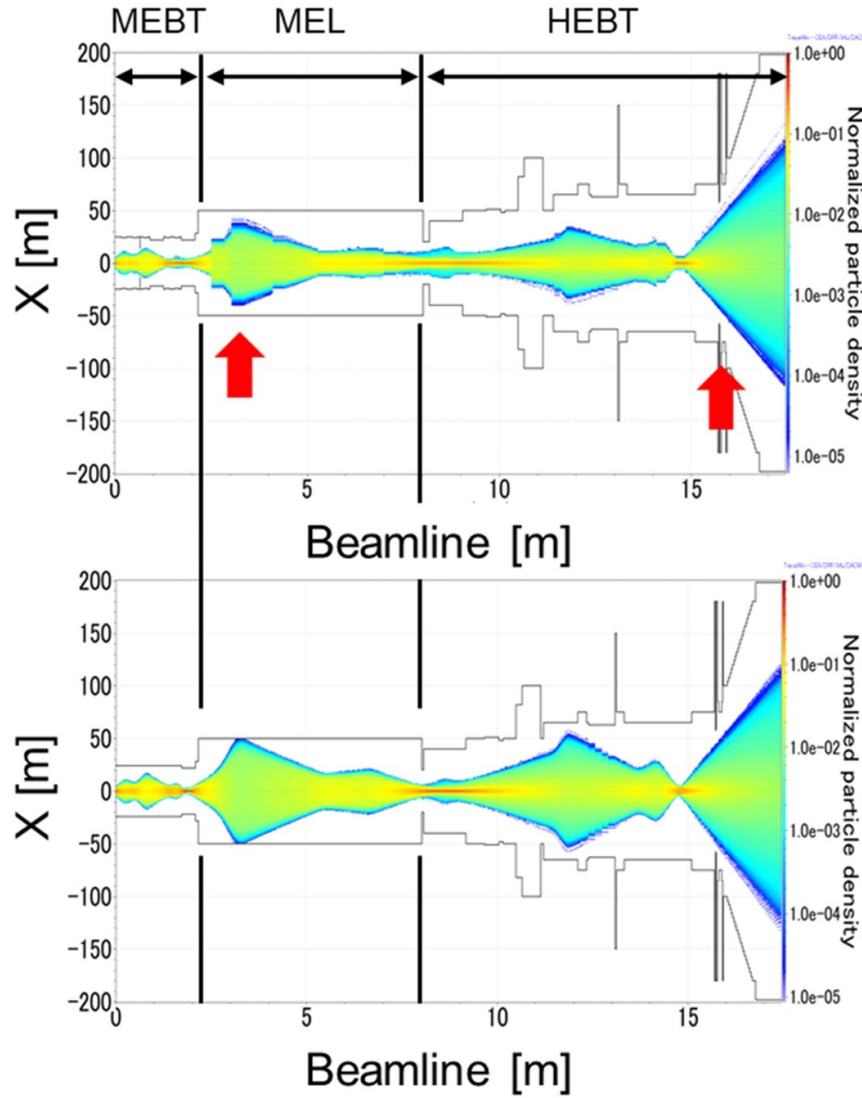
The main goal of Phase B+, as mentioned in the previous chapter, was to demonstrate high duty cycle operation of the RFQ. To reach this goal, following three stages of the beam commissioning were planned in the Phase B+,

- Stage 1: smaller currents of 10 mA  $H^+$  and 20 mA  $D^+$  at low duty cycle ( $<0.05\%$ ) (we called them pilot beams). The purposes were to check the injector chopper, newly installed transport elements and diagnostics in the MEL, the HEBT and the BD.
- Stage 2: nominal current of 125 mA  $D^+$  at low duty cycle ( $<0.1\%$ ). The purposes were 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 [11].

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 [12]. 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. The simulated particle densities from the RFQ exit (MEBT) to the beam dump in the horizontal plane is shown in figure 4 [13]. To investigate, beam simulations were performed using two models: the hard edge (HE) model (figure 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 an 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 (figure 4 bottom) show larger beam size than the HE model. Figure 5 shows a comparison between the measured rms beam sizes (red dots with error bars) and simulations performed under three conditions: hard-edge (black line), field maps (yellow line), and field maps with calibrated ‘GtoI’ conversions (blue line). As shown in the figure, the simulation results obtained with the initial hard-edge model (black line) fail to reproduce the measurements, particularly exhibiting a large discrepancy at the beamline position of 11 m where the simulation stays well outside the experimental error bars. When field maps for all quads are considered (yellow line), the simulation results become closer to the measured data. Furthermore, after calibrating the ‘GtoI’s (blue line), the simulated beam sizes approach the measured ones much more closely. However, a complete agreement has not yet been achieved, primarily due to the remaining discrepancy at the position of 11 m. This discrepancy is likely attributed to additional effects, such as the influence of the beam halo or differences in the initial beam distribution upstream of the beamline between the simulation and the



