OVERVIEW OF THE VALIDATION ACTIVITIES OF IFMIF/EVEDA: LIPAC, THE LINEAR IFMIF PROTOTYPE ACCELERATOR AND LIFUS 6, THE LITHIUM CORROSIO INDUCED FACILITY

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Abstract

The results of the activities on the Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA) project under the framework of the Broader Approach agreement are overviewed. For the validation of the accelerator design to provide 40 MeV and 125 mA continuous wave deuteron beam on the liquid lithium target, the demonstration of the low energy section up to 9 MeV, called as Linear IFMIF Prototype Accelerator (LIPAc), is under the stepwise commissioning in Rokkasho. The first step to demonstrate the 100 keV deuteron and 50 keV proton beams from the LIPAc injector was completed by satisfying the target value of beam emittance, 0.25π mm mrad or less, at the beam current of 140 mA and 70 mA for deuteron and proton, respectively. The second goal for verifying the design of 175 MHz Radio-Frequency Quadrupole (RFQ) linear accelerator with the RF power system to accelerate deuteron to 5 MeV and the associated beam transport line to the beam from RFQ into the superconducting RF linear accelerator, has been started and a 2.5 MeV and 35 mA proton beam was obtained with the beam transmission, 90% or more. As for the validation of lithium target system, Lifus 6 plant was built in Brasimone to validate the design goal of erosion-corrosion rate for target material caused by 15 m/s lithium flow, and has been operated for one year with the continuous impurity monitoring and control, nitrogen < 30 wppm. The requirement of 1 μm/y or less was confirmed with a long-term test up to 4,000 h.

1. INTRODUCTION

The Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA) project is conducted under the framework of the Broader Approach (BA) agreement between Japan and EURATOM since June 2007 [1]. The original concept of the IFMIF and EVEDA including the strategy of the accelerator prototyping was derived from the international collaboration under the auspices of the International Energy Agency [2]. The mission of the IFMIF/EVEDA project is to provide the detailed engineering design of the IFMIF plant and to validate the technological challenges on an accelerator-based neutron source to generate a DT fusion reactor relevant neutron flux higher than 10^{18} $m^{-2}{\cdot}s^{-1}$ and energy spectrum for fusion material development and testing [3]. The demonstration of the low energy section up to 9 MeV of one of two linear accelerators (Linac) of the IFMIF to generate the deuteron beam with the current of 125 mA in Continuous Wave (CW) up to 40 MeV is the most challenging activity in the project, named as Linear IFMIF Prototype Accelerator (LIPAc) [4,5]. As shown in the top-level project schedule (Fig. 1), the commissioning of LIPAc is ongoing in Rokkasho, Japan. After the demonstration of the injector performance (Phase A) and the preparation of 5 MeV deuteron beam commissioning (Phase B) were completed in 2017 [6,7], the experimental tests of the accelerator components have been started using 50 keV proton beam with pulse mode and the current smaller than 40 mA as the primary step in Phase B commissioning [8,9,10].

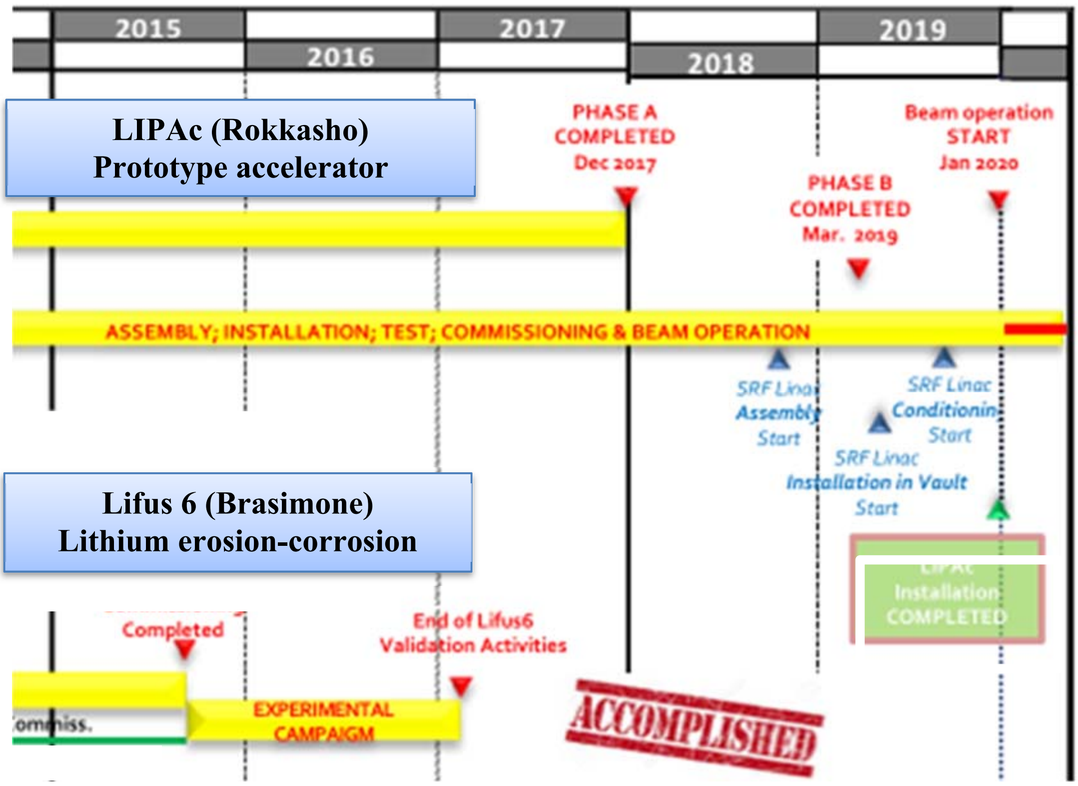

FIG. 1. Top-level schedule of the IFMIF/EVEDA project during January 2015 – March 2020.

