ISBN: 978-3-95450-194-6 doi:10.18429/JACoW-LINAC2018-TU2A04

PROGRESS REPORT ON LIPAC*

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Abstract

LIPAc (Linear IFMIF Prototype Accelerator) for challenging the technical validation of the low energy section up to 9 MeV of the IFMIF accelerator, consisting of 2 units of 40 MeV, 125 mA CW deuteron accelerator, is under construction and staged commissioning is ongoing in QST Rokkasho, Japan. The injector commissioning was completed in summer 2017 and the latest results of the beam characteristics showed good emittance acceptable for RFQ injection. The installation and checkout of 5 MeV deuteron RFQ, beam transport & instrumentation, temporary beam dump and RF power system were finished in early 2018 including the RF conditioning of RFQ in low duty pulsed mode. At the initial beam commissioning of RFQ in June 2018, the 50 keV proton beam with <30 mA and 0.3 ms pulse was used for simulating the 100 keV deuteron beam acceleration in RFQ and transport up to beam dump, without a risk of activation. The good transmission around 93% was observed for input beam current of 8–30 mA. The installation work for the final configuration of LIPAc with a superconducting RF linac is continuing and ready to start by end of 2018.

INTRODUCTION

The Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA) project is underway as one of three projects of the Broader Approach (BA) agreement between the Japanese government and EURATOM [1]. The concept of the IFMIF was matured through the activities under the IEA's Fusion Materials Technology Collaboration Program over 10 years since 1994 [2]. The mission of IFMIF is to provide an accelerator-based, D-Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume to test samples of candidate materials up to about a full lifetime of anticipated use in fusion energy reactors. IFMIF would also provide calibration and validation of data from fission reactor and other accelerator-based irradiation tests. It would generate an engineering base of material-specific activation and radiological property data, and support the analysis of materials for use in safety, maintenance, recycling, decommissioning, and waste disposal systems.

The mission of the IFMIF/EVEDA project is to provide the detailed engineering design of the IFMIF and to validate the technological challenges on the major components. One of the major technological challenges is the demonstration of the low energy section of one of two accelerators of the IFMIF called as LIPAc (Linear IFMIF Prototype Accelerator) to accelerate the 125 mA CW D+ beam up to 9 MeV, while the IFMIF accelerator is a 40 MeV linac (see Fig. 1 for full IFMIF linac design in 2013 [3]).

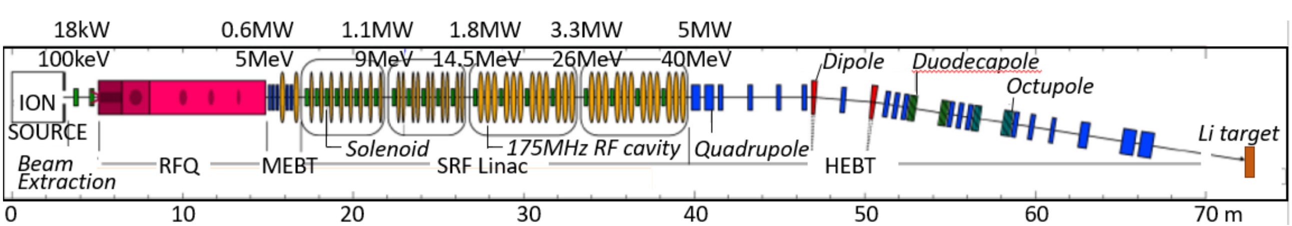

Figure 1: Schematic representation of IFMIF linac. LIPAc is a prototype up to 9 MeV including the first SRF linac.

