ACCOMPLISHMENT OF HIGH DUTY CYCLE BEAM COMMISSIONING OF LINEAR IFMIF PROTOTYPE ACCELERATOR (LIPAC) AT 5 MEV, 125 MA D+

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Abstract

The Linear IFMIF Prototype Accelerator (LIPAc) is being commissioned under the Broader Approach agreement between Europe and Japan, with the aim of validating the low-energy section of the accelerator for the International Fusion Materials Irradiation Facility (IFMIF). LIPAc is designed to accelerate a 125 mA deuteron beam up to 9 MeV in continuous-wave (CW) operation. This paper reports the outcomes of high-duty cycle beam commissioning at 5 MeV using the RFQ referred to as Phase B+. In this phase, a maximum duty cycle of 8.75% and a beam current of 119 mA were achieved. This corresponds to an average beam power of 40–45 kW, which is the highest beam power among operational RFQs. It was also identified that the RFQ RF couplers are a bottleneck for further duty cycle increases, leading to the preparation of brazed high-duty couplers. These achievements establish a solid foundation for the next commissioning phase, which will include SRF Linac commissioning and aim for CW operation to demonstrate the IFMIF accelerator concept.

1. INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-driven, high-intensity neutron source using the D-Li stripping nuclear reaction, aimed at evaluating the effects of 14 MeV high-energy neutrons produced in D-T fusion reactions on structural materials for a fusion reactor. IFMIF requires an extremely high-intensity accelerator capable of accelerating 40 MeV / 125 mA deuterons in continuous-wave (CW) operation [1].

As part of the Broader Approach activities since 2007 between Europe and Japan, the commissioning of the Linear IFMIF Prototype Accelerator (LIPAc) is being conducted in Rokkasho, Japan, jointly between Europe and Japan to validate the low-energy section of the IFMIF accelerator [2]. The goal of the LIPAc is to accelerate a 125 mA deuteron beam up to 9 MeV and demonstrate CW operation. In this project, the components and subsystems are designed and manufactured in Europe, while assembly and testing are carried out in Japan, at QST-Rokkasho facilities.

2. LIPAC CONFIGURATION AND PHASE B+ OBJECTIVES

LIPAc consists of an injector, a Radio Frequency Quadrupole (RFQ), a Medium Energy Beam Transport (MEBT) line, a Superconducting Radio Frequency (SRF) Linac, a High Energy Beam Transport (HEBT) line, and a Beam Dump (BD). The commissioning of LIPAc has been progressing step-by-step toward the final configuration, Phase C/D. In Phase B, acceleration of 125 mA pulsed deuteron beam by the RFQ was achieved in July 2019 with duty cycle of 0.1% [3]. Subsequently, the installation of the HEBT, BD, and the MEBT Extension Line (MEL), which is planned to be replaced by the SRF Linac in the future, was completed. High-duty beam commissioning

(Phase B+) began in 2021 and was completed at the end of June 2024. The LIPAc configuration for the Phase B+ is shown in Fig. 1.

The objectives of the Phase B+ commissioning were to demonstrate 5 MeV deuteron beam acceleration at higher duty cycle, to validate the newly installed components HEBT and BD, and to characterize the beam to be injected into the SRF Linac in future phases. The Phase B+ beam tests were conducted in three stages, with beam current and duty factor gradually increased. Stage 1: low beam current, low duty pilot beams (10 mA H+ and 20 mA D+) with short pulses (100 µs/1 Hz), allowing the use of interceptive diagnostics; Stage 2: nominal beam current (125 mA) at low duty; Stage 3: nominal beam current (125 mA) at high-duty. The outcomes of Stage 1 were reported at the FEC2023 [4]. The following sections report the results obtained from the remaining stages up to the completion of Phase B+ commissioning.

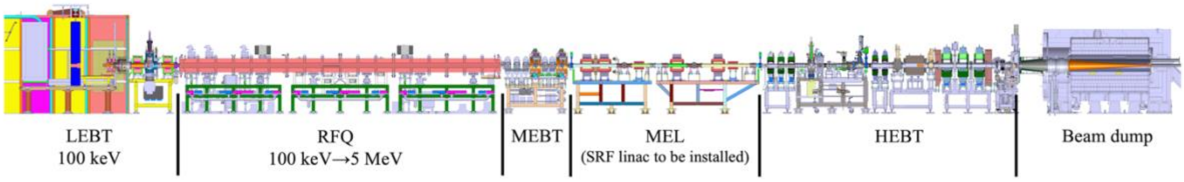

FIG. 1. The LIPAc Phase B+ configuration.