The engineering design of the IFMIF employed the flowing liquid lithium (15 m/s nominal) as a neutron generating target bombarded by 40 MeV/250 mA deuteron beam with a footprint of 200 mm width by 50 mm height [5]. The erosion-corrosion rate of the candidate material of target structure, Reduced Activation Ferritic/ Martensitic steel (RAFM), is a concern which affects the stability of flatness over the beam footprint and thickness (25 ±1 mm) of lithium flow and limits the service lifetime of the target assembly. As shown in Fig. 1, a lithium loop, called as Lifus 6 [11], for studying the erosion-corrosion phenomena was built in 2015 at ENEA Brasimone, Italy, and the experimental tests with exposure time up to 4000 h at 603 K were conducted with the impurity monitoring and control (especially, concentration of nitrogen < 30 wppm), until November 2016.

The main results of the activities on the LIPAc and the Lifus 6 obtained in these two years are summarized in sections 2 and 3, respectively.

2. LIPAC, PROTOTYPE ACCELERATOR FOR IFMIF

The layout of the major components of the LIPAc is shown in Fig. 2, without the building structure including the radiation shielding of 1.5 m thick concrete around the beam line and the ancillaries, such as primary electricity distribution, cooling water supply and presurized air/nitrogen gas supply systems.

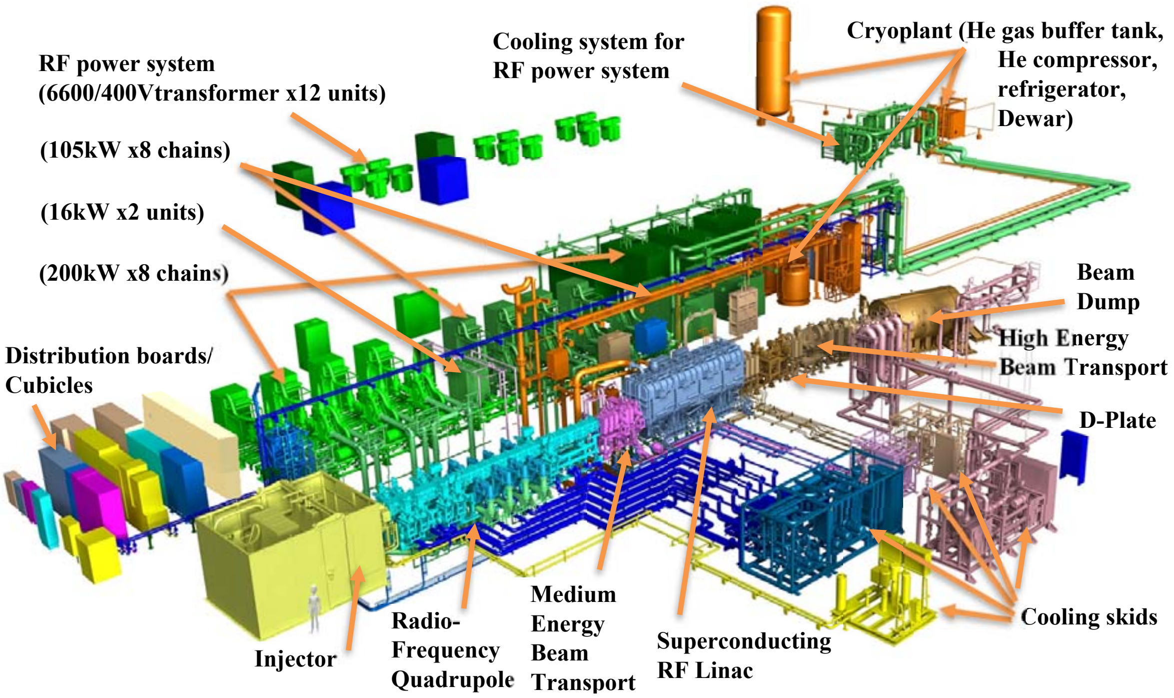

FIG. 2. 3D mock-up of the LIPAc plant excluding building, shielding structure and ancillaries (total length between injector and beam dump is 36 m and these components are surrounded by 1.5 m thickness concrete shield).

