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LIPAC (LINEAR IFMIF PROTOTYPE ACCELERATOR) BEAM COMMISSIONING & FUTURE PLANS

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Abstract

The Linear IFMIF Prototype Accelerator (LIPAc) has been constructed in Rokkasho, Japan, to demonstrate the validity of the low energy section of an IFMIF deuteron accelerator up to 9 MeV with a beam current of 125 mA in continuous wave (CW) under the joint collaboration between EU and Japan. Short-pulse 125 mA deuteron beam acceleration to 5 MeV was successfully demonstrated in 2019. The LIPAc is under commissioning toward the CW beam acceleration. The effort to realize the high-current CW beam and next scope are presented.

INTRODUCTION

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 [1]. 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, Li target facility and test facility [2]. This paper focuses on the accelerator facility and one of the major technological challenges is the demonstration of the low energy section, where space charge effects are significant. The Linear IFMIF Prototype Accelerator (LIPAc), which is a front end of the IFMIF, aims at demonstrating the acceleration of the 125 mA CW D^+ beam up to 9 MeV, while the IFMIF is 40 MeV.

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COMMISSIONING STRATEGY

The LIPAc is a 36-meter-long accelerator under commissioning in Rokkasho, Aomori, Japan. The LIPAc final configuration is shown in Phase C & D in Fig. 1. It consists of a 100 keV D^+ beam Injector [3, 4] with an ECR ion source, an acceleration column and a Low Energy Beam Transport line (LEBT), a 5 MeV RFQ [5-7] driven by 175 MHz eight 200 kW tetrode-based RF power system (RFPS) [8, 9], a Medium Energy Beam Transport line (MEBT) [10, 11] with re-bunchers [12], a superconducting RF (SRF) Linac [13, 14], a High Energy Beam Transport (HEBT) line [15]

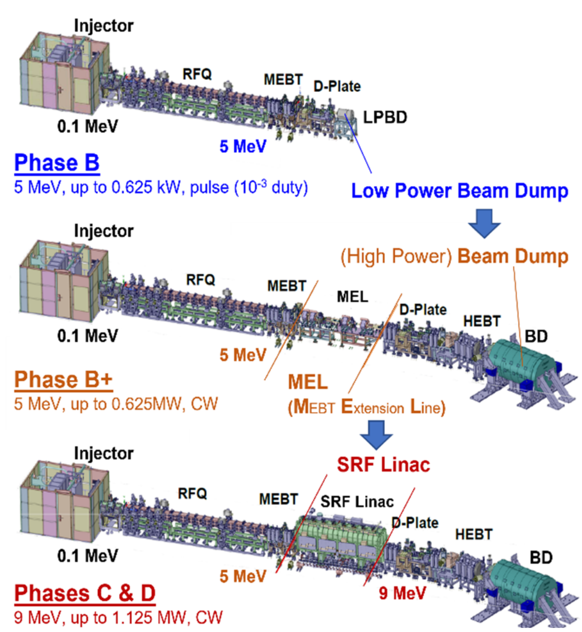

Figure 1: The three configurations of the LIPAc stepwise commissioning Phases.

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with a beam Diagnostic Plate (D-Plate) [16, 17], and a Beam Dump (BD) [18].

The LIPAc requires cutting edge technologies: the world's highest current in CW, the world's longest and powerful RFQ, the highest hadron current through an SRF-Linac, 1.1 MW of CW beam power, etc. Therefore, to mitigate a risk, a stepwise approach, called Phase, has been and will be applied to the installation and beam commissioning as shown in Fig. 1.

- Phase A (not shown in Fig. 1): validation of the injector. 140 mA D^+ beam with required characteristics.
- Phase B: validation of the RFQ, the RF power system, the MEBT and diagnostics at low duty cycle.
- Phase B+: validation of the RFQ, MEBT, MEL, HEBT and Beam Dump system at high duty cycle up to CW.
- Phase C: validation of accelerating a D^+ beam to 9 MeV at low duty cycle through all the components including SRF-Linac.
- Phase D: validation of the accelerator capacity for all the components at the duty cycle up to CW.