**Figure 4.** The simulated particle densities from the RFQ exit to the beam dump in the horizontal-direction (top: HE model, bottom: FF model). Reproduced from [13]. CC BY 4.0.

actual machine. Based on these findings, the beam optics were reconfigured to minimize particle loss with GtOI calibration—and follow-up measurements confirmed the improvement.

Stage 3 was started in March 2024 after the winter maintenance. Further details are described in the reference documents [14, 15]. 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  $1 \text{ ms} \times 1 \text{ Hz}$ . The low-level radio frequency (LLRF) optimization due to the slower rising time without chopper was performed to reach a longer ( $>2 \text{ ms}$ ) pulse operation. The final and maximum configuration was  $3.5 \text{ ms}$  pulse width and  $25 \text{ Hz}$ , which deduces a duty cycle of  $8.75\%$ . The beam current was about  $119 \text{ mA}$  at the HEBT (figure 6), and the RFQ transmission was about  $90\%$ , as expected.

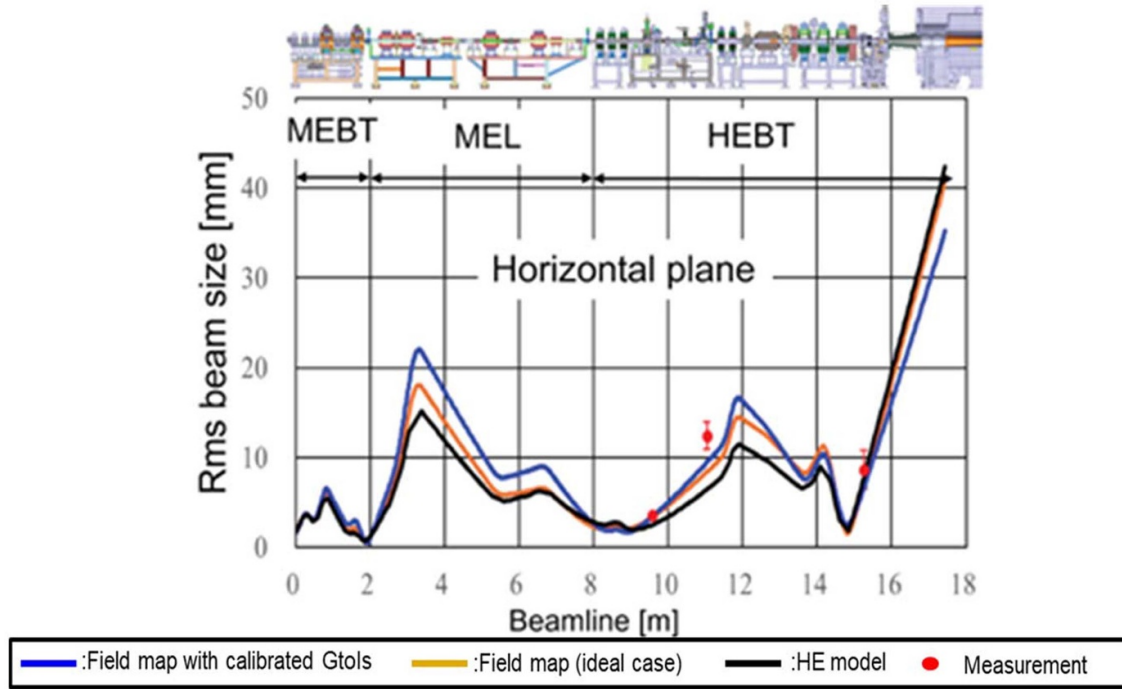
A lot of valuable data were collected such as for beam diagnostics validation and further improvement, beam characterization and modeling, understanding beam losses along the

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

While section 2.4 presents the chronological progress of Phase B+ beam commissioning, the RFQ-coupler issues described in this section unfolded in parallel with those beam activities. This section, therefore, provides a topic-based summary of the RF challenges rather than a continuation of the timeline.

After completing Stage 1 of Phase B+, conditioning of the RFQ to prepare for CW operation was started. The goal was to reach a cavity voltage of  $132 \text{ kV}$ , which was necessary to accelerate deuterons. By December 2021, RF power in CW mode at  $105 \text{ kV}$  was successfully injected, about  $80\%$  of the target voltage, marking the first time the system operated steadily under high thermal load [16].



