

# PLANNED FUTURE UPGRADES OF LINEAR IFMIF PROTOTYPE ACCELERATOR (LIPAc)

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## Abstract

The Implementing Agencies of the Broader Approach (BA) agreement, namely Fusion for Energy (F4E) and National Institutes for Quantum Science and Technology (QST), are developing the Accelerator Facility validation activities that aim at demonstrating the acceleration of 125 mA D<sup>+</sup> beam up to 9 MeV in continuous wave (CW) [1,2]. This is the main goal of the Linear IFMIF Prototype Accelerator (LIPAc) under installation, commissioning and operation in Rokkasho, Japan.

LIPAc has been operated until June 2024 in its Phase B+ configuration, which consists of all the beamline except the SRF Linac (high duty cycle operation results up to 5 MeV are reported by T. Akagi in this conference).

In parallel, the upgrades for several systems are being designed and procured taking into account the lessons learned so far during commissioning and operation and will be the main object of this paper. These systems are: a new injector encompassing a new design of beam production and extraction system together with LEPT; a new RF system based on SSPA technology for the RF-RFQ, whose full-scale prototype is being manufactured and validated in 2024; a new set of RF-RFQ power couplers with improved design to overcome the limitations suffered by the couplers currently installed in LIPAc.

## INTRODUCTION

The LIPAc [1, 2] in its Phase B+ configuration consists of a 100 keV injector, a 5 MeV Radio-Frequency Quadrupole (RFQ) accelerator, a Medium and High Energy Beam Transport lines (MEBT and HEBT respectively) and a Beam Dump (BD). Its final configuration will include a Superconducting Radio-Frequency (SRF) Linac and will target to commission a beam in CW of 125 mA at 9 MeV. A temporary MEBT Extension Line (MEL) replaced the SRF linac during Phase B+.

The beam generated at the ion source has an emittance below  $0.3\pi\text{mm.mrad}$  at the entrance of RFQ. The LIPAc commissioning is currently on-going at Rokkasho Institute for Fusion Energy [3]. In 2019 the beam commissioning campaigns achieved RFQ acceleration at nominal current 125 mA, 5 MeV at low duty cycle (DC) of  $\sim 0.1\%$  (1ms pulse) [4, 5]. Since the installation of the HEBT and the DP in 2020 and 2021, a deuteron beam of around 20 mA at

0.01 % duty cycle was transported up to the High-Power Beam Dump in December 2021 [6, 7].

## ENHANCED INJECTOR

The LIPAc Injector CW commissioning campaigns have been conducted with  $\phi 9$ ,  $\phi 10$ ,  $\phi 11$ , and  $\phi 12$  mm plasma electrodes (PE) apertures. By using the  $\phi 11$  mm PE, a total current of 150 mA was extracted in CW (11 hours continuous operation) with D<sup>+</sup> fraction of 91% (D<sup>+</sup> = 137 mA), and a low emittance ( $0.24\pi\text{mm.mrad}$ ). Also, by using a  $\phi 12$  mm PE, CW operation and a total current of 160 mA were achieved, but the emittance increased to  $0.3\pi\text{mm.mrad}$  and the beam current stability deteriorated. The  $\phi 11.5$  mm is considered the optimum electrode diameter for stable extraction of the target CW current [8, 9], and was used during the Phase B+.

## General Layout and Design Features

The upgrade of the Injector (see Fig. 1) should encompass studies of the current CW campaigns and the beam operation results to identify the best design options for the injector subparts. It is likely that the most important efforts and changes will target to upgrade the accelerator column and the Emittance Meter Unit (EMU). The efforts will nevertheless not be limited to optimize those components, but rather to design a full upgraded injector.

For the EMU, the development of an optimized design target to improve its overall performance. It is very important for LIPAc to study the possibility to perform emittance measurements up to at least 10%DC. The optimized design can be based on the improvement of the cooling system, the better choice of the materials to maximize the heat dissipation and minimize deformations, an upgrade of its LCS, and the improvement of the manufacturing. The upgrade of the accelerator column will target to improve the overall performance in particular the stability at high duty cycle and continuous wave operation modes. Elements to take into account for the design upgrade are the optimization of the distance between the electrodes, the profiles of the electrodes, the improvement of the behaviour against the voltage breakdown, the optimization of the magnetic field into the plasma chamber, the magnetic shielding between the plasma chamber and the electrodes, and the capability to check the electrodes mechanical alignment.