BEAM COMMISSIONING

Commissioning in Phase A and B

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 [19].

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 [20-22].

Impact and Measures of the COVID-19 Pandemics

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.

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 system to access LIPAc data from Europe. Connecting the accelerator control system network to the Internet poses great security concern. Therefore, a data relay server is placed in a DMZ accessible from the Internet and allowing only one-way access so-called data-diode (from the accelerator network to the DMZ, and from the DMZ to the Internet) via this data relay server. In October 2020, data was successfully transferred to the receiving server in the Fusion for Energy (F4E) in Barcelona, Spain. This system enables to transfer the LIPAc data in real time and European experts can access the data with OPIs. By using this system as well as a video conference system, European experts can participate in the commissioning under the similar conditions as if they were on-site. High duty cycle RFQ conditioning and beam commissioning can be jointly performed, and we have overcome the COVID-19 restrictions.

Commissioning in Phase B+

To implement the Phase B+ configuration, the HEBT line and high-power beam dump (BD) were installed in addition to the systems present in the previous phase B (Injector, RFQ and MEBT). The D-plate was moved to the final position. Instead of the SRF-Linac, the MEBT extension line (MEL) between the MEBT and the HEBT was designed and installed [23]. In the MEL, several components, such as beam ducts, Q magnets, diagnostics, and vacuum systems, are on the same stage. The MEL should 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 Institute and QST. The completed Phase B+ configuration is shown in Fig. 2.

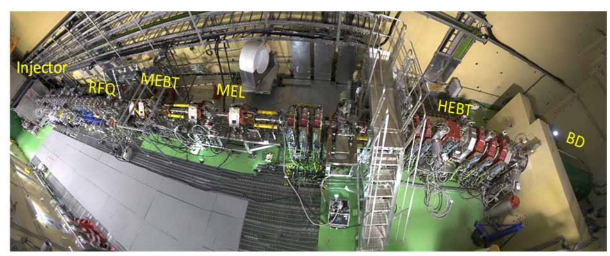

Figure 2: The LIPAc Phase B+ configuration. The beam goes from left side (Injector is in the cage) through the RFQ, MEBT, MEL, HEBT and Beam Dump (behind the shielding wall). Note: the accelerator is straight, but some distortions are due to the wide-angle lens.

The major goals of the phase B+ are the validations of the following systems: (1) the Injector, RFQ, MEBT, MEL and HEBT up to CW with 125 mA D^+ beam, (2) beam diagnostics for low and high duty operations, (3) the high-power beam dump up to 0.625 MW, and (4) beam properties to be injected to the SRF-Linac. Therefore, three stages of beam commissioning are 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 chopper, newly installed transport elements and diagnostics in the MEL, the HEBT and the BD.

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- Stage 2: nominal current of 125mA D^+ at low duty cycle (<5%). 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 initiated in July 2021. It was resumed after the 3-month scheduled summer maintenance and was completed in December 2021. A total duration of the campaign was around 7 weeks. Detail results of the Stage 1 are shown in [24].

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. Figure 3 shows waveforms measured at 4 current transformer positions. A shorter width of 60 µsec was tested in preparation to the Stage 2 in order to avoid damages to the SEMs. The beam pulsing was accomplished successfully by use of the chopper in the LEBT.

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. Figure 4 shows the measured phase space profiles of the 20 mA D^+ pilot beam, and compares with simulations in three cases with different setting of buncher

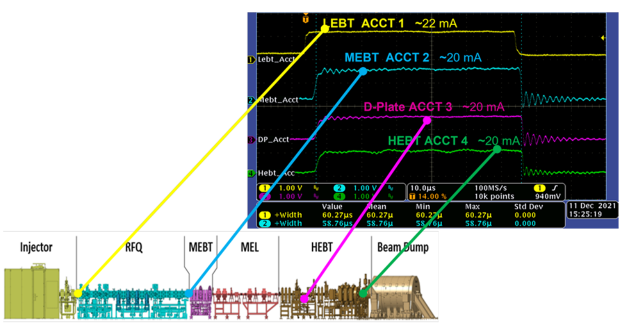

Figure 3: Waveforms measured at 4 current transformer positions. The pulse length is 60 µs by the chopper, and the current is 20 mA D^+ at the RFQ exit (entrance of the MEBT).