**Figure 5.** The simulated and measured rms beam sizes from the RFQ exit to the beam dump in the horizontal-direction. Reproduced from [13]. CC BY 4.0.

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 figure 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 figure 7 (bottom).

Initially, the first solution was adopted. 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. The 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 did not 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 +.

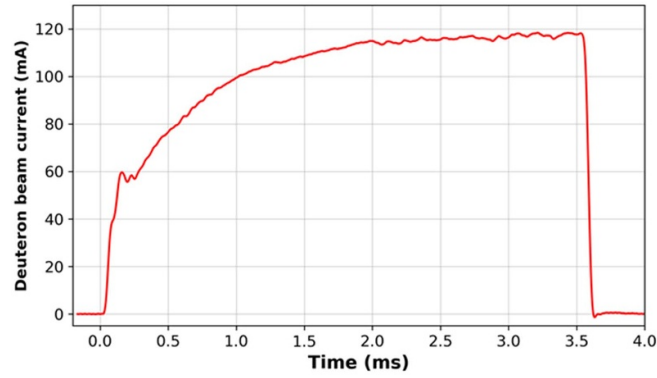
At the Stage 3, we tried to increase to 10% duty cycle, but it was limited up to 8.75% at the beam operation. Achieving longer pulses or higher duty cycles is limited by the current O-ring RF couplers [14, 17]. At long pulses and high duty cycle, RF input/reflections vary over time due to load changes as shown in figure 8—likely from multipacting—and each coupler has different multipacting characteristics, and these characteristics change over time. This causes imbalance across the RF chains and difficult to control, then ultimately triggers the RF interlock, preventing further duty-cycle increases.

## 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.

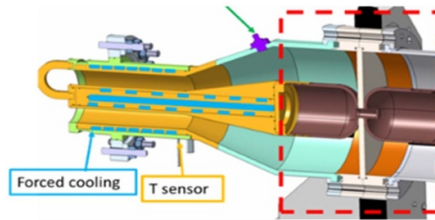
Preparations for Phase C/D have been already underway. The first major task is assembling and testing the SRF Linac's Radio-Frequency Power System, which will supply power to the eight accelerating cavities using four modules, each delivering  $2 \times 105$  kW.

Assembly of the SRF Linac began in early 2019 but faced delays due to manufacturing issues with the focusing solenoids

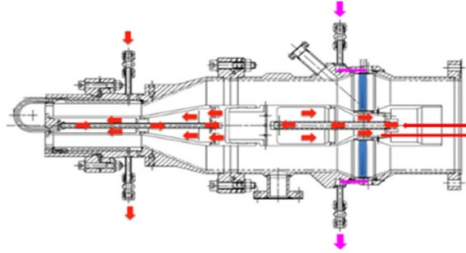


**Figure 6.** Beam current waveform at the HEBT at 8.75% duty cycle. Reproduced from [14]. CC BY 4.0.

### Present coupler (using EPDM O-ring)



### High-duty coupler (brazed)



**Figure 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. Reproduced with permission from [17]. Copyright © Particle Accelerator Society of Japan. All Rights Reserved.

and necessary measure for repairs. The assembly contractor from Europe was paused by the entry restriction to Japan due to the COVID outbreak.

