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COMPLETION OF PHASE B+ BEAM COMMISSIONING OF LINEAR IFMIF PROTOTYPE ACCELERATOR (LIPAc)*

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Abstract

The Linear IFMIF Prototype Accelerator (LIPAc) is being commissioned under the international collaboration between the EU and Japan. LIPAc aims to accelerate a deuteron beam of 125 mA to 9 MeV and operate in CW mode, and consists of an injector, an RFQ, a Superconducting RF Linac (SRF Linac), a beam transport line, and a beam dump. Until recently, the LIPAc beamline was in its final configuration except for the SRF Linac, which was for a high-duty beam operation called Phase B+ commissioning. The main objective of this commissioning was to validate high duty cycle deuteron beam operation and characterization of the beam. Phase B+ was completed at the end of June 2024, with a beam current of about 119 mA and duty cycle of up to 8.75% have been achieved. After the completion of the Phase B+, the SRF will be delivered to the accelerator room and installed in the beamline. The results of Phase B+ are presented in this paper.

INTRODUCTION

As one of the Broader Approach (BA) projects, an international cooperation between Europe and Japan in the field of fusion energy, the International Fusion Materials Irradiation Facility (IFMIF) Engineering Validation and Engineering Design Activity (IFMIF/EVEDA) is underway [1]. This is to research and develop an accelerator-driven intense neutron source using the D-Li stripping nuclear reaction to study the effects of 14 MeV high-energy neutrons produced in the D-T fusion reaction on potential candidate materials constituent of a fusion reactor.

The prototype accelerator of IFMIF, called Linear IFMIF Prototype Accelerator (LIPAc), is being commissioned in Rokkasho-mura, Japan as part of the IFMIF/EVEDA project. The IFMIF accelerator concept is designed to operate in continuous wave (CW) mode with two deuteron beams with a total of 250 mA (2 × 125 mA) at 40 MeV. LIPAc is designed to demonstrate the low-energy part of the accelerator, which is the most challenging part from a beam dynamic standpoint, and its goal is to accelerate a 125-mA deuteron beam to 9 MeV and operate in CW mode. LIPAc consists of an injector, an RFQ driven by 175 MHz eight 200 kW RF power system, an SRF Linac, a beam transport system and a Beam Dump (BD). Each system was designed and manufactured at European research institutes and shipped to QST Rokkasho Institute for Fusion Energy in Rokkasho for installation and commissioning. The commissioning of LIPAc is performed in several phases: Injector Stand-Alone Validation (Phase A), RFQ Validation (Phase B) and SRF-Linac Validation (Phase C/D) as shown in Fig. 1. Phase B was completed in July 2019 with the successful acceleration of a 125-mA deuteron short pulse beam (1 ms, 1 Hz) at 5 MeV thanks to the RFQ [2]. The installation of the MEBT Extension Line (MEL) in place of the SRF Linac, the High Energy Beam Transport (HEBT) line and the beam dump enabled to begin the Phase B+ in 2021 toward high-duty beam operation and it was completed at the end of June 2024. The SRF Linac installation preparations are currently underway for Phase C. The following sections report on the test results obtained from the Phase B+.

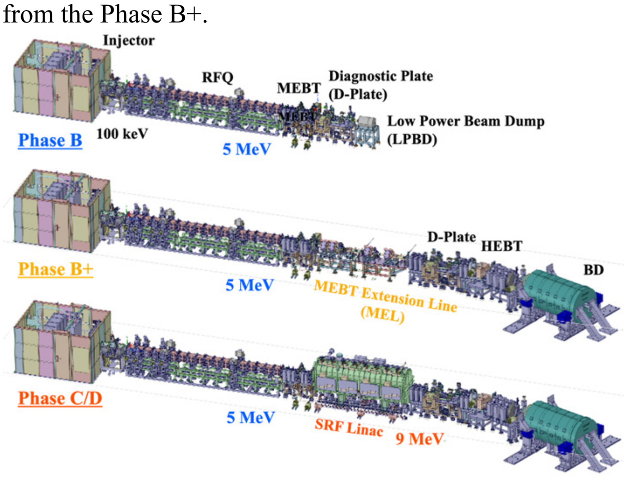

Figure 1: The three configurations of the LIPAc stepwise commissioning phase.

PHASE B+

The main purpose of Phase B+ is to demonstrate the operation of the 5 MeV deuteron beam with long pulses and to characterize the beams injected into the SRF-Linac (which will be installed after the completion of Phase B+).

