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Status of the RFQ linac installation and conditioning of the Linear IFMIF Prototype Accelerator

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A B S T R A C T

The Radio Frequency Quadrupole (RFQ) linac and 1.6 MW RF power system of the Linear IFMIF Prototype Accelerator (LIPAc) facility in the International Fusion Energy Research Center (IFERC) in Rokkasho (Japan) has been installed and conditioned. During the assembly and tuning process, the RFQ cavity was protected with a temporary tent from the potential deterioration of performance caused by dust. The vacuum in the cavity was improved through the 100 °C baking process of the cavity. The high power test of the 175 MHz RF systems up to 200 kW in CW for each of the eight RF chains was performed for checking its stable output reproducibility in Japan, before connecting 9–3/16 inch coaxial transmission lines from the RF chains to the RF input couplers of the cavity. It was confirmed that the eight RF chains provided the balanced RF power to the single RFQ cavity in-phase using a feedback loop and a synchronization system. The peak power in the cavity achieved 150 kW in the pulsed mode, which corresponds approximately to the required electric field to accelerate proton beam. Such RF conditioning process is ongoing to achieve 600 kW approximately required for deuteron beam commissioning planned in 2018.

1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator-driven neutron source that profiting from Li(d,n) stripping reactions will become a fusion relevant neutron source [1–3]. In the IFMIF, the accelerator facility counts with two beam lines accelerating deuterons at 40 MeV with 250 mA output (125 mA × 2) in continuous wave (CW). In an accelerator facility under installation in Rokkasho (Japan) (Fig. 1) with equipment designed and constructed in Europe, the Linear IFMIF Prototype Accelerator (LIPAc) aims to conduct a 9 MeV deuteron beam at 125 mA in CW) [4–7]; this will validate the 40 MeV IFMIF's accelerators since space charge phenomena inherent of such high current accelerators are more severe the lower the particles energy. LIPAc is the only remaining activity of the three main validation ones in the on-going IFMIF Engineering Validation and Engineering Design Activities (IFMIF/EVEDA) phase under the Broader Approach Agreement between Japan and EURATOM.

LIPAc consists mainly of beam accelerating equipment (in superconducting approach in its final stage), beam transports, diagnostics, ancillary equipment, RF power systems and a beam dump. In a first phase, commissioning of the injector and the Low Energy Beam Transport line (LEBT) was performed in 2015–17, so-called Phase-A [8,9]. The injector extracts 0.1 MeV deuteron beam with emittance values within 0.25 mm mrad, and the LEBT transports and matches the extracted beam to the Radio Frequency Quadrupole (RFQ) linac entrance by means of two solenoids. The 4-vane type 175 MHz RFQ linac is designed to accelerate a deuteron beam of 125 mA from 0.1 MeV to 5 MeV in CW, that demands a total RF injected power of about 1.6 MW

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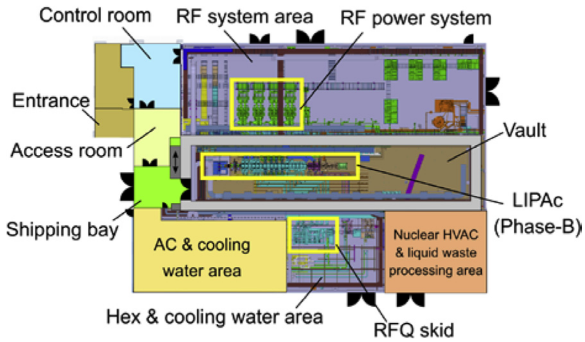

Fig. 1. Schematic of the LIPAc facility in Phase-B.

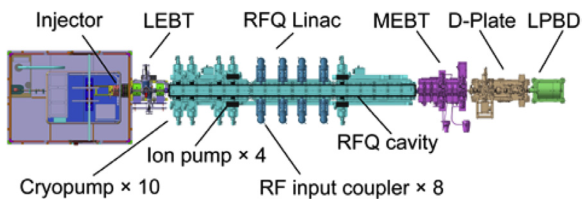

Fig. 2. Drawing of the LIPAc in Phase-B.

in CW [10]. In the ensuing phase B (Fig. 2), the commissioning of the beam through the world's longest RFQ is to be performed within a low duty cycle of 0.1% with a proton beam (0.05 MeV to 2.5 MeV) in preparation of a deuteron beam (0.1 MeV to 5 MeV). It is to be noted that in terms of beam dynamics, both beams are equivalent if current holds a factor x2 between proton and deuteron beams. This, in this exercise, the proton beam operation requires an RF power which is one-quarter (half current and integrated voltage) of that for a deuteron beam. The neutron production with a proton beam at that output energy would be negligible in Phase-B; that is the reason underpinning the decision to operate the accelerator performance and subsystems with a proton beam in advance. In Phase-B, the Medium Energy Beam Transport line (MEBT), the Diagnostic plate (D-Plate), and the Low Power Beam Dump (LPBD) are also to be commissioned.

During the preparatory works towards Phase-B, the installation of the RFQ linac and its RF power system have been conducted stepwise as described in Sections 2 and 3; the RF conditioning of the RFQ cavity and the commissioning of the RF power system is reported in Section 4.