During the LIPAc injector campaigns a quicker than expected degradation of the Boron Nitride (BN) disk was

observed. It is important to address studies to improve the BN disks lifetime and potentially of alternative materials. The injector performances are strongly affected by the quality of the alignment of its subcomponents. Besides, during the maintenance campaigns the check and realignment of the injector has always been challenging or not possible. Thus, the workplan includes the improvement of the alignment capabilities and control with the use of an external reference to reconstruct the position of the accelerator column mechanical axis.

A number of design features are planned to be implemented in the LEBT. It is important to maximize the accessibility of components to minimize the intervention time. The alignment of the solenoids will be improved and the solenoid aperture will be optimized for maximizing the linear region of the magnetic field. A new LEBT-RFQ interface will be designed to improve power handling capabilities and allow for more space to ease the assembly and maintenance.

It is under study for implementation the use of a diaphragm/scrapper to adjust the beam intensity at the injector's output without changing the plasma electrode and thus minimize the machine downtime. Such diaphragm would allow the extraction column to work always at nominal working point (with scraper used for pilot beam during tuning phases, tests, etc.). A diaphragm should have an allocated length of 20-30 cm and the most appropriate installation location would be right after the first solenoid of the LEBT.

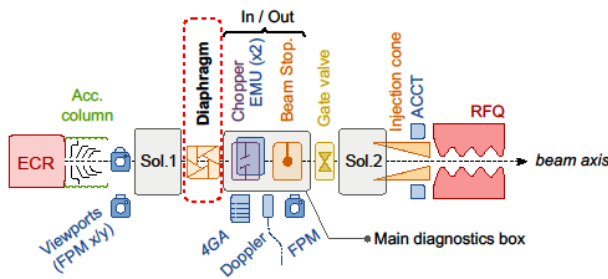


Figure 1: Upgraded injector layout.

### Timeline

Figure 2 shows the current timeline for the deployment of the LIPAc upgraded injector up to commissioning in Rokkasho. The design phase is estimated to last ~10-12 months, with following 20-24 months for the manufacturing and factory acceptance tests (whose detailed content has to be defined). The injector should be then transported for assembly and onsite commissioning in LIPAc.

### ENHANCED RFPS FOR THE RFQ

The main goal of the RF-RFQ conditioning campaign is to reach CW operation with nominal cavity voltage of 132kV for D+ operation. The Radio Frequency Power System (RFPS)-RFQ reliability was improved very much during Phase B+ thanks to the continuous efforts to solve chronic issues due to flawed design and not optimal cabling

configuration (noise and earthling troubles). The RFPS could achieve CW injection in the RFQ at 105kV (proton level voltage) at the end of 2021. During the following RFQ conditioning campaigns the installed RFQ couplers limited the maximum DC to 10% at nominal voltage. A number of actions are in place to ensure that when resuming LIPAc operation for phases C and D, LIPAc will be equipped with RFQ couplers able to withstand CW operation at nominal power.

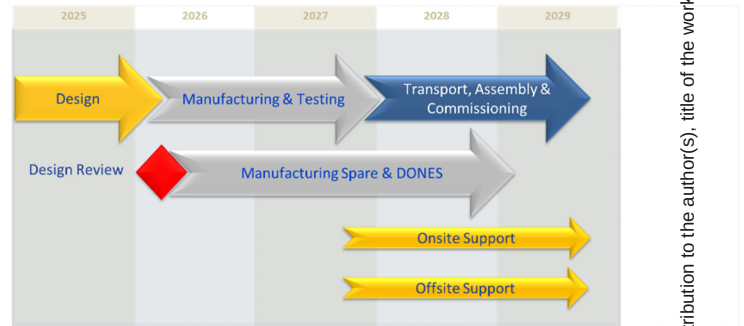


Figure 2: Upgraded injector timeline.

### SSPA Design Features

The RFPS upgrade aims to replace the RFPS of the RFQ currently based on the tetrodes technology with a Solid-State Power Amplifier (SSPA) based technology with the objectives to increase its reliability, availability, and maintainability. The activity encompasses a design phase and a prototyping to demonstrate compliance with the expected performances before launching the series production. The functional requirements imposed to the 8 chains of the new SSPA for the RFPS of the RFQ are the same as the ones of the current RFPS and are reported in Table 1.