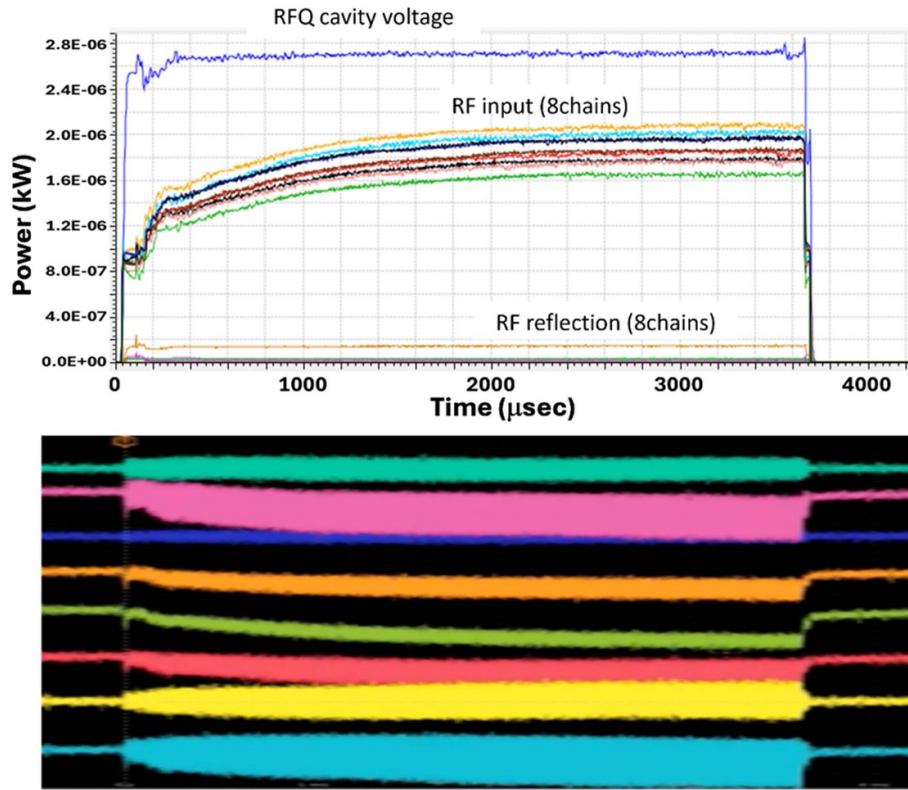
In August 2022, assembly work resumed after the COVID outbreak. In the initial stage, the assembly work proceeded with all cavity coupler assemblies and mounted on the cold mass support frame. One solenoid could not get its Beam Position Monitor leak tight and additional rework were needed. The assembly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

In September 2024, the string assembly as in figure 9 (connection work of cavities and solenoid coils) was completed and extracted from the clean room [18]. 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 as shown in figure 10. The unloaded cryomodule was transferred to the accelerator vault. Two shock detectors were attached but no events were recorded during the transport [19]. The assembly was continued in the vault. The current leads, which supply the superconducting solenoids, was expected to be inserted, but an interference issue 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 figure 11 [20].

### 3. Fusion neutron source design activities

It is important that the validation of the LIPAc accelerator constitutes the technological foundation for realizing a future



**Figure 8.** The RFQ cavity voltage, and the RF input/reflection powers for 8 RF chains (top), and the Arc sensor signals on the 8 RF couplers (bottom) at the duty cycle of 8.75% beam operation. Reproduced with permission from [17]. Copyright © Particle Accelerator Society of Japan. All Rights Reserved. The cavity voltage is measured at the pick-up antenna in watt (not corrected with the pick-up coupling factor to make absolute value), and the input/reflection powers are measured by the directional couplers (not exactly corrected with the coupling factors and cable losses at each chain). The reflection power is relatively lower than the input power. The chain in yellow has a large reflection, while the other seven chain signals have small reflections that overlap.



**Figure 9.** Installation of the component of the beam line in the clean room. Reproduced from [18]. CC BY 4.0.

fusion neutron source. Building on these accelerator based achievements, the Fusion Neutron Source Design (FNSD) activities extend the development pathway toward a complete fusion neutron source by addressing target technologies, engineering design, and long term operational issues essential for the next stage of the BA program. As part of the 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 FNS facility. They encompass the lithium target facility (LF) activities and Engineering Design (ED) activities. The LF framework comprises EVA performing additional R&D in order to improve the reliability of the

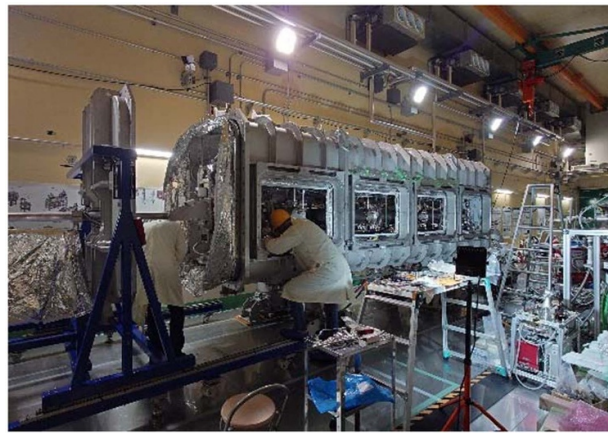
individual systems from the viewpoints of maintenance and long-term operation. While the ED activities are a set of tasks aiming to obtain relevant information for the design of an IFMIF-like Neutron Source carried out in an independent way.

### 3.1. 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



**Figure 10.** Loading of the cryomodule on the articulated lorry. Reproduced from [20]. CC BY 4.0.



**Figure 11.** Cryomodule assembly work in the accelerator vault. Reproduced from [20]. CC BY 4.0.

analysis of lithium fire risks, and technologies for impurity detection in lithium.