3. INJECTOR AND DIAGNOSTICS COMMISSIONING

Injector commissioning demonstrated the capability to simultaneously achieve the high current and low emittance required for the beam delivered to the RFQ. The measured normalized rms emittance was 0.18 π·mm·mrad at a total extracted beam current of 158 mA, which meets the target value of <0.25 π·mm·mrad. Additionally, by using the chopper installed in the LEBT, short-pulse beams of approximately 120 mA with a pulse width of 100 µs were generated, enabling beam characterization using interceptive diagnostics installed after the RFQ.

LIPAc beam diagnostics are mainly installed in the Diagnostic Plate (DPlate) and HEBT (Fig. 2). Interceptive diagnostics such as Slits and Secondary Emission Monitor (SEM) grids were used for transverse beam profile and emittance measurements at low duty cycles. These systems worked as expected and were essential for beam optics tuning under low-duty conditions [5]. On the other hand, for beam monitoring at high-duty cycles, non-interceptive diagnostics such as Fluorescence Profile Monitor (FPM) and Ionization Profile Monitor (IPM) were introduced. Basic functionality of these systems was verified, and transverse beam profiles were successfully obtained. However, these systems showed sensitivity to vacuum conditions, radiation background, and high-voltage stability, indicating the need for further optimization for stable operation.

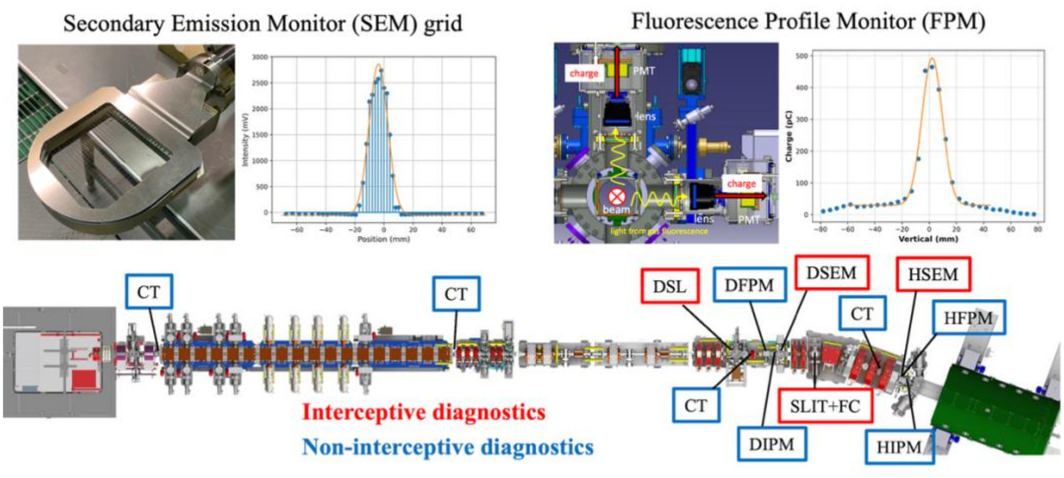

FIG. 2. Location of LIPAc beam diagnostics and examples of transverse beam profile measurement results.

4. BEAM TRANSPORT SIMULATION VALIDATION

During the tuning of the beam transport line, unexpected particle losses were observed in the MEL/HEBT. Following this, the beam modelling was improved from the hard-edge model to one using the exact quad field distribution, fully implementing fringe fields. Additionally, beam-based calibration was performed to update the conversion factor between the magnetic field gradient of quadrupole magnets g (T/m) and excitation current I (A) [6, 7]. The updated optics with calibrated conversion factor and Fringe Field model significantly enhanced the agreement between the measurements and simulation results (Fig. 3), and the particle losses previously observed in MEL/HEBT were significantly reduced.