The LIPAc consists of the following subsystems:

(a) Injector (2.45 GHz ECR type ion source and Low Energy Beam Transport (LEBT) line using dual solenoid focusing system) to provide the beams with 100 keV/140 mA deuteron and 50 keV/70 mA proton,

(b) Radio-Frequency Quadrupole (RFQ) Linac (resonant frequency 175 MHz, 9.8 m-long, 4-vane type, 5 MeV output energy,125 mA output current in CW) and the associated RF power system (eight 200 kW CW RF chains using tetrode amplification system and RF transmission lines connected to RFQ cavity),

(c) 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 the 175 MHz, 5-gaps, IH type re-buncher cavities (two 16 kW CW solid-state power amplifiers (SSPA) for each),

(d) Superconducting RF (SRF) Linac (175 MHz, 9 MeV/125 mA output in CW) containing eight pairs of Half-Wave Resonator (HWR) cavity and superconducting solenoid magnet coil, and the associated RF power system (eight 105 kW CW RF chains using tetrode amplification system and RF transmission lines connected to each HWR cavities),

(e) High Energy Beam Transport (HEBT) line to transport the ion beams to the final Beam Dump (BD) safely without beam loss to avoid mechanical damage and radio-activation caused by beam hitting except for BD,
(f) Diagnostic plate (D-Plate) dedicated for the beam diagnostics which is used to qualify the beam at the exit of MEBT for RFQ commissioning and then moved to integrate with HEBT for SRF Linac commissioning,
(g) Low Power Beam Dump (LPBD) for low duty operation within 0.1% for RFQ commissioning (which is a temporary equipment located after D-Plate and not shown in Fig. 2),
(h) Control System/Timing System and safety management systems (Personnel Protection System and Machine Protection System),
(i) Cryoplant to produce and supply the liquid helium for maintaining superconductivity of SRF Linac and
(j) Other ancillaries providing electricity, cooling water, pressurized air, nitrogen gas and HVAC.

The validation of the LIPAc is scheduled in 3 phases (A: injector, B: up to MEBT through RFQ and C: up to BD through SRF Linac and HEBT). The phase A for validating injector was started in February 2014 and its commissioning conducted in several campaigns was completed in August 2017. In parallel with these campaigns, the components for the phase B (RFQ, MEBT, D-Plate, LPBD and RF power system), to confirm the beam characteristics at the entrance of SRF Linac, were assembled in June 2017 (Fig. 3). Also, the Cryoplant was installed and commissioned in April 2017. Table 1 summarizes the interim and final targets of the major parameters to be achieved in phase B and phase C, respectively.

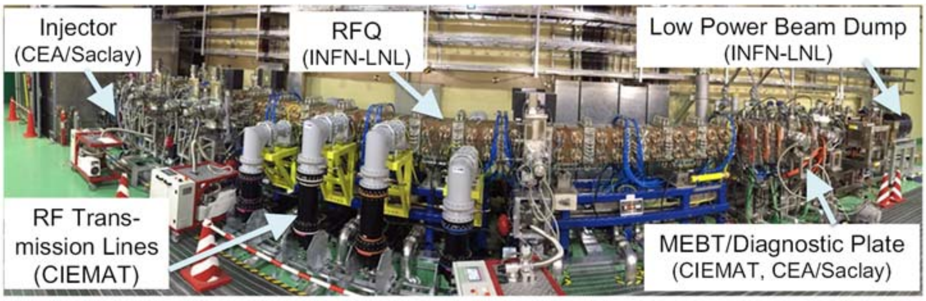

FIG. 3. Major LIPAc components installed in the accelerator vault for starting the RFQ beam commissioning.

TABLE 1. MAIN TARGETS OF LIPAC VALIDATION

Items	Interim Target*	Final Target
Particles	deuteron (proton)**	
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
Normalized rms emittance, transversal (π mm mrad)	< 0.25† @ RFQ in / < 0.30 @ RFQ out	< 0.36‡ @ SRF Linac out
longitudinal (MeV deg)	< 0.2 @ RFQ out	< 0.2 @ SRF Linnac out
Pulse mode	0.3 ms/1 Hz (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.

** Proton beam with half-energy and half-current of deuteron is used for machine tuning to simulate the beam acceleration/transport with the perveance equivalent to that for deuteron.

† As for the criterion of the injector commissioning, < 0.3π mm mrad is acceptable.

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

The details of the progress of the LIPAc subsystems are described in the following subsections.

2.1. Injector

The injector developed by CEA/Saclay [12] has an ECR ion source driven by a 1.2 kW CW magnetron with a capability of pulsing, fast blanking (beam reset to zero (BRTZ) within 50 μs in a pulse at low duty cycle mode) and conventional type fast (10 μs)/slow beam inhibition interlocks [13]. 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 two 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 five 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 three- or four-electrodes systems [12]. 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 much attention on this point to reproduce the specification values, which were optimized for 155 mA beam extraction from the PE with an aperture of 12 mm diam. Through the several campaigns to qualify and improve the beam characteristics predicted by the design simulations, a good emittance (< 0.15π mm mrad, normalized rms) was obtained in December 2017 for 100 keV deuteron with extracted beam current, 155 – 170 mA, at 5% duty cycle (Fig. 4) [9,14]. Iext shown in the figure is the total extracted current measured at the power supply for terminal high voltage, and it includes molecular beams (D_2, D_3 and D_2O). The measured fraction of deuteron to total beam is typically 93%, so the target of emittance value at RFQ input (< 0.25π mm mrad, normalized rms, Table 1) was achieved at deuteron beam current of 140 – 160 mA in the present configuration of the electrodes.

As 50 keV proton beam with low beam current and good emittance/stability is required for the initial beam injection into RFQ, PE with smaller aperture sizes should be properly chosen for each beam current. An intensive experiment of the proton beam extraction was performed until May 2018 [14], and the working points for the extracted beam current of 13 – 83 mA were obtained with the normalized rms emittance requirement, < 0.25π mm mrad. As a conclusion, PE with aperture of 6, 9 and 10.5 mm diam. are recommended to extract the proton beam for the ranges of current, 13 – 40, 40 – 75 and 75 – 83 mA, respectively. As described in section of RFQ, the first beam commissioning carried out in June – August 2018 employed 6 mm diam. aperture PE for which the normalized rms emittance < 0.15π mm mrad was achievable in the range of current, 13 – 35 mA. However, since a strong steering magnet field was necessary to achieve the best transmission through 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.