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The Phase B+ was planned to be conducted in stages as follows with the ultimate goal of reaching CW (100% duty cycle). Stage 1: Low current and low duty cycle, Stage 2: nominal current of 125 mA and low duty cycle, and Stage 3: 125 mA and high duty cycle. The Stage 1 started with a proton beam acceleration test in July 2021, and by the end of December, a deuteron beam of about 20 mA was successfully injected into the beam dump with no significant beam loss. More details on the results of the Stage 1 are reported in [3].

RFQ CW CONDITIONING

After completion of Phase B+ Stage 1, RFQ conditioning was performed aiming CW RF injection at a cavity voltage of 132 kV, which is required for deuteron acceleration. In December 2021, RF injection in CW at about 80% of nominal voltage (105 kV) was achieved, demonstrating for the first time steady-state conditions under high thermal load [4]. However, in March 2022, a vacuum leak event occurred at the RF coupler during RFQ conditioning. All RF couplers were removed from the RFQ and a visual inspection of the inside of the couplers was carried out. As a result, it was confirmed that the vacuum side O-ring of the couplers where the vacuum leak occurred had melted. At that time, the cause of the O-rings overheating was thought to be joule heating from the dissipated RF power or multipacting.

The two actions were taken in parallel because it is highly likely that similar issues will arise in the future during high-duty operation. These actions are (1) improvement of the current O-ring RF couplers [5] and (2) preparation of an RF coupler with the inner conductor brazed to the vacuum window [6]. This section briefly describes the actions and results of (1). As a countermeasure for the current RF coupler, an inner conductor with enhanced cooling capacity was designed and manufactured. Specifically, the very limited contact area between the anchor in contact with the RF window and the cooled portion of the inner conductor was found to be a thermal weak point, so a new anchor was designed to improve thermal conduction by increasing the contact surface between these two parts. In March 2023, the coupler assembly with the new anchor, installation on the RFQ, and vacuum leak test were completed, and RFQ conditioning resumed in June. Shortly after conditioning resumed, the necessary conditions at the nominal deuteron acceleration voltage were met, allowing Stage 2 to start in August. In parallel, the RFQ conditioning for high duty cycle continued and 27% duty cycle was achieved at nominal voltage by the end of December 2023. Unfortunately, the heat generated by the RF coupler did not dissipate, and signs of vacuum leakage were again observed. On the other hand, observation of the transient change within the RF pulse of the optical signal from the arc sensors installed in the RF couplers showed a light emission signal different from the arc discharge (Fig. 2). This light emission was observed in all five RF couplers that warmed up during conditioning, leading to the conclusion that multipacting was the cause of the O-rings overheating. The decision was made to stop further high duty cycle conditioning and limit the operation to a maximum of 10% of duty cycle in phase B+.

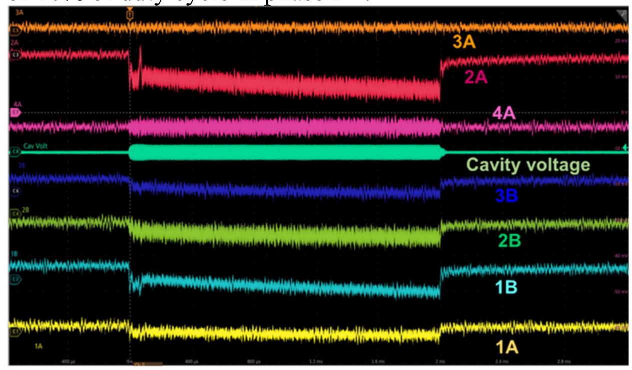

Figure 2: Arc sensor signals installed in RF couplers.

PHASE B+ STAGE 2

The Stage 2 started with a low duty cycle, and the deuteron beam current was adjusted to about 70 mA at the RFQ exit by tuning the ion source. The beam current was then increased to about 115 mA. Using a deuteron beam current close to nominal, the buncher was tuned, the beam profile and emittance were measured using interceptive diagnostics. Also, the operations of non-interceptive beam profilers such as the Fluorescence Profile Monitor and beam loss monitors were verified [7]. On the other hand, during the optimization of the beam transport, unexpected particle losses were observed, especially upstream/downstream of the MEL. Beam modelling advanced concurrently to study the reason of the losses. For instance, the impact of quadrupole magnets' fringe field was examined by comparing simulation results from the hard edge (HE) model and the fringe field (FF) model. Calibration tests for the magnetic field gradient of quadrupole magnets and the conversion equation for excitation current were also conducted using the beam. The calculated results with the FF model using the calibrated conversion equation were compared with the measured results and found to be in good agreement [8, 9]. So, the beam optics were reconfigured to reduce particle loss, and the new measurement during operation confirmed the reduction. The beam characterization using interceptive diagnostic was performed at the low duty cycle beam finalizing the Stage 2 at the end of November 2023.