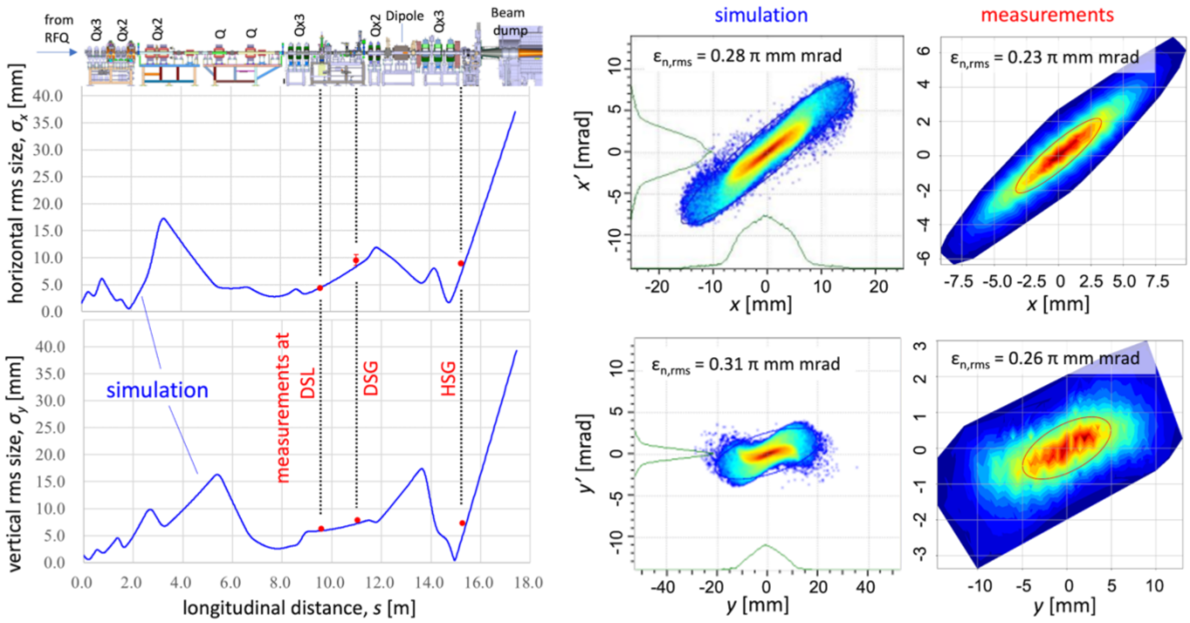

FIG. 3. Comparison between simulated and measured transverse beams sizes and emittance along the LIPAc beamline.

5. MACHINE LEARNING BASED OPTICS OPTIMIZATION

As the duty cycle was gradually increased, the vacuum level in the MEL section approached the interlock threshold due to particle losses suspected to be caused by beam halo. To address this issue, machine learning (ML)–based optimization was introduced to tune the four quadrupoles and two horizontal/vertical steerers in the MEL. The optics settings proposed by ML successfully reduced the vacuum pressure in MEL under equivalent beam conditions compared to pre-optimization settings [8], providing valuable guidance for reducing particle losses.

6. HIGH DUTY OPERATION AT 5 MEV

With the optimized optics, the target D+ beam current of 125 mA at the RFQ exit was achieved and transported through the HEBT to the beam dump with almost no losses. Commissioning then proceeded, and the maximum achieved duty cycle was 8.75%, corresponding to a 3.5 ms pulse width at a 40 ms repetition period. Under these conditions, the beam current in the HEBT was about 119 mA (Fig. 4), and the RFQ transmission was approximately 90% (consistent with the RFQ design). The RFQ's average beam power reached 40–45 kW, which is the highest average beam power among operational RFQs.

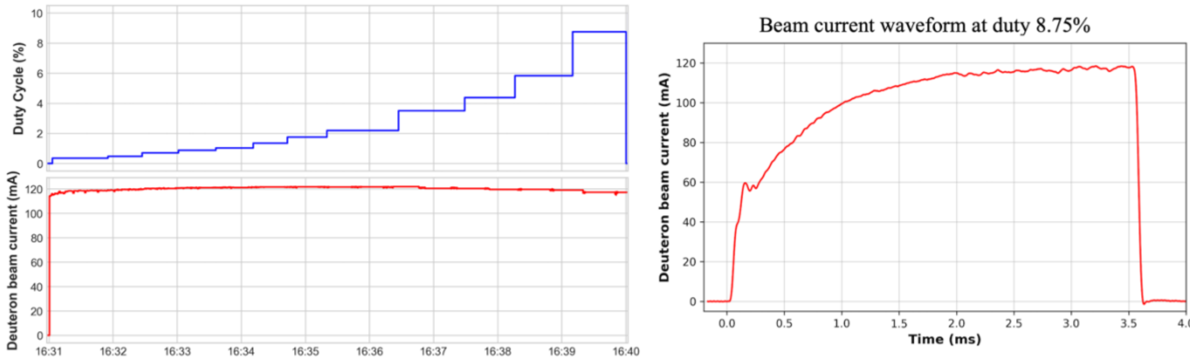

FIG. 4. Time evolution of the duty cycle and beam current (left), and waveform of the deuteron beam current at duty cycle of 8.75% (right).

7. TECHNICAL CHALLENGE OF RF COUPLER

In Phase B+, the RFQ-RF couplers were identified as the bottleneck for achieving high-duty operation.