2. Installation of the RFQ linac

2.1. Assembly of the RFQ cavity and installation of the RF couplers

The 9.8 m RFQ cavity was designed and manufactured in INFN (Italy), and transported to Rokkasho (Japan) in 2016, divided into three super-modules (SMs). Each super-module consists of six modules, which are minimum blocks of the cavity, and these were precisely assembled using a laser tracker system in INFN. Once arrived in Rokkasho, the three SMs were precisely assembled and aligned in the IFMIF/EVEDA accelerator vault using laser tracker system [11,12]. The cavity was tuned to have the nominal voltage profile on the vane tips at 175 MHz using the bead-pulling system with dummy and final tuners [13–15]. Since the commissioning of the injector was concurrent, the assembly and tuning were performed at a provisional position with the RFQ shifted around three meters downstream. After conclusion of the injector commissioning, the RFQ cavity was moved upstream to its final position by disassembling again the three supper modules, and their re-alignment with the laser tracker system that allowed a precision with 30 μm uncertainties thanks to the performant fiducials cloud of the accelerator vault. Only then, the vacuum system and eight RF couplers were installed on the RF cavity [16].

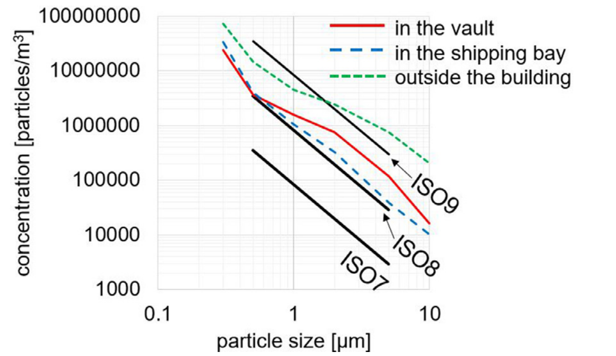

Fig. 3. The average cleanliness in the vault (solid line), shipping bay (dashed line), and outside the building (dotted line), measured in July - September 2016.

2.2. Protection of the RFQ cavity and other equipment from dust during its installation

During the assembly and tuning of the RFQ cavity at the provisional position, provisions to mitigate the risk of dust entering the RFQ cavity were implemented. The cleanliness of air in the vault, shipping bay, and outside the building was measured using a handy particle counter (MET ONE HHPC6 + , 0.3 μm to 10 μm) in July–September 2016. The cleanliness of air can be expressed by the ISO class, defined as the concentration of particle as a function of the particle size. The vault has an air-tight door to the shipping bay (Fig. 1). The measured average cleanliness in the period is shown in Fig. 3. The cleanliness in the vault and shipping bay were ISO 8-9, and outside the building was ISO 9-10. The cleanliness in the vault was one class lower than that of outside the building, and enough clean for the RFQ cavity assembly and tuning.

However, dust in the vault was increased by activities in the vault, such as cooling water piping installation from the RFQ skid to the RFQ linac and movement of wooden boxes containing components for the RFQ linac, MEBT, and D-Plate. Areas reserved for the cooling water piping and carrying-in-and-out components are shown in Fig. 4. MEBT and D-Plate were also installed to a provisional position in this period. To prevent dust entering the RFQ cavity during the activities, a tent covering the RFQ linac with plastic sheets (PCV) supported by metallic frames was installed (Fig. 5). The MEBT and D-Plate were also protected from the dust using tents. The cleanliness inside tent remained ISO 8-9, while outside it reached ISO 9-10.

2.3. Baking of the RFQ cavity

After completion of the installation of RFQ vacuum system, the baking of the cavity was initiated to reduce the water adsorbed on the cavity copper surface. This baking is usual practice to enhance the vacuum performance saving time for the time consuming high power RF conditioning of an RFQ cavity.

The baking system consisted of two heater blowers, its controllers and temperature monitors, cavity insulation (EJ™ Jacketing and SilicoSoft™ advanced fiber) covering the whole cavity except components protruding from the cavity, such as RF couplers, manifolds for the vacuum system, cryopumps and ion pumps. Hot air through the heater

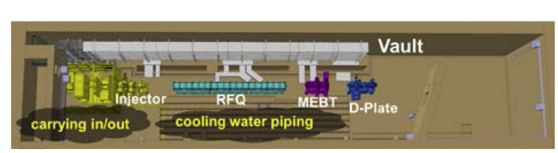

Fig. 4. Top view of the vault showing areas reserved for the cooling water piping installation and carrying-in-and-out components, and the provisional positions of the RFQ linac, MEBT, and D-Plate.