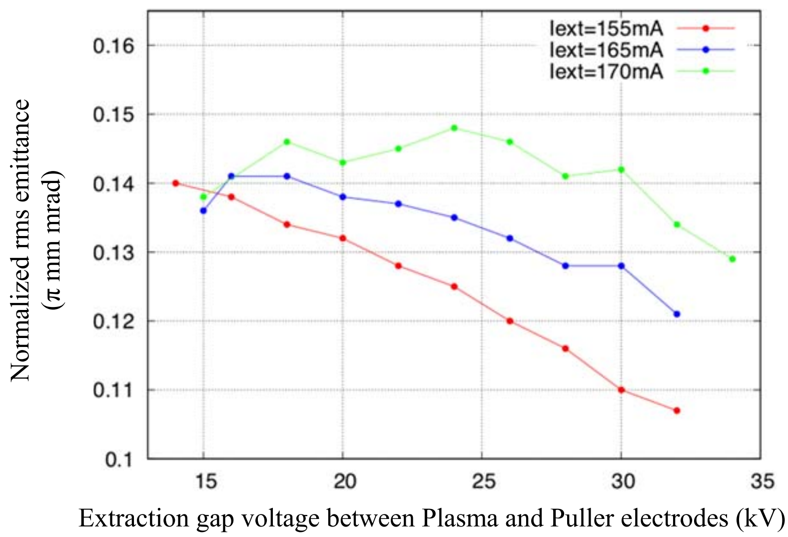

FIG. 4. Injector beam performance on emittance vs. first gap voltage for 100 keV deuteron beam.

2.2. RFQ and RF Power System

The RFQ developed by INFN-LNL is a 9.8 m-long cavity composed of 18 short section modules, each of which was made by brazing of OFE copper parts and connected together using stainless steel flanges. The cavity is designed to have a ramping vane voltage rule from 79 to 132 kV at the middle region of cavity, 3 – 7.4 m, which was realized by precise tuning process [7]. The RF power system for all the RF cavities of LIPAc (RFQ: 200 kW tetrode amplifiers, SRF Linac: 105 kW tetrode amplifiers and re-bunchers: 16 kW SSPAs) [15] was procured by CIEMAT, CEA/Saclay and SCK-CEN, and installed by QST in Rokkasho (Fig. 5) [6,10,16].

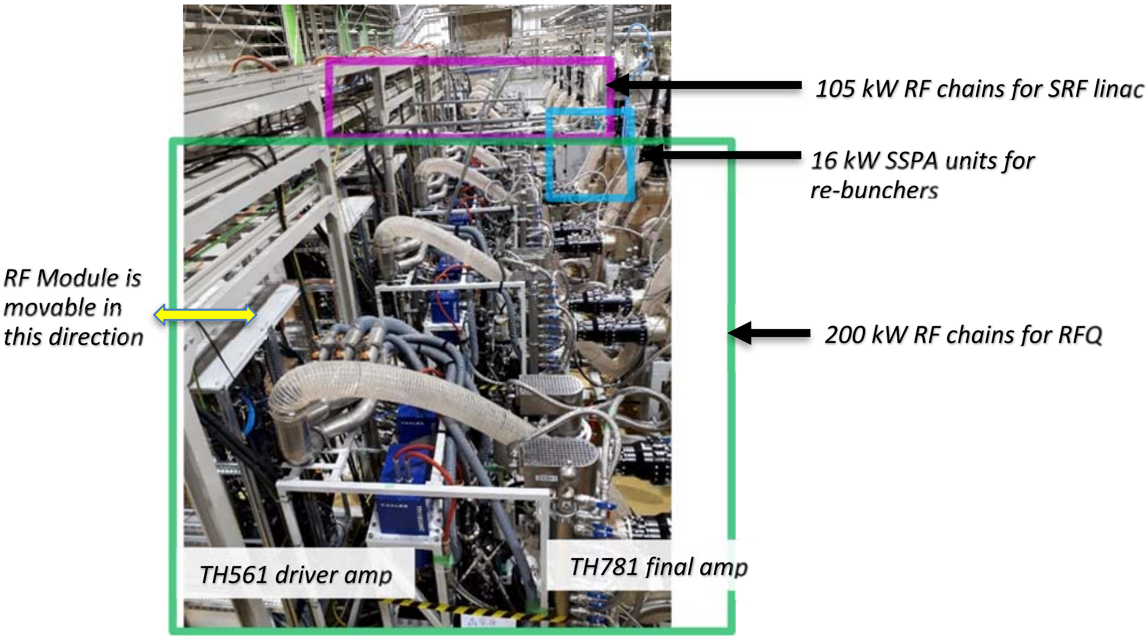

FIG. 5. RF power amplifiers for RFQ (8 x 200 kW chain of tetrode), re-bunchers (2 x 16 kW unit of solid-state power amp) and SRF Linac (8 x 105 kW chain of tetrode) installed at RF power room in LIPAc building.