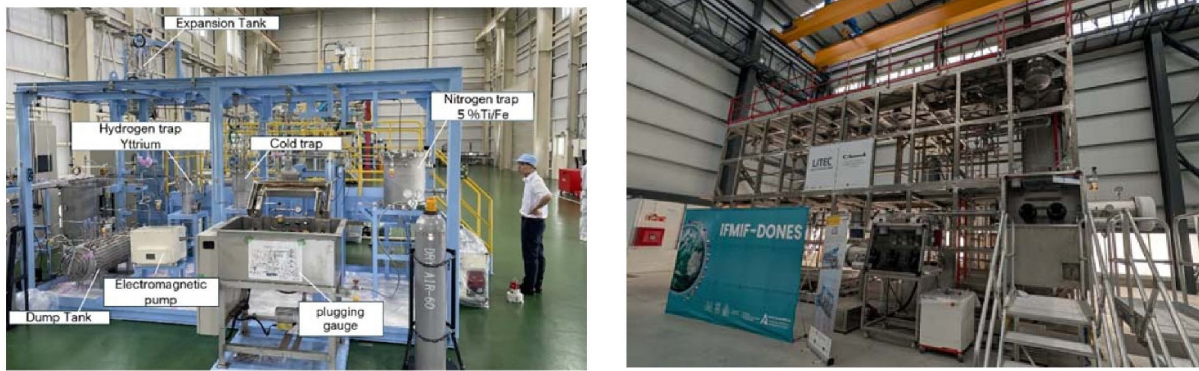
Figure 12 shows the lithium loop pilot plants constructed in Japan (1:10 scale) and Europe (1:1 scale) to validate technologies for impurity retention and monitoring in liquid lithium. The construction of the plant in Japan was completed in December 2024. The operation campaigns were carried out in January–February, 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 [21].

Diagnostics must be designed to monitor the lithium target under facility-specific conditions such as radiation fields. Figure 13 (left) shows a lithium loop diagnostic method at Osaka University [22]. The flow diagnostics were carried out at a distance of 10 m between the laser head and the Li target with flow velocities of  $15 \text{ m s}^{-1}$ . The wave height 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. Figure 12 (right) shows the EU-side diagnostics [23]. A sensor similar to the ITER IVVS (In-Vessel Viewing System) sensor had been used. The

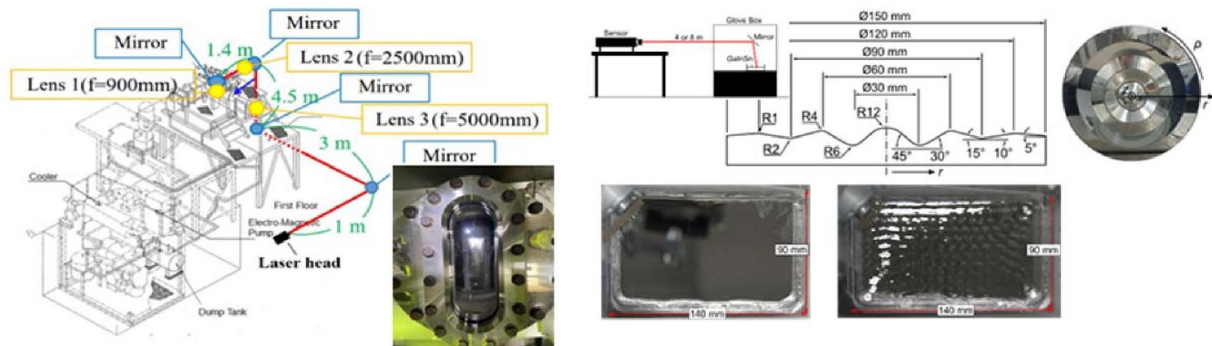
assembly of the prototype was completed. The experiments were carried out up to 8 m away from the target of the Galistan (Alloy of Ga–In–Sn) liquid metal. A vertical resolution better than the required 0.3 mm was achieved.

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 the ELTL pipe at the cavitation location. The observed cracks were characteristic of fatigue fracture, reducing nitrogen impurities could limit the corrosion.

Due to the high lithium chemical reactivity, stabilization was critical for safety operation. The Li stabilization test set-up was developed in 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<sub>2</sub>–D<sub>2</sub>, Li–D<sub>2</sub>–CO<sub>2</sub>, Li–D<sub>2</sub>–H<sub>2</sub>O–CO<sub>2</sub>, and Li–H<sub>2</sub>–D<sub>2</sub>O(purge)–CO<sub>2</sub> (LHDC) of Li vapor deposition and gas exposures. These experiments demonstrated that direct CO<sub>2</sub> exposure to lithium would not be suitable for the stabilization of tritium included in lithium.