As show in in Fig. 2, the LIPAc plant consists of the following subsystems:

* Work 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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1. Injector (2.45 GHz ECR ion source and Low Energy Beam Transport (LEBT) line using dual solenoid focusing system);
2. RFQ (175 MHz, 9.8 m-long, 4-vane, 5 MeV/125 mA output) with the associated RF power system (8 x 175 MHz, 200 kW CW chains of tetrode system);
3. Medium Energy Beam Transport (MEBT) line consisting of a sequence of a triplet quad – first re-buncher – a doublet quad – second re-buncher with the associated RF power system for 5-gaps, IH type re-bunchers (2 x 175 MHz, 16 kW CW solid-state amplifiers);
4. Superconducting RF linac (SRF linac, 175 MHz, 9 MeV/125 mA output) containing 8 pairs of Half-Wave Resonator (HWR) and superconducting solenoid magnet coil;
5. High Energy Beam Transport (HEBT) line and final Beam Dump (BD);
6. Diagnostic plate (D-Plate) dedicated for the beam diagnostics (moved after MEBT for RFQ commissioning);
7. Low Power Beam Dump (LPBD) for low duty operation of RFQ commissioning (not shown in Fig. 2);
8. Control System/Timing System and safety management systems (Personnel Protection System and Machine Protection System);
9. Cryoplant for supplying liquid helium and
10. Other ancillaries providing electricity, cooling water, pressurized air, nitrogen gas and HVAC.

The specification/target of major parameters in 2 step validation of LIPAc are shown in Table 1, interim target for confirming the beam characteristics at the entrance of SRF linac, and final target for qualifying the output beam from SRF linac.

Table 1: Main Targets of LIPAc Validation

Items	Interim Target*	Final Target
Particles	D^+ (H^+)**	
Output energy (MeV)	0.1 @ RFQ in / 5.0 @ RFQ out	8.0-9.0 @ BD
Output current (mA)	140 @ RFQ in / 125 @ RFQ out	125 @ BD
rms emittance (π mm mrad)	<0.25 @ RFQ in <0.30 @ RFQ out	<0.36 @ SRF linac out***
(MeV deg)	<0.2 @ RFQ out	<0.2 @ SRF linac out
Pulse mode	0.3 ms/1Hz (typ.) using chopper + source magnetron pulsing	
Linacs	175 MHz 4-vane RFQ	same and 8 x 175 MHz HWR
Re-bunchers	to provide the proper matched beam at the end of the MEBT both in transverse and longitudinal phase space to the SRF LINAC input	
Max. RF power (kW)	1.2 @ injector 1600 @ RFQ 32 @ re-bunchers	840 @ SRF linac
Total length (m)	20	36

* Interim target is set for validating the beam characteristics before entering the SRF linac.

** H^+ beam with half-energy/half-current is used for machine tuning to simulate the beam acceleration/transport with the perveance equivalent to that for D^+.