In March 2022, during RFQ conditioning, a vacuum leak occurred in an RF coupler. Investigation revealed that in 5 out of 8 couplers, Viton O-rings were melted or deformed, which was attributed to overheating caused by multipacting. As a short-term solution, the inner conductor was replaced with one having enhanced cooling capability [9], enabling Phase B+ beam operation. However, to avoid further coupler damage, the duty cycle was limited to a maximum of 10% in Phase B+.

Detailed observations at long-pulse, high-duty beam operation confirmed that multipacting varies in different ways between couplers, resulting in imbalances across the eight RF chains. Consequently, the RF interlocks were triggered before the cavity temperature and vacuum level reached steady state, leading to the conclusion that achieving duty cycle above 10% is difficult with the present RF coupler.

Currently, brazed couplers (high-duty couplers) designed for high-duty operation are undergoing high-power testing. A key feature of the high-duty coupler is that its inner conductor is directly brazed to the RF window. In contrast to the present coupler, where the bowl-shaped anchor tends to induce multipacting, the high-duty coupler adopts an anchor geometry that is perpendicular to the RF window, thereby mitigating the occurrence of multipacting. Furthermore, to remove heat generated by RF losses, the high-duty coupler incorporates cooling channels within the loop antenna and the inner conductor around the RF window. The structural differences between the present coupler and high-duty couplers are shown in Figure 5. In the high-power test bench, four couplers have successfully achieved CW operation at 190 kW, demonstrating promising results. The remaining couplers are currently under preparation, with installation into the RFQ cavity and subsequent RF conditioning planned.

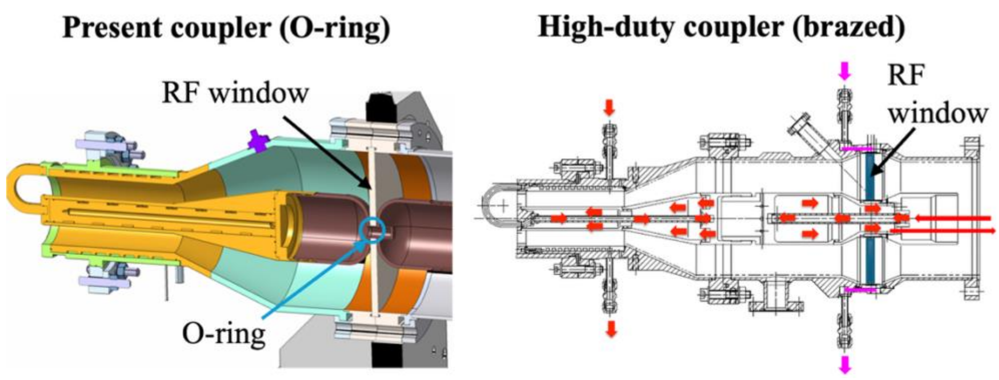

FIG. 5. Present RF coupler (left) and the high-duty coupler (right). Red arrows indicate the cooling water flow.

8. SRF LINAC ASSEMBLY STATUS

In parallel with Phase B+, the SRF Linac cryomodule assembly progressed. The assembly of cavities and solenoids in the clean room was completed in September 2024, and transportation to the accelerator vault was successfully carried out in March 2025. Currently, the assembly of the cryomodule in the accelerator vault is ongoing, followed by installation into the beamline, warm conditioning, and the first cooldown, with the target of starting Phase C beam test in 2027.

9. CONCLUSION

In the Phase B+ commissioning of LIPAc, high-duty cycle beam operation at 5 MeV was successfully demonstrated, achieving a maximum duty cycle of 8.75% and transporting a 119 mA deuteron beam through the HEBT to the beam dump. The RFQ transmission was approximately 90%, and these results confirm that the RFQ achieves stable acceleration as designed, with the nominal beam current and high-duty conditions. The average beam power reached 40–45 kW, which is the highest value among currently operational RFQs worldwide.

In addition to validating the HEBT and beam dump with the nominal beam current, improvements in beam transport simulations and optics optimization using machine learning successfully reduced beam losses, enabling reliable high-duty operation.

The RFQ-RF couplers are identified as a bottleneck for further increases in duty cycle, and it was confirmed that operation beyond duty cycle of 10% is difficult with the current RF couplers (O-ring). To overcome this issue, preparation and high-power testing of couplers with brazed inner conductor to the vacuum window are underway, and this is considered a promising solution toward achieving continuous-wave (CW) operation.

In parallel, assembly of the SRF Linac cryomodule is progressing inside the accelerator vault, and Phase C beam test is scheduled to start in 2027. These achievements establish a solid foundation for future progress toward CW operation to demonstrate the IFMIF accelerator concept.

ACKNOWLEDGEMENTS

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

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