**Figure 12.** Lithium loop pilot plants in Japan (left) and in Europe (right).



**Figure 13.** Lithium target diagnostics in Japan (left). Reprinted from [22], Copyright (2024), with permission from Elsevier and in Europe (right). Adapted from [23]. © 2025 The Author(s). Published by IOP Publishing Ltd on behalf of the IAEA). CC BY 4.0.



**Figure 14.** Experiment of lithium ignition and extinguishing by Argon gas. Reprinted from [24], Copyright (2026), with permission from Elsevier.

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 conditions for lithium ignition were clarified. The suppression and extinguishment of the Li fires were successfully achieved by supplying argon gas as shown in figure 14 [24].

Monitoring impurities was essential for safe plant operation. Hydrogen concentration in lithium was measurable via

the heavy water dissolution method. To improve accuracy, D<sub>2</sub> 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<sub>3</sub>N) 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.

### 3.2. EDA

The EDA comprise tritium migration estimation, erosion/deposition modeling in the target system, accident analysis in safety, study on the optimization of the Li-Oil heat exchanger, and use of LIPAc as a testing facility.

To ensure safety in fusion facilities like DONES and A-FNS, it is 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 [25]. 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 (QT) 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 the 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 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  $2 \mu\text{m yr}^{-1}$ , based on the LIFUS data.

The accident analysis covered failure modes effects and criticality analysis (FMECA), safety control system (SCS), and materials at risk (MAR). On the JA side, failure modes and severity were analyzed based on LF (LS) plant breakdown structure (PBS) from IFMIF/EVEDA. Rescue measures were defined for high-severity failures, leading to updates in LS Piping and Instrumentation Diagram (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

reevaluated 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  $\sim 1.5\times$  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.

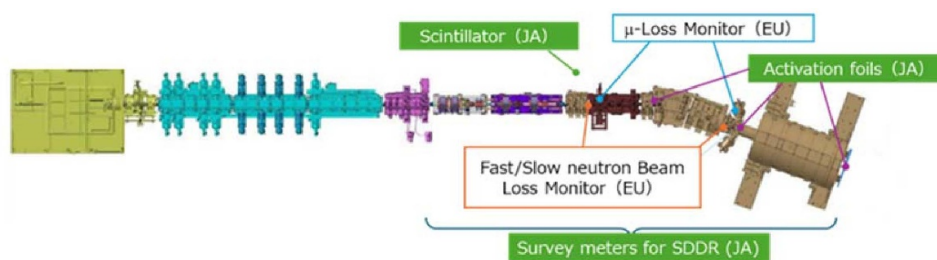
A range of activities was planned to use the LIPAc facility as a testing facility for technologies needed in fusion neutron source development. These activities were selected because each represents a prerequisite for FNS realization:

- Validating sensors and diagnostic tools (Layout is in figure 15), which ensure reliable beam monitoring in a high-radiation field
- Studying how real materials respond to neutron activation (Layout is in figure 15), which supports safe component design
- Collecting data on reliability, availability, maintainability, and inspectability (RAMI), which enables lifecycle planning
- Performing neutronics validation calculations, which reduces design uncertainties
- 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<sub>3</sub> 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 [26].

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  $3.2 \times 10^5$  per deuteron, projecting  $3 \times 10^{13}$  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, Micro Ionization Chamber (MIC), and Chemical Vapor Deposition (CVD) detectors. The 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.



**Figure 15.** Quantitative evaluation of beam loss based on radiation detection in high-duty beam commissioning of LIPAc RFQ.

#### 4. Outlook of the IFMIF/EVEDA

The project is transitioning from Phase B+ to Phase C following the successful completion of high duty cycle RFQ beam operation and preparations for the SRF Linac. The assembled cryomodule was transported to the LIPAc building in March 2025, and helium piping installation is currently underway inside the accelerator vault. Subsequently, the cryomodule 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 scheduled to commence in 2027.

It has been identified that the current O-ring type RF couplers for the RFQ imposes a limitation on CW operation due to the multipacting phenomena. Mitigation measures are in progress; alternative brazed-type couplers are undergoing high power testing, and additional brazed couplers under the collaborative framework between F4E and CERN are being prepared as a backup solution. CW beam tests will be conducted during SRF-Linac beam commissioning in Phase D.