Based on the modular design concept for improving the system availability, both 200 kW and 105 kW RF chains employed the same configuration of tetrodes, Thales TH561 and TH781 as driver and final amplifiers, respectively. The other components are almost same except for those related to the maximum RF power to be handled, such as circulator, coaxial transmission lines and high voltage power supply (HVPS) for anode of final amplifier.

For the beam commissioning of RFQ, a precise phase synchronization among 8 RF chains is critical and it was realized by distributing 10 MHz reference signal to the Low-Level RF controllers of each RF module and applying the White Rabbit technology [17]. Through the RF conditioning of RFQ cavity using 8 RF chains (1 master and 7 slaves), the cavity vane voltage of 132 kV with 5% margin was achieved with short pulse mode (20 µs) [7]. Further conditioning is continued to extend the pulse width to reach CW mode, however, for starting the beam commissioning of 50 keV proton beam to confirm the basic functions of RFQ, MEBT and beam diagnostics, the extension of pulse length was concentrated to achieve the condition for accelerating proton beam with cavity voltage of 66 kV. For the stable operation of anode HVPS in pulsed mode, it was effective to apply the pulsed RF power (typically 1 ms) superimposed over a portion of CW power. The control of power balance of 8 RF chains is also critical to establish the stable operation. 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, after the first success of beam acceleration by RFQ. 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.

At the very beginning of the beam commissioning with 50 keV proton, 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 1 s 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% [18]. 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 normalized rms. The transmission down to LPBD was >90% for all cases except for 40 mA case (89%). The typical snap shot of oscilloscope to show the beam current signals at four points along the beam line is gi\ven in Fig. 6. As a result, in this first campaign, the RFQ output current of 26 mA at maximum was observed.

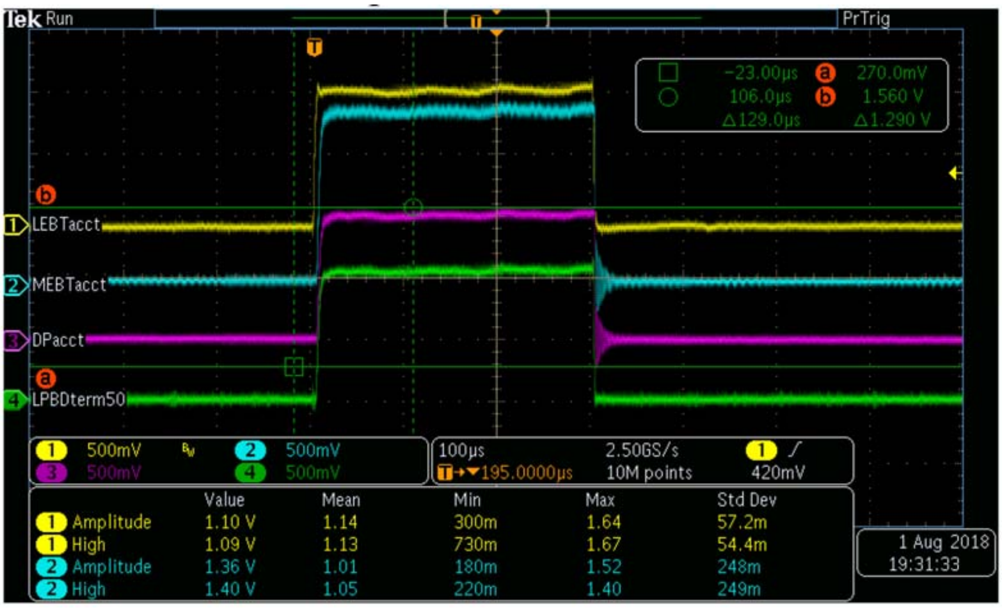

FIG. 6. Beam current signals measured at four locations of the LIPAC for extracted current 30 mA with 0.3 ms pulse width (yellow: RFQ input, cyan: RFQ output, magenta: middle of D-Plate and green: LPBD).

The output energy was measured using time-of-flight method for comparing the 175 MHz bunch signals detected by 3 Beam Position Monitors (BPM) [19] 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.

The obtained results are still preliminary values which should be confirmed again and extended the injection parameter range in the next beam commissioning and compared with the prediction derived from the beam dynamics simulation [20].

2.3. Beam Transport Line and Beam Dump

In the RFQ beam commissioning, the MEBT line developed by CIEMAT is used to transport the beam from RFQ to LPBD through D-Plate, using 5 electromagnetic quadrupole magnets (1 triplet and 1 doublet) and 8 steering coils embedded at the centers of quadrupoles (4 pairs of horizontal/vertical steerers located at first and third quadrupoles of triplet and both quadrupoles of doublet) [21]. 2 movable scrapers to cut the tail part of beam in horizontal and vertical directions are installed for protecting undesired beam hitting in the downstream side elements, especially SRF Linac. After a careful integration and final tests at Rokkasho, the commissioning of MEBT was completed in February 2018 with the re-conditioning of the re-buncher cavities using SSPA RF power system up to 11.8 kW (effective cavity voltage E0LT > 350 kV) in January 2018 [22]. Since all the 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.

The LPBD developed by INFN-LNL is used to stop the beam safely during the RFQ beam commissioning campaigns. The water cooled, aluminum conical beam stop is able to measure the transported current with secondary electron suppressor in front of LPBD.

The HEBT line and final BD developed by CIEMAT are mostly procured and ready for transportation to Rokkasho except for the local control system. However, a part of components was transported to Rokkasho and its installation has been started in August 2018.