PHASE B+ STAGE 3

Beam operation was suspended for winter maintenance in early 2024, and Stage 3 began at the end of March 2024 with the objective to increase duty to 10%. In this stage, the LEBT chopper was extracted from the beamline and the beam pulse from the ion source was injected directly into the RFQ. The duty was increased by adjusting the width and repetition rate. It was started with a pulse width of 1 ms and a repetition rate of 1 Hz, and gradually increasing the duty cycle. The Low-Level Radio Frequency optimization was performed again because the rise time of the beam pulse without the chopper is much slower than with the chopper, reaching a plateau with a pulse width above 2 ms.

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The Stage 3 was scheduled to be completed by the end of June 2024, taking into account the constraint of subsequent SRF Linac installation schedule. By the end of the Phase B+, the maximum duty cycle of 8.75% was achieved with a pulse width fixed at 3.5 ms and the repetition period was gradually decreased from 1 s to 40 ms to reach 8.75% duty cycle. The beam current was about 119 mA at HEBT (Fig. 3), and the RFQ transmission was about 90%.

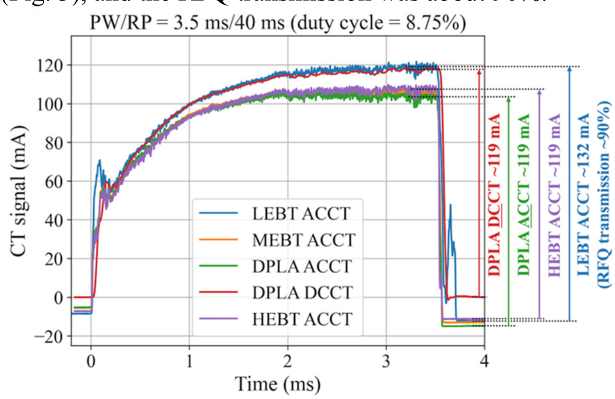

Figure 3: Beam current waveform when 8.75% duty cycle is achieved.

CHALLENGES OF HIGH DUTY CYCLE

It was confirmed that longer pulse lengths or higher duty cycles are difficult to achieve with the current O-ring RF couplers. Specifically, at long pulses and high duty cycle, the time variation of RF reflections became significant due to load variations that may be caused by multipacting, and they varied at different rates between each RF coupler, resulting in unbalance in each RF chain. As a result, the duty cycle could not be increased further due to the RF interlock.

In addition, RFQ tuning using cooling water requires restarting from low duty cycle each time the beam is stopped for more than 1 s due to interlock, whereas, with the current interlock system in LIPAc, it takes at least one min to restart the beam from the low duty cycle. Relatedly, the current timing system needs to be improved so that the pulse width/repetition frequency can be adjusted smoothly with finer steps while the beam is on. Moreover, Phase B+ has been extremely valuable and LIPAc effectively fulfilled its role as a prototype accelerator, as it enabled the identification of multiple enhancements that will be incorporated into future phases.

PREPARATION FOR PHASE C

In parallel with the Phase B+, SRF Linac preparations for the Phase C are underway at QST Rokkasho, where eight superconducting cavities and solenoid magnets have been connected in the clean room. In the accelerator room, the disassembling of the MEL started in July 2024, after the completion of Phase B+. The future plan is to move the cryomodule into the accelerator room in 2024 to proceed with its integration with the beam line and to start its commissioning and beam operation in 2026.

SUMMARY

The high duty cycle beam operation of LIPAc, in its Phase B+ configuration, concluded at the end of June 2024. The beam operation aimed to demonstrate and validate the operation of the new components and beam diagnostics installed after Phase B, and to characterize the beam. Finally, we achieved a duty cycle of 8.75% and a beam current of about 119 mA, and identified improvements that will be implemented for the upcoming phases aiming at higher duty cycles up to CW. Meanwhile, preparations for the Phase C are underway, with the disassembly of MEL in progress so that the SRF Linac, which is currently being assembled, can be moved to the accelerator room. Finally, the beam operation of the Phase C with LIPAc in its final configuration, is targeted to begin in 2026.

DISCLAIMER

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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