*** Assuming 0.2π mm mrad at RFQ exit. About 3/4 of emittance growth will be produced in MEBT.

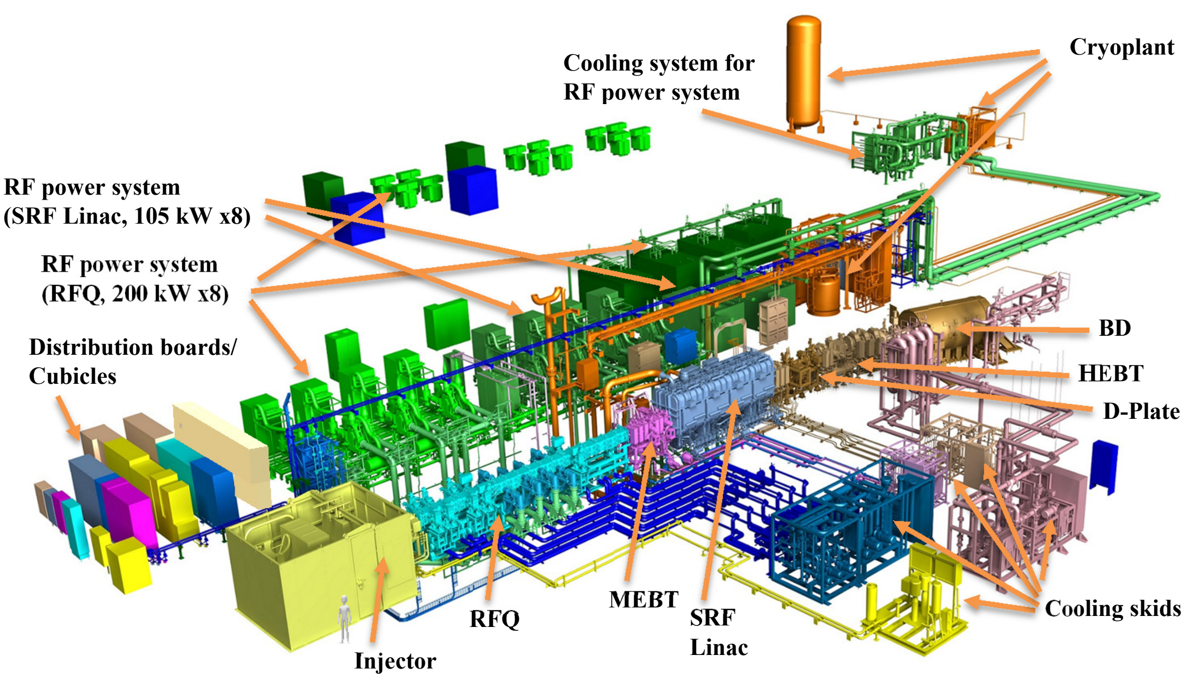

Figure 2: Layout of main components of LIPAc at the final stage. For the RFQ beam commissioning, the D-Plate and LPBD are temporarily installed immediately after the MEBT.

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The paper provides a general view on the progress of the IFMIF/EVEDA project and the phased approach employed for the installation, checkout and commissioning of the LIPAc. Next, we summarize the present status of each subsystems and major outcomes obtained in the latest beam commissioning performed in June – August 2018.

PROJECT PLAN AND LIPAC PHASES

From the project management view, the BA activities are authorized by the steering committee through Project Plan and Work Programme for annual schedule, and the components necessary to achieve the project mission are delivered through Procurement Arrangements dedicated to each system. In LIPAc project case, all the accelerator equipment and the infrastructure on site are shared by Japan and Europe, and agreed by the Implementing Agencies responsible to procure them. Such organizations, QST in Japan and F4E in Europe, jointly work together to provide the components to assemble and to commission at Rokkasho. The IFMIF/EVEDA Project Leader in Rokkasho takes leadership to coordinate all the work as a chief project manager. In Europe the actual work is contributed from the Voluntary Contributors, France, Italy, Spain and Belgium, and institutions designated by these countries. A deep collaboration among many contributing organizations is an essential key to reach the final objectives. In the Project Plan a top-level project schedule is given with the achieved milestones. The validation using LIPAc is the latest mandate on the project.

The validation of the LIPAc is scheduled in 3 phases (A: injector only, B: up to RFQ and MEBT, and final C: whole system up to BD through SRF linac and HEBT). The first phase A was started in February 2014 and its commissioning was conducted in several steps, which were completed in August 2017. In parallel with these commissioning campaigns, the installation of the components for the phase B (RFQ, MEBT, D-Plate, LPBD and RF power system) and the installation and commissioning of Cryoplant (phase C) were conducted and completed in June and April 2017, respectively (Fig. 3).

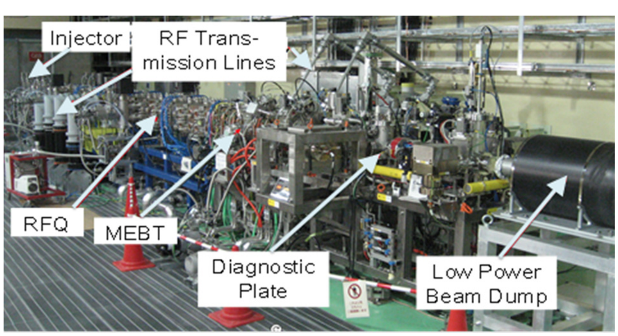

Figure 3: Components of LIPAc installed in the accelerator vault for RFQ beam commissioning.