2.4. Beam Diagnostics and Control System

The beam diagnostics developed by CEA/Saclay, CIEMAT and INFN/LNL, consist of (1) non-interceptive devices and (2) interceptive devices [23], and the layout in D-Plate is shown in Fig. 7. As for category (1), Current Transformers (CT), 3 ACCTs (in LEBT near the entrance of RFQ, in MEBT immediately after the exit of RFQ and in D-Plate) for beam transmission measurement, a Fast CT at the same location of ACCT in MEBT for measuring the beam bunch shape directly, and a DCCT in D-Plate (unused in the last campaign); 7 BPMs (4 in MEBT and 3 in D-Plate) [19]; 2 profile monitors in D-Plate, fluorescence-type (FPM) and ionization-type (IPM), where the signal intensity of IPM was too small to detect profile, while FPM detected some patterns varying with the beam transport condition, at vacuum pressure around 10^{-7} mbar. The Residual Gas Bunch Length Monitor (RGBLM) is also available in D-Plate, to be used in the next step with the re-bunchers operation. In LEBT, Doppler shift spectrometer for ion species fraction measurement and four-grid analyzer for space charge compensation measurement are available, however they are unused in the last campaign. About category (2), except for the beam-stop current monitors (one in LEBT and the aluminum cone inside LPBD), secondary electron emission (SEM) grid profiler + slits (width 100-200 µm, water cooled) + 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. 7 Beam Loss Monitors (BLoM) were installed along the beam line from the RFQ exit up to the LPBD (LHC-type Ion Chambers, 2 at RFQ exit, 2 at MEBT, 3 at D-Plate (in phase C, more BLoMs, 8 at around SRF Linac cryostat and 3 at HEBT, are added). They have low sensitivity [24], however, which is compliant for requirement of LIPAc and requiring the further threshold tuning to be used as the alarm for beam loss events.

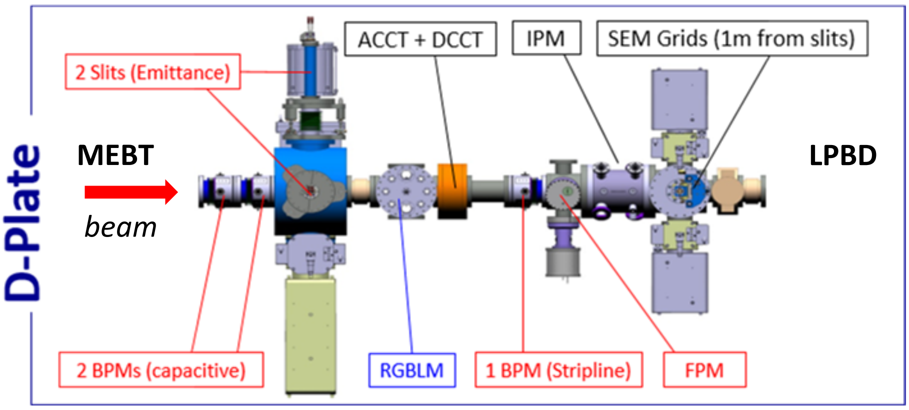

FIG. 7. Top view of beam diagnostics installed at the D-Plate, located after MEBT in the RFQ beam commissioning.

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.

2.5. SRF Linac and Cryoplant

After the manufacturing studies needed for the licensing of the cavities [25] 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 on-going. All the bare cavities have been tested in vertical cryostat and are over the requirements (unloaded quality factor $Q_0=5\cdot10^8$ at nominal accelerating field 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 [26].

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 [27]. The plant was installed and commissioned in April 2017.

3. LIFUS 6

The Lifus 6 developed by and built at ENEA Brasimone [11] is a facility to conduct the experimental tests of erosion-corrosion phenomena at the components of lithium target assembly of the IFMIF, especially at the nozzle and backplate, which are made from the RAFM steel and exposed to the liquid lithium with nominal flow speed of 15 m/s and average temperature of ~571 K at the downstream of 10 MW deuteron beam injection. Fig. 8 shows the layout of the Lifus 6 plant composed of the main loop to circulate lithium through the test section (30 L/min), the impurity monitoring and control loop (0.3 L/min) using resistivity meter (RM) and cold trap (473 K), storage tank and hot trap. In the test section, a rod composed of eight annular specimens, four for each material of Eurofer97 and F82H was mounted concentrically into a flow channel, with an annular gap size of 0.5 mm for the lithium flow (flow velocity 15 m/s, temperature 603 K and nitrogen concentration < 30 wppm). The required value of nitrogen concentration in lithium was achieved by a hot trap containing a titanium sponge getter, operated at temperature 823–873 K, and by applying the validated offline chemical analysis of nitrogen concentration in sampled lithium [28]. At operating temperature of hot trap, 823 K, it is hard to achieve the value lower than 30 wppm, while at 873 K the minimum value 14.1±2.1 wppm can be attained. The uncertainty of the derived nitrogen concentration for the wppm level impurity is estimated as 2.5% at maximum in systematical error and lower than a few % in random error. The sensitivity of the RM as an online non-metal impurity monitor is 0.1 μΩ (equivalent to 6 wppm N or 1 wppm H), however the observed noise level was ±0.5 μΩ. The further improvement is required for the design to reduce noise and the measurement method to detect the small variation of resistance.