The SSPA power amplifier modules utilize ART2K0FE transistors for high gain and hot-swappable capability. The power distribution features a passive power splitting system for signal distribution and a power combining system for signal summation. The new design of the SSPA system has undergone a comprehensive Reliability, Availability, Maintainability, and Safety analysis to ensure that its performances will meet high requirements during operation. For this purpose, the MoSCoW method has been adopted to prioritize and validate requirements effectively. The Mean-Time-To-Failure (MTTF) of critical components, such as power transistors, driver transistors, and power supplies, has been calculated based on their operating conditions. Redundancy has been adopted for critical systems in order to enhance the reliability. In particular, implementing one redundant power supply out of three in each module, the MTTF of the complete power amplifier module is estimated at 710,000 hours (81 years) with an overall availability that exceeds 98%. Each SSPA chain includes 30 power amplifier modules, and the system is designed to tolerate failures up to 10 transistors (equivalent to a whole power amplifier module and 4 individual transistors in failure), without affecting the output power requirements. For the entire SSPA system

made of 8 chains, the redundancy in power amplifier modules and power supplies is taken into account, resulting in a high overall MTTF of 55,551 hours (6.34 years).

Table 1: SSPA Functional Requirements

| Requirement                                                                         | Value              |
|-------------------------------------------------------------------------------------|--------------------|
| Number of chains                                                                    | 8                  |
| Nominal operating frequency $f_0$                                                   | 175 MHz            |
| -1dB bandwidth (Operation 1dB below saturated output power)                         | $\geq \pm 1$ MHz   |
| Power required                                                                      | 180kW              |
| Operation mode                                                                      | Pulsed and CW      |
| Repetition rate                                                                     | < 1kHz             |
| Duration of RF pulse plateau                                                        | 10 $\mu$ s to CW   |
| Voltage Standing Wave Ratio (VSWR) without beam                                     | 2.8 +/-10%         |
| RFQ max reflected peak power (discharge time ~15us)                                 | 660 kW             |
| RFQ max reflected peak power (discharge time ~15us) in case of interlock            | 400kW +/-10%       |
| Peak output power at saturation and load VSWR $\leq 1.05$                           | $\geq 220$ kW      |
| Average output power at saturation and load VSWR $\leq 1.05$                        | $\geq 200$ kW      |
| Operating point, below SSPA saturation                                              | 180 kW             |
| Saturated gain                                                                      | $\geq 82.55$ dB    |
| DC to RF conversion efficiencies at saturated output power and load VSWR $\leq 1.1$ | $\geq 65$ %        |
| Amplitude and phase coupling at the output                                          | < 0.1 %            |
| Emergency stop for the 8 chains                                                     | $\leq 5-6$ $\mu$ s |

### SSPA Timeline

The SSPA final design was successfully achieved mid of 2023. The first module is undergoing full tests and is showing high RF performances, high efficiency and temperatures lower than calculated. The first full chain with 30 modules will be tested at the factory in December 2024. The timeline of the enhanced SSPA project up to delivery and commissioning onsite is reported in Fig. 3.

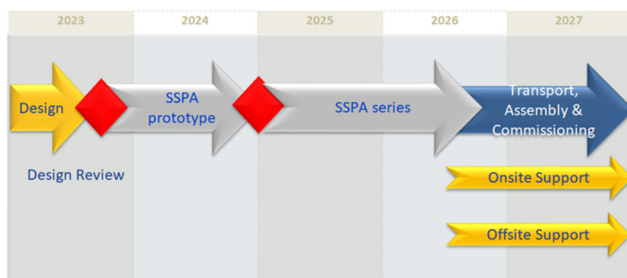


Figure 3: Upgraded SSPA timeline.

### OTHER ENHANCEMENTS

In parallel the project is addressing other upgrades encompassing a new set of RF-RFQ power couplers with improved design to overcome the limitations suffered by the couplers currently installed in LIPAc; enhancement and tests of beam diagnostics based on operational feedback; enhancement of specific components (like PS) as outcome

of a comprehensive obsolescence study; a new MPS based on centralized design and COTS.

### CONCLUSION

In parallel to the ongoing LIPAc commissioning and operation activities, F4E and QST are jointly working to ensure that LIPAc reliability and availability can be maximised in future campaigns, after reaching the current commissioning goals covered by Phases B+, C and D. The efforts to prepare and launch procurement activities have firstly focused on the analysis of the systems design, performances during commissioning and weaknesses. Those analyses and efforts must be parts of the processes of the lifecycle of a prototype like LIPAc. The main efforts are currently focusing on the study, design and procurement of a new injector and the design and procurement of an upgraded RFPS.

### 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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