After completion of the fundamental check of the integrated behavior of RFQ cavity and RF power system, the RF conditioning of RFQ cavity was started and succeeded to reach the power level equivalent to 132 kV of maximum vane voltage, to accelerate D+ beam in February 2018 [4]. At the beginning of the beam commissioning in phase B, low duty cycle ~0.1% and low current 50 keV H+ beam was proposed to check the proper behavior of all the systems and to avoid the risk of errant beam which could induce activation and mechanical damage. In the first beam commissioning stage, June – August 2018, 50 keV H+ with various injection currents (8 ~ 30 mA) were succeeded [5] and functional tests of the equipment of MEBT and beam diagnostic elements were performed.

STATUS OF SUBSYSTEMS

Injector

The injector developed by CEA/Saclay [6] has a 2.45 GHz ECR type ion source driven by a 1200 W CW magnetron with a capability of pulsing, fast blanking (beam reset to zero (BRTZ) within 50 µs in a pule at low duty cycle mode) and conventional type fast (10 µs)/slow beam inhibition interlocks [7]. To produce a high density and stable D_2/H_2 plasma, 4-stub automatic tuning unit is incorporated to control the RF reflection from plasma and 2 coils are used to adjust magnetic field pattern along the axis of 100 mm-long and 90 mm-diam. cylindrical copper plasma chamber, for keeping the value near 0.0875 T at both BN disks placed at end sides of the chamber. The resultant axial magnetic field inside the chamber is well approximated by the simple parabolic shape.

The 5 electrodes extraction system (named as plasma – PE, puller/intermediate – IE, first ground – GE1, repeller – RE and second ground – GE2) was employed to satisfy lower divergence and less sparking compared with 3- or 4-electrodes systems [6]. From the beam optics point of view, the gap distances among PE, IE and GE1 and the concentricity of apertures are critical. In the recent beam campaign, we paid attention on this point to reproduce the specification values, which were optimized for 155 mA beam extraction from the PE with 12mm-diam. aperture.

Through the several campaigns to improve the beam characteristics predicted by design simulation, a good emittance (< 0.15 π mm mrad, rms norm.) was achieved in December 2017 for D+ 140 ~ 160 mA at 5% duty cycle [8].

As low beam current with a good stability and emittance was requested for the initial RFQ beam commissioning, PE with appropriate aperture size should be used for each current level. An intensive characterization of the extracted beam was performed in advance until May 2018 [9].

As mentioned in the section of First Beam Commissioning of RFQ, a misalignment of beam axis of injector is suspected and to be remedied. The characterization of CW beam, which is not completed yet, should be planned in the coming campaigns.

RFQ with RF Power System for RFQ

The RFQ developed by INFN/LNL is a 175 MHz, 4-vane 9.8 m-long cavity with a ramping vane voltage rule from 79 to 132 kV at the middle region of cavity, 3 – 7.4 m [4]. The RF power system for all the cavities (except the

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injector magnetron) were procured by CIEMAT, CEA/Saclay and SCK-CEN, and installed (Fig. 4).

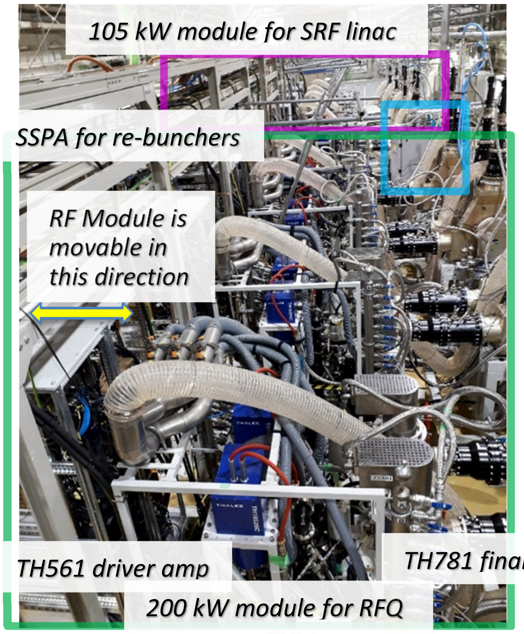

Figure 4: Components of RF power system in RF room.