The results of erosion-corrosion tests are summarized in Fig. 9, for four cases: short term campaign (1222 h), first and second medium campaigns (2000 h) and long term campaign (4000 h as a total of two 2000 h) [29]. The maximum corrosion rate of the individual samples in the last case was 0.28 μm/y, however the average was < 0.2 μm/y, and no relevant difference between two RAFM steels was identified. Both materials satisfied the IFMIF requirement on thickness change rate, < 1 μm/y. Through the inspection by optical microscope, the surface remained smooth and the surface roughness remained essentially unchanged.

The SEM analysis of the surfaces of specimens showed no widespread signs of corrosion phenomena, and only very few and isolated items are seen, especially after the 2000 and 4000 h tests. The Energy Dispersive X-ray Spectroscopy (EDS) analysis showed that compositions of the surfaces of specimens were changed as follows.

- Cr: -1 ~ -1.5 wt% in all the specimens, with larger decreases after longer tests.
- W: reduced at the surface, down to values < 1 wt% after longer tests.

- In the rare case, at the locally damaged regions, concentrations are changed with presence of a few % of O, Ca; and in one case, changes of 16.5% of Ti and 56% of Ta (probably carbides are created and galvanic corrosion is occurred).

The EDS analysis is applied to the depth profile of concentrations of Cr and Fe. The results showed that (1) no morphological alteration is seen in the inner metallographic structure, (2) no trend is found in concentration vs. depth, (3) possible Cr depletion is confined within 1 μm surface layer.

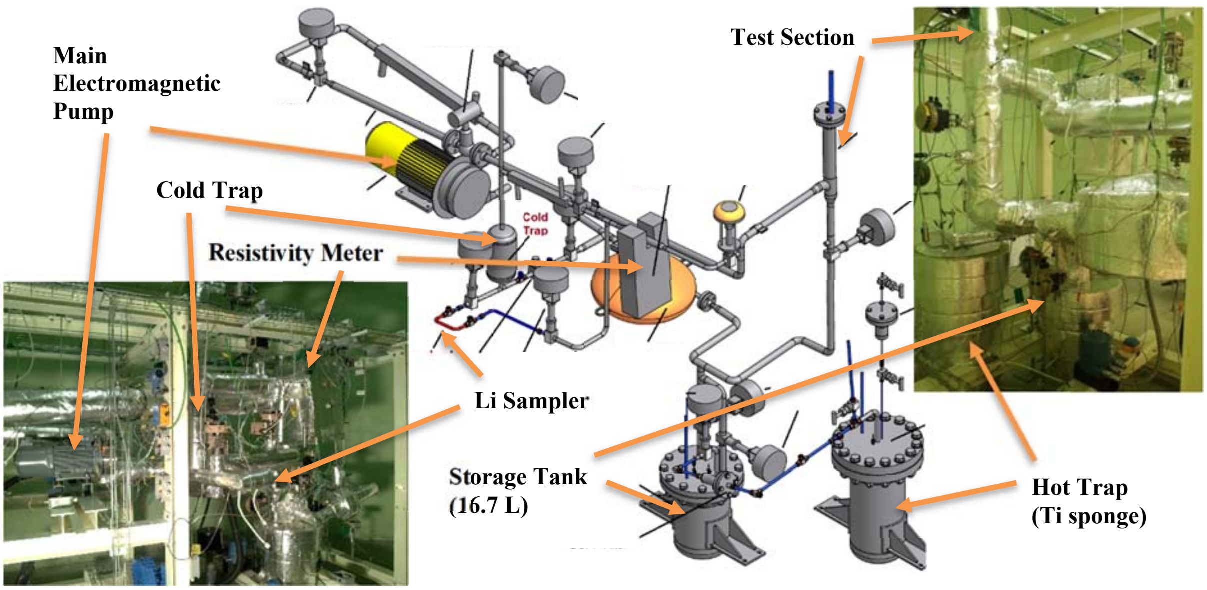

FIG. 8. Configuration of Lifus 6 plant for testing the erosion-corrosion of RAFM steel under the flowing liquid lithium (photographs are (left) main loop and impurity monitor/control loop using resistivity meter and cold trap, and (right) test section and storage tank/hot trap).