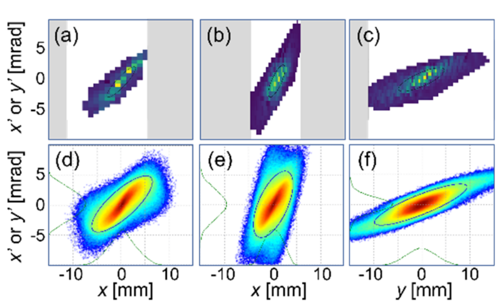

Figure 4: Transverse phase space profiles measured using slit-grid combination in the D-plate in three different settings of buncher cavity and Q magnet in the MEBT, comparing measurements (top) and simulations (bottom). White and grey backgrounds in the top images indicate the measurement windows.

cavity voltages and quadrupole magnet settings [24]. The simulations were carried out by use of TraceWin and Toutatis codes.

The Stage 1 of Phase B+ was successfully ended in December 2021. We expected to start Stage 2 after the new year holiday, but it was suspended by a circulator and RFQ couplers troubles as described later.

PERFORMANCE DEMONSTRATION OF THE INJECTOR

The Injector is required to provide a stable deuteron beam of 100 keV, 140 mA with low emittance (≤0.25π mm·mrad). Beam commissioning of the Injector has been conducted by time shared to the Stage 1 beam commissioning and/or parallel to the RFQ RF conditioning. The duty cycle of the emittance measurement is limited to less than 10%, because the use of an interceptive (Allison type) unit. In order to determine the optimal plasma electrode (PE) size, we have conducted commissioning with ϕ9, ϕ10, ϕ11 and ϕ12 mm apertures as shown in Fig. 5. We have successfully extracted a total (including molecular ions) current of 150mA, a D^+ fraction of 91% (D^+ current of 136.5 mA), and a low emittance (0.27 π mm·mrad) beam using ϕ11 mm PE. Continuous CW long run operation for 11 hours was also achieved [24], and this is one option of the PE. We are trying to find better conditions with beam current margins. Another option is that a total current of 160 mA using ϕ12 mm PE and long run of CW operation was performed in Fig. 6. A CW run of more than 3 hours has been reached that can be used for commissioning. In this case, however, the emittance increased to 0.3 π mm·mrad

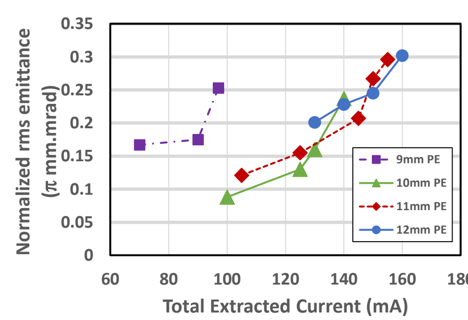

Figure 5: Stably operational emittance (at 5% duty cycle) and total extracted current with different PE apertures.

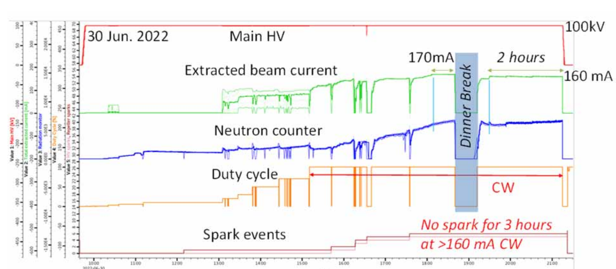

Figure 6: A CW long run with a ϕ12 mm PE. The stable 160 mA was performed. (Note. Beam stop at around 19:00 was due to the operator's dinner break.) No spark events were found for 3 hours.

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and the beam current stability is not as good as ϕ11 mm PE. The best condition is to be determined in terms of beam current, emittance, D^+ fraction and stability for the Stage 2 operation. Another campaign including PE's of intermediate apertures (i.e. 11.5 mm) will be performed.