Through the RF condition of RFQ cavity using 8 RF chains with a precise phase synchronization 132 kV with 5% margin was achieved with short pulse mode (20 µs). Further conditioning is ongoing to extend the pulse width to reach CW mode, however, for starting the beam commissioning of H+ 50 keV at half cavity voltage, this trial was concentrated on the condition with a half cavity voltage. For stable operation of anode HVPS in pulsed mode, it was effective to apply the pulsed RF power (1 ms) superimposed over a portion of CW power. The control of power balance of 8 RF chains is a critical to establish the stability. Particularly, we encountered a failure of anode HVPS or a 6.6 kV breaker, and we were obliged to use 7 RF chains instead of 8. The unused RF chain received the reflection power from RFQ cavity through the coupling of coupler and it should be kept within a limit acceptable by circulator dummy load.

In the last beam commissioning, it was unnecessary to apply the frequency feedback control loop based on the cooling water temperature (mixing of hot and cold flows) control, due to very low heat generation rate by RF power. To use this function, we must refurbish the RFQ cooling skid, of which piping is planned to be repaired in autumn 2018. The secondary cooling system to supply the chilled water to the primary loop was designed without a control of intermediate level of heat load, which causes a serious problem when the low to medium level power is dissipated in RFQ cavity. These points will be tackled in the period of maintenance until next beam commissioning.

MEBT with RF Power System for Re-bunchers

The MEBT developed by CIEMAT has a sequence of elements, Q-triplet, fist rebuncher, Q-doublet and second rebuncher [10]. Since magnets were properly characterized in a test bench prior to installation, during the RFQ beam commissioning, all the magnetic parameters were set to the recommend values given by beam dynamics simulation. About the rebunchers, the reconditioning of cavities using SSPA RF power system tests up to 11.8 kW (E_0LT>350kV) were successfully carried out in January 2018.

SRF Linac and Cryoplant

After the manufacturing studies needed for the licensing of the cavities [11] and the validation of the application form by KHK in March 2016, the manufacturing of the pre-series cavity and the 8 series HWRs is ongoing. All the bare cavities have been tested in vertical cryostat and are over the requirements ($Q_0=5\cdot10^8$ @ E_{acc_nom}=4.5 MV/m). Seven cavities have been through the final qualification process: heat treatment, tank welding and controls needed for the licensing at the manufacturer, fine chemical etching, clean room preparation and vertical qualification test at CEA Saclay. The tank integration process of the last series-cavity is close to completion. Operational equivalent tests -in a dedicated test stand named SaTHoRi - were performed on two different accelerating units (i.e. HWR cavity equipped with its tuning system and power coupler). The nominal accelerating field of 4.5 MV/m was achieved with an injected power of 14 kW and the tuning range exceeds the requirement of 50 kHz [12].

The manufacturing of the power couplers ended in April 2017. Three pairs have been successfully conditioned up to 100 kW. The conditioning of the fourth pair is ongoing. The superconducting solenoids are under manufacturing and shall be ready by end of 2018 for the assembly of the cryomodule. This assembly will take place at Rokkasho Fusion institute where a clean room is built.

Cryoplant procured by CEA/Saclay is needed for cryogenic cooling of the SRF linac and consists of cryogenic power equipment providing helium refrigeration (He refrigerator, He compressor, oil removal system etc.) and cryogenic transfer lines (including liquid He Dewar, gas He buffer tank, etc.), in addition to the Cryomodule fluid supplying equipment [13]. The plant was installed and commissioned in April 2017.