A principal objective of the LIPAc is the full validation of the engineering design for high duty cycle operation, ultimately achieving CW at nominal beam intensity. Beyond Phase D, the scope will expand to address enhance reliability and availability, which are crucial for future IFMIF-like irradiation facilities, such as IFMIF-DONES in Europe and A-FNS in Japan. To meet these requirements, refurbishment and improvement of some key subsystems, collectively referred to as ‘enhancements,’ are being implemented [27]. For example, tetrodes currently used in the high power RF sources may be replaced by solid-state RF amplifiers, leveraging advances in semiconductor technology and mitigating risks associated with tetrode supply instability. Additionally, the control system, originally designed over a decade ago, requires modernization due to component obsolescence, necessitating renewal and validation for future facility construction. The injector upgrade is also in progress, targeting improved beam current and CW, as well as enhanced maintainability and operational availability. The ultimate LIPAc goal remains the demonstration of high availability operation.

Regarding FNSD, significant progress has been achieved in the lithium target facility activities and EDA.

The accomplishments of IFMIF/EVEDA exemplify the success of the EU-Japan partnership under the BA Agreement. These achievements directly support the deployment of the European FNS facility, IFMIF-DONES, in Spain [28] by

providing qualified designs, validated technologies, and operational expertise through close collaboration between the two Projects.

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#### References

- [1] Knaster J. et al 2017 Overview of the IFMIF/EVEDA project *Nucl. Fusion* **57** 102016
- [2] Dzitko H. et al 2024 Overview of broader approach activities *Fusion Eng. Des.* **201** 114259
- [3] Carin Y. et al 2023 Overview of achievements of the IFMIF/EVEDA project *Proc. FEC2023 (London, United Kingdom, 16–21 October 2023)* p IAEA-CN-316-1681 (available at: <https://conferences.iaea.org/event/316/papers/29091/files/10784-Manuscript%20-%20IAEA-FEC2023%20-%20IFMIF-EVEDA%20Project%20-%20v2%20-%20clean.pdf>)
- [4] Hasegawa K. et al 2023 LIPAc (Linear IFMIF Prototype Accelerator) beam commissioning & future plans *Proc. IPAC'23, MOYD2\_talk (Venice, Italy, 7–12 May 2023)* (JACoW) (<https://doi.org/10.18429/JACoW-IPAC2023-MOYD2>)
- [5] Cara P. et al 2021 IFMIF/EVEDA project achievements and outlooks beyond 2020 *28th IAEA Fusion Energy Conf. (Virtual Event, 10–15 May 2021)* (available at: <https://conferences.iaea.org/event/214/contributions/17098/>)
- [6] Grand P., Batchelor K., Blewett J.P., Golland A., Gurinsky D., Kukkonen J. and Snead C.L. 1976 An intense Li(d,n) neutron radiation test facility for controlled thermonuclear reactor materials testing *Nucl. Technol.* **29** 327
- [7] Carin Y. et al 2024 IFMIF/EVEDA achievements overview *Fusion Eng. Des.* **201** 114258