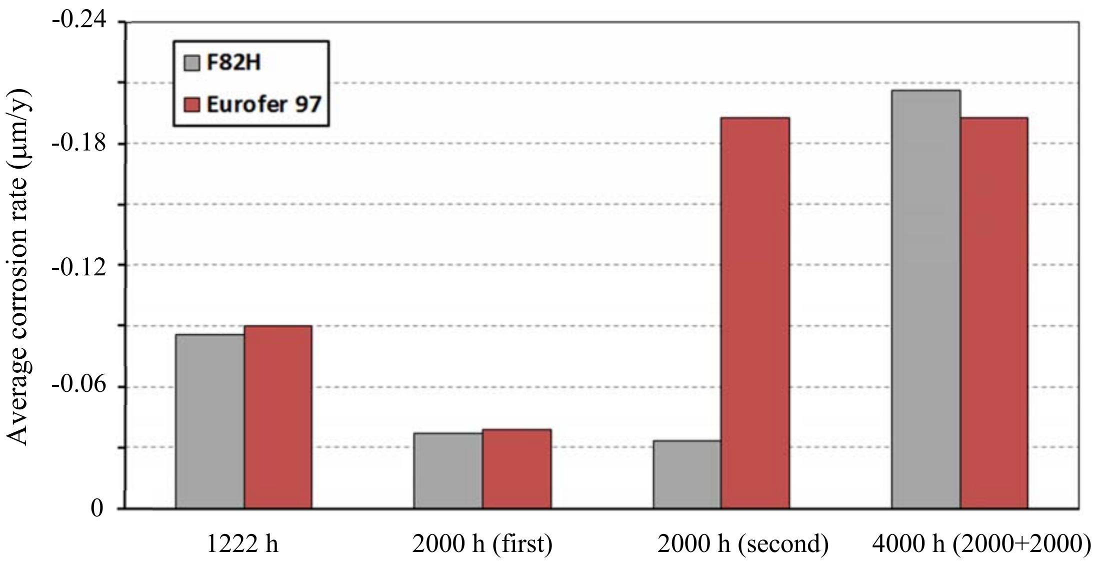

FIG. 9. Comparison of erosion-corrosion rates for F82H and Eurofer97 caused by flowing lithium at Lifus6 (15 m/s, 603 K)).

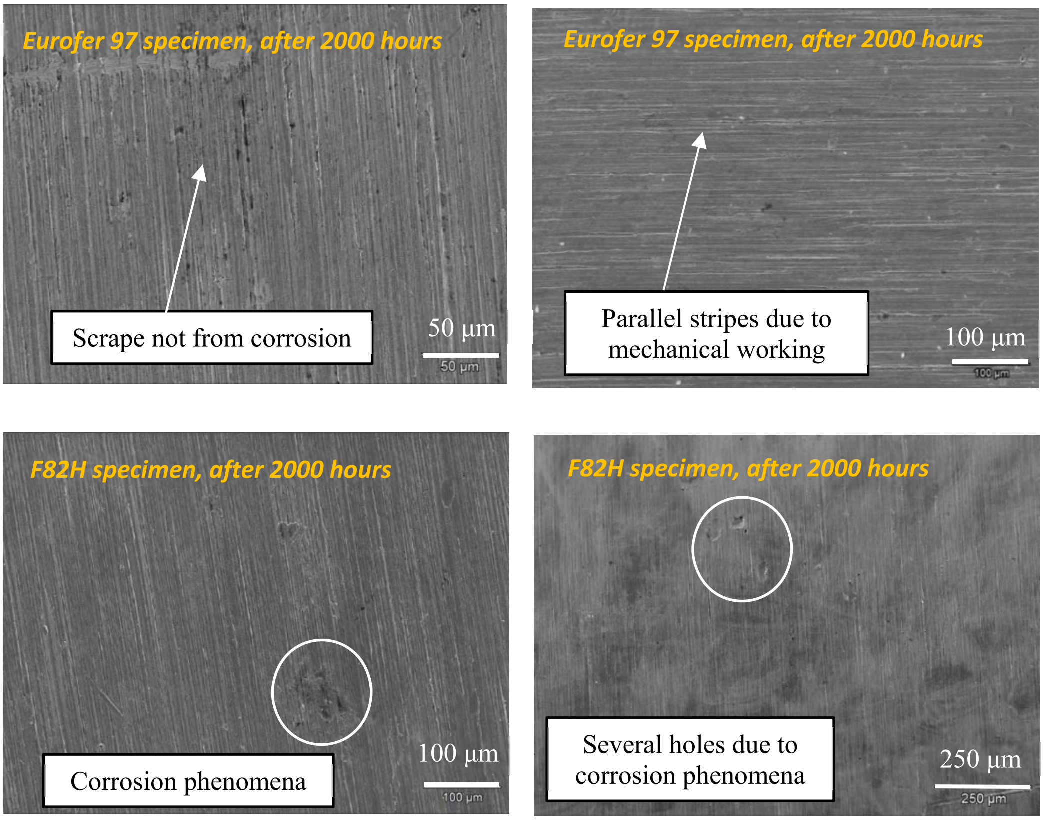

FIG. 10. Surface analysis of erosion-corrosion effect forEurofer97 and F82H after 2000 h operation at LiFus6.

4. SUMMARY

About the LIPAc, the important progress was made through the activities in 2017–2018, and the major outcomes are: (1) kick-off of the RFQ beam commissioning was achieved in June 2018, (2) a good sign of RFQ design validity was obtained at beam transmission, >90%, and output energy, 2.5 MeV, under the condition of current up to 35 mA, which is about half of required value, (3) the other important beam characteristics, like beam size, emittance and bunch length, were tried to examine, however it was uncompleted in the first campaign, (4) 50 keV/ 70 mA proton and 100 keV/140 mA deuteron beams to satisfy the required emittance < 0.25π mm mrad were obtained and ready for test in the next campaign, (5) the further RF conditioning of RFQ is required to conduct the high current beam injection in deuteron and (6) the assembly work of SRF Linac is waiting for the completion of delivery of the last components in Rokkasho.

About the Lifus6, all the activities including the reporting were completed by end of March 2017, and the major conclusions of the tests are: (1) purification of lithium from non-metallic impurities, mainly N < 30 wppm, is feasible, (2) erosion-corrosion rate in RAFM steel can be kept under control (< 1 µm/y) at least up to 4000 h operation and (3) online monitoring of the non-metal impurity in lithium requires the further efforts to improve the design of RM and the measurement method of small variation of resistance.

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