RFQ CW CONDITIONING

Following the achievement of the nominal RFQ vane voltage in pulsed mode in the Phase B [20,21], RF conditioning of the RFQ to reach CW has been pursued [25]. The original strategy is to keep the nominal voltage of 132 kV and increase the duty cycle (repetition and pulse length). The RF conditioning was performed in the night shift, in parallel to the Stage 1 beam commissioning in the daytime. The duty cycle of 25 % at the nominal voltage was achieved. But interlock events (reverse power) occurred frequently, and it was difficult to increase the duty cycle. Then it was decided to reduce the vane voltage to 105 kV (80 % of nominal) and increase the duty cycle until CW, then increase the power until the nominal level. This procedure led to a successful achievement by reaching CW at 80 % of the nominal RFQ voltage as shown in Fig. 7. Though the voltage was not the nominal one, regulation of the field along the RFQ with the cooling water temperature was successfully demonstrated [25].

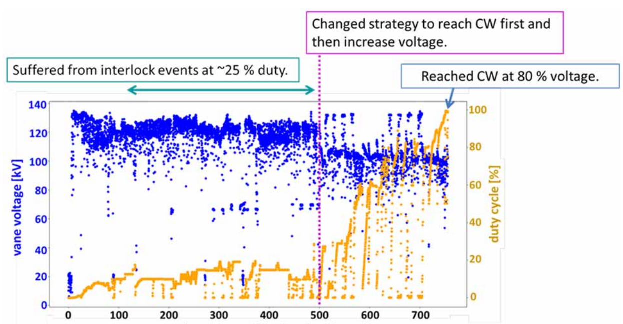

Figure 7: RFQ voltage and duty cycle histories during RF conditioning of the RFQ. Finally, we reached to CW.

CHALLENGES FACEING WITH HIGH DUTY CYCLE

After the new year break between 2021 and 2022, the RF conditioning was resumed to aim at the nominal RFQ voltage in CW. But it was postponed due to the two issues: damage of circulator and RFQ vacuum leak [25].

A circulator in the RF Power Supply (PS) was found damaged in February 2022. One of the eight circulators reported arcs and conditioning was stopped. After visible inspection of the inside, significant signs of sparks were found at the inner electrode as shown in Fig. 8 (left). Other seven circulators were carefully inspected, and we found no similar issues. The root cause is not clearly identified, but we have a hypothesis that the repeated thermal cycles lead to loosening of screws between the electrodes, made a gap and degraded the contact. The parts of the damaged circulator were replaced on-site, but to reduce the risks of future failure, and by taking a period of treatment of coupler vacuum leak, it was decided to ship back to the manufacturer for repair. It was returned in March 2023 and installed as in Fig. 8 (right).

Figure 8: Damaged inner conductor of the circulator (left) and installation at the RF platform after the repair (right).

In the meantime, the RFQ conditioning continued with the rest of seven RF chains, which can provide enough power to reach nominal vane voltage in case of no beam loading. We resumed the RF conditioning, but we encountered another issue in March 2022. A vacuum leak was appeared in the RFQ during the RF injections. We inspected the leak source, and we suspected the couplers. After removing the wave guides, we performed leak tests at the couplers. We found a large leak at one coupler and small leak at another one. Then all the couplers were removed from the RFQ and inspected. The five couplers which were consistently warmer than the others showed a black ring deposit near the centre of the ceramic window and on the inner copper conductor anchor as shown in Fig. 9. We are using viton O-rings for vacuum seal and it was found deformed by high temperature. A new anchor was designed to improve the thermal contact with the water-cooled inner conductor. Details are described in [25].

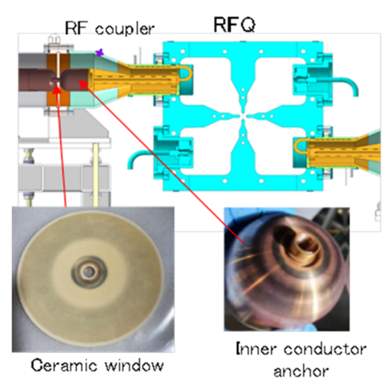

Figure 9: Ceramic window and inner conductor anchor in the coupler.