Beam Diagnostics

The beam diagnostics of LIPAc developed by CEA/Saclay, CIEMAT and INFN/LNL, consist of (1) non-interceptive devices and (2) interceptive devices. As for category (1), Current Transformers, 3 ACCTs in LEBT, MEBT and D-Plate for RFQ beam commissioning (FCT worked properly, and DCCT was not used); 7 BPMs (4 in MEBT, 3 in D-Plate); 2 profile monitors, fluorescence-type (FPM) and ionization-type (IPM), were installed in D-Plate, where the signal intensity of IPM was too small to detect profile, while FPM detected some patterns varying with the beam transport condition. The residual gas bunch length monitor is also available in D-Plate, to be used in the next step. In LEBT, Doppler shift spectrometer for ion species fraction measurement and four grid analyzer for space charge compensation measurement are available. About

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category (2), secondary electron emission (SEM) grid profiler+slits+steerers were installed for measuring emittance at very low duty cycle, however it is necessary further tuning to complete the commissioning of the diagnostics and to have them fully operational to allow a full characterization of the beam.

Control System

The EPICS-based central control, timing system, safety protection (personnel and machine) systems, developed by QST in collaboration with F4E for the central control, are already running daily. However, the integration work considering the interfacing with the individual local control systems provided by EU Home Team is not obvious and required a proper coordination within the LIPAc Unit. For preparing the licensing requirement in RFQ beam commissioning, new function in personnel protection system to count up the amount of beam particles entering into RFQ was successfully tested, including the careful calibration to avoid underestimating the amount of particles from a safety point of view.

FIRST BEAM COMMISSIONING OF RFQ

The detail of the preliminary result of beam experiment is presented elsewhere [5], however the essential outcomes are summarized below.

At the very beginning of the beam commissioning with 50 keV H+, the beam current extracted from ion source (I_{ext}) was set to 13 mA to inject a minimal current <10 mA achievable by PE with 6 mm diam. aperture, and also duty cycle was set with 0.3 ms pulse per 1s repetition, for reducing the possible beam induced damage to the interceptive diagnostic devices. The proton fraction in this case was small and actual injection current was 6.6 mA. However, its emittance was so small 0.09π mm mrad rms norm that the transmission was 95%. On the other hand, total transmission to LPBD was 87%.In this campaign, a large amount of steering for beam injection was required, which means re-alignment of injector is mandatory.

When I_{ext} is increased systematically (20, 30, 35 and 40 mA), the proton faction was improved (>70%) and the emittance was kept <0.2π mm mrad rms norm. The transmission down to LPBD was >90% for all cases except for 40 mA case (89%). As a result, in this first campaign, the RFQ output current of 26 mA at maximum was observed.

The output energy was measured using time-of-flight method for comparing the 175 MHz bunch signals detected by 3 BPMs installed in D-Plate with fixed drift lengths (0.16 and 1.27 m). The results, 2.5±0.02 MeV, showed a good agreement with the design value.

CONCLUSION

Many activities were carried out in 2017 – 2018, to focus primarily on the kick off of the RFQ beam commissioning achieved in June 2018. It was a true integration work to solve the interface problems not experienced in the individual tests on each subsystem. Firstly, a good indication of validity of RFQ design was achieved at beam transmission, >90%, and output energy, 2.5 MeV, under the condition of current, 35 mA, which is about half of required value. The other important characteristics, like beam size, emittance and bunch length, were tried to examine, however it was unfinished. The injector beams with current up to 70 mA for 50 keV H+ and 140 mA for 100 keV D+ satisfying required emittance have been already established and will be tested in the next beam commission time. In parallel, further RF conditioning of RFQ is required to conduct the high current beam injection in D+. The assembly work of SRF linac is waiting for the completion of delivery of the last components in Rokkasho.

ACKNOWLEDGEMENT

The present work was performed in the framework of the Broader Approach Agreement. The authors thank all the members in the home institutions and research founders, especially those who have involved or supported the LIPAc project, the former IFMIF/EVEDA project leaders, P. Garin, H. Matsumoto and J. Knaster, the home team/ILIC unit leaders, R. Heidinger, Y. Okumura, T. Nishitani, S, O'hira and A. Mosnier. Views and opinions expressed herein do not necessary reflect those of QST, Fusion for Energy, or of the authors' home institutions or research founders.

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