- [8] Akagi T. et al 2020 Commissioning of high current  $H^+/D^+$  ion beams for the prototype accelerator of the international fusion materials irradiation facility *Rev. Sci. Instrum.* **91** 023321
- [9] Kondo K. et al 2020 Validation of the Linear IFMIF Prototype Accelerator (LIPAc) in Rokkasho *Fusion Eng. Des.* **153** 111503
- [10] Shimosaki Y. 2019 Lattice design for 5MeV-125mA CW RFQ operation in LIPAc *Proc. IPAC'19 (Melbourne, Australia, 19–24 May 2019)* p **MOPTS051**
- [11] Masuda K. et al 2023 Beam Commissioning of Linear IFMIF Prototype Accelerator (LIPAc) toward high-duty operation at 5 MeV, 125 mA  $D^+$  *Proc. FEC2023 (London, United Kingdom, 16–21 October 2023)* p IAEA-CN-316-1741 (available at: [https://conferences.iaea.org/event/316/papers/27955/files/11091-IAEA-FEC2023-Beam%20Commissioning%20of%20LIPAc\\_rev2\\_submitted.pdf](https://conferences.iaea.org/event/316/papers/27955/files/11091-IAEA-FEC2023-Beam%20Commissioning%20of%20LIPAc_rev2_submitted.pdf))
- [12] Kwon S. et al 2024 High beam current operation with beam diagnostics at LIPAc *J. Instrum.* **19** T05013
- [13] Hyun J. et al 2025 Characterization of beam optics considering fringe fields of quadrupole magnets in a LIPAc 5 MeV beamline *Proc. IPAC'25, WEPW112 (Taipei, Taiwan, 1–6 June 2025)* vol 3094 p **012033**
- [14] Akagi T. et al 2024 Completion of phase B+ beam commissioning of Linear IFMIF Prototype Accelerator (LIPAc) *Proc. LINAC2024 (Chicago, USA 25–30 August 2024)* pp **705–7**
- [15] Akagi T. et al 2026 Accomplishment of high duty cycle beam commissioning of Linear IFMIF Prototype Accelerator (LIPAc) at 5 MeV, 125 mA,  $D^+$  *Nucl. Fusion* **66** 096043
- [16] Scantamburlo F. et al 2024 Linear IFMIF Prototype Accelerator (LIPAc) Radio Frequency Quadrupole's (RFQ) RF couplers enhancement towards CW operation at nominal voltage *Fusion Eng. Des.* **204** 114508
- [17] Kondo K. 2025 Progress in validation of the linear IFMIF prototype accelerator (LIPAc) *Proc. Particle Accelerator Society of Japan 2025 (Tokyo, Japan, 6–8 August 2025)* p WEPO703 (available at: [https://www.pasj.jp/web\\_publish/pasj2025/proceedings/PDF/WEPO/WEPO703\\_oral.pdf](https://www.pasj.jp/web_publish/pasj2025/proceedings/PDF/WEPO/WEPO703_oral.pdf))
- [18] Chambrillon J.K. et al 2024 Cleanroom assembly of the IFMIF SRF linac *EPJ Web Conf.* **315** 02015
- [19] Chambrillon J.K. et al 2025 Assembly of the IFMIF SRF linac cryomodule *Proc. IPAC'25 (Taipei, Taiwan, 1–6 June 2025)* (<https://doi.org/10.18429/JACoW-IPAC25-TUPS062>)
- [20] Chambrillon J.K. et al 2025 Assembly of the LIPAc SRF linac cryomodule *Proc. 22nd Int. Conf. on RF Superconductivity (SRF2025) (Tokyo, Japan, 18–26 September 2025)* (<https://doi.org/10.18429/JACoW-SRF2025-THP61>)
- [21] Garcinuño B., García A., Sánchez-arenillas M. and Rapisarda D. 2024 LITEC: an experimental facility for the validation of the IFMIF-DONES impurity control system *Fusion Eng. Des.* **201** 114283
- [22] Okita T., Okunaka S., Kojima T., Hoashi E., Oyaizu M. and Ochiai K. 2024 Investigation of applicability of long-distance LP system for Li target diagnostics in fusion neutron source *Fusion Eng. Des.* **202** 114326
- [23] Nitti F.S., Maestre J., Dezsi T., Gordeev S., Holstein N., Brenneis B., Buligins L., Molla J. and Ibarra A. 2025 The lithium systems of the IFMIF-DONES facility *Nucl. Fusion* **65** 122004
- [24] Kenjo S., Oyaizu M., Obata K., Sakamoto R., Ochiai K., Sato S. and Masuda K. 2026 Experimental study on ignition conditions and remote extinguishment method for Li fire in fusion neutron source *Fusion Eng. Des.* **228** 115778
- [25] Kenjo S., Oyaizu M., Ochiai K., Oya Y., Yokoyama S., Sato S., Masuda K., Kasugai A. and Hasegawa K. 2026 Radiological safety assessments for fusion neutron source in engineering design activities under IFMIF/EVEDA project *Nucl. Fusion* **66** 066014
- [26] Kumagai K., Hasegawa K., Kondo K., Kwon S., Masuda K., Ochiai K., Carin Y., Dzitko H., Jimenez-rey D. and Lopez V. 2026 Quantitative evaluation of beam loss based on radiation detection in high-duty beam commissioning of LIPAc RFQ *Nucl. Fusion* **66** 056037
- [27] Cismondi F. et al 2024 Planned future upgrades of Linear IFMIF Prototype Accelerator (LIPAc) *Proc. LINAC2024 (Chicago, USA, 25–30 August 2024)* (<https://doi.org/10.18429/JACoW-LINAC2024-MOPB071>)
- [28] Ibarra A. 2025 Overview of the DONES experimental programme *Proc. FEC2025 (Chengdu, China 13–18 October 2025)* p IAEA-CN-316/3069 (available at: [https://conferences.iaea.org/event/392/papers/35604/files/13589-Manuscript%20OV%20\\_IBARRA\\_%20FEC%202025%20v3.pdf](https://conferences.iaea.org/event/392/papers/35604/files/13589-Manuscript%20OV%20_IBARRA_%20FEC%202025%20v3.pdf))