PREPARATION OF SRF-LINAC FOR PHASE C/D

In parallel to the Phase B+, preparation of Phase C and D is in progress. The main components are the SRF-Linac. The eight Half Wave Resonator (HWR) cavities accelerate the beam from 5 to 9 MeV and eight solenoid magnet

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packages focus and steerer the beam. Almost all the components were delivered and the assembly initiated in 2019. But the solenoid magnets were suffered from welding quality issues. A repair process was implemented and passed the cold test. Then the solenoids were delivered at Rokkasho in December 2021. The solenoids underwent high pressure rinsing in June 2022 in Japan. The entry ban due to COVID-19 was an obstacle to resume assembly, but it was released in June 2022 and engineers from Europe could enter Japan. In August 2022, the assembly in the cleanroom restarted with mounting of all power couplers to the SRF-Linac cavities as shown in Fig. 10. Despite good progress, the assembly had to be paused again due to vacuum leak issues on a BPM interface flange, which was repaired during the manufacturing process, and on a cold-warm-transition flange. The repair work and/or mitigation procedure is under discussion. After the treatment, the assembly work is expected to resume in summer 2023 and will be finished by the time of completion of Phase B+ operation.

Figure 10: Series of HWRs with couplers in the cleanroom.

NEXT STEP AND FUTURE PLAN

We are making every effort to resume beam operation as soon as possible to recover the beam operation suspension. We have completed the assembly of the RFQ couplers, which are modified to improve the cooling capacity of the inner conductor anchor, and we are working on installation of the waveguides. The damaged circulator was returned back from the manufacturer in March 2023. The checkout test was completed and high-power test is underway. After overcoming these two difficulties, the RFQ conditioning is scheduled to resume in June 2023, and beam commissioning of Phase B+ Stage 2 starts in July 2023.

Phase B+ Stage 3 will be performed by the end of 2023. It will be followed by dismounting and removal of the MEL. The SRF-Linac will be assembled, installed and integrated into the beam line. The checkout tests of the cryomodule, cooling, RF conditioning will be carried out. The beam commissioning of the Phase C is expected to start in November 2025 and to complete the Phase D in 2027.

One of the main objectives of the LIPAc is the fully validation of the engineering design of the performance towards high duty cycle up to CW at nominal beam intensity, for 30 minutes to reach the thermal equilibrium. But considering the accelerator for IFMIF-like irradiation facility, such as IFMIF-DONES in Europe [26] and A-FNS in Japan [27], 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.

We are using tetrodes 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. In the control system, it has been more than 10 years since the design of the current system, some parts are not available and it is a timing to renew and validate some subsystems in a view of future facility construction. The injector upgrade is underway not only for its performances, but also for its maintainability and availability. The ultimate LIPAc goal will be demonstration of the high availability operation.

CONCLUSION

The Phase B+ Stage 1 beam commissioning was completed in December 2021. The injector was tuned to produce the pilot beams, H^+ and D^+ beams at low currents of 10 mA and 20 mA, respectively. The beams were transported to the BD successfully without significant beam losses, and the beam characterisation was carried out with satisfactory agreement with the simulations. The newly installed components were mostly checked and validated.

In preparation to the following stages, RF conditioning of the RFQ up to CW is being pursued. So far, 25 % duty at the nominal vane voltage and 100 % duty (CW) at a reduced voltage (80 %) have been reached. The CW beam commissioning of the Injector is conducted with some aperture sizes.

In the RFQ conditioning in early 2022, we faced issues with the circulator failure and the RFQ coupler vacuum leaks. The repair of the circulator has been completed. The cooling capacity of the RFQ coupler anchors has been improved to cope with the issue. Mounting the anchors to the RFQ and connecting the waveguides are underway. We expect the RFQ conditioning in June and beam in July 2023. The high duty operation for the RFQ (Phase B+ Stage 3) will be completed in 2023. After that, we will prepare for the SRF-Linac commissioning and expect to resume beam operation in 2025.

The feedback from the LIPAc experiences is underway. These results can be reflected to the design of the IFMIF-like fusion neutron source facility.

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