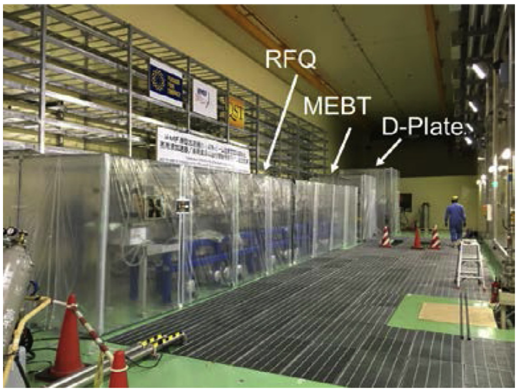

Fig. 5. Tents for protecting the RFQ linac, MEBT, and D-Plate from dust in the vault.

blowers was circulated from both end sections to the middle section in the cavity insulation. Such convection baking system has the advantage to suppress the risk of local thermal expansion leading to vacuum leaks from module vacuum sealing flanges. In order to prevent mechanical stresses on the RFQ driven by thermal expansion during baking, the cavity was allowed to smoothly expand in the longitudinal direction by means of movable supports. The maximum baking temperature was set at 100 °C to (1) prevent damage of the copper-stainless steel brazed surfaces through differential thermal expansion and (2) hold safe margin to indium based vacuum seals whose melting temperature is 130 °C. In turn, the inlet air temperature was limited by the melting point of the Viton O-ring (~180 °C) used in a gate valve at the end section of MEBT side, which was close to the inlet port. The water evaporated by the baking was removed by three pump stations. The pump station equipped with a rotary pump and a turbo pump. The pressure was about 4×10^{-5} mbar before the baking.

The performance of the baking system was initially insufficient with low temperature inlet air, about 50 °C driven by non-negligible underestimated radiation losses from the RF couplers and manifolds; thus, the RF couplers were also covered with commercial glass wool sheets. After such optimization of the cavity insulation, the cavity temperature reached the target 100 °C at the both end sections and 90 °C at the middle section with 160 °C inlet air. This layout was kept for about 100 hours at the stable conditions. The pressure was reduced to 2×10^{-5} mbar, half of it original value, it was decided to stop and continue to pumping down in preparation to the high power RF conditioning.

The ultimate pressure in the RFQ cavity with the 10 cryopumps in operation was about 5×10^{-8} mbar, which is compliant with the pressure specified target of 5×10^{-7} mbar to start beam operation.

3. Installation of the RF power system for the RFQ linac

The RF power system, designed and delivered 'in-kind' by CIEMAT (Spain), was installed in the RF bay building. The high power tests of the system was accomplished in July 2017. The co-axial transmission lines connecting the RF system and RF couplers were installed immediately after.

3.1. RF system

The RF power system consists of eight RF chains at 175 MHz of 200 kW each in CW or pulse waveform [17]. A schematic drawing of the RF power system is shown in Fig. 6. The RF signal generated by the Low-level RF (LLRF) is amplified through three amplifiers (Pre-Driver, Driver, Final Amplifier), and the amplified RF power is supplied to the RFQ cavity via a RF coupler. The reflected RF power from the RFQ cavity is absorbed by a 50 kW dummy load through a circulator. Each

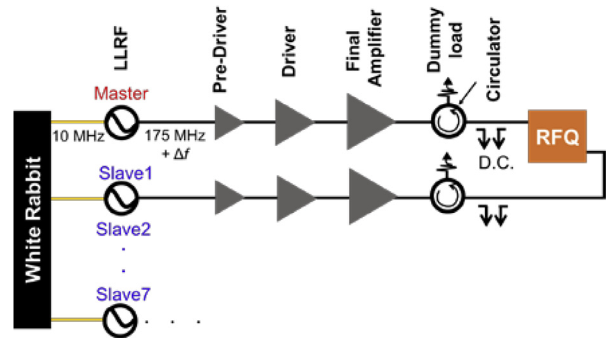

Fig. 6. Schematic of the RF power system.

RF chain synchronizes to the master RF chain through 10 MHz distributed with White Rabbit technology to LLRF of the eight chains [18,19]. The forward input power to the RFQ cavity and the reflected power from the cavity are detected from the directional coupler (D.C.), with an attenuation of about −70 dB. Using a feedback system, based on the PI loop, the forward power from seven slave RF chains follow the reference RF power from the master RF chain, and the relative phases between the every two chains of the master and one of the slave are tuned to set-up values. This function is essential to the RFQ linac since the RF power into the cavity must be balanced and in-phase. The output frequency is also tuned to the cavity resonance frequency.

3.2. High power test

High power test of each of the RF chains was performed to confirm the stable maximum design output of 200 kW, both one-by-one in CW and pulsed modes. High power test of the RF chains had been already conducted before it was delivered to Japan. It was also checked on site because the RF power system was reassembled in Japan. In the high power test, the output from the RF chain was split and absorbed by two dummy loads (100 kW × 2) cooled with water (Fig. 7). All RF chains were operated at 200 kW in CW fulfilling the specifications.

3.3. Installation of transmission line

9-3/16 inch coaxial lines are used for the RF power transmission to the RFQ. The transmission lines start from the output of the circulator, pass through an underground pit of several meters in depth and width, and end at the port of the RF coupler (Figs. 8 and 9). The pit was designed from the radiation safety point of view in order to prevent the radiation streaming effect while operating the 1.1 MW high power deuteron linac. The large U-shaped transmission lines in the pit were connected by lifting them up with two jacks as the final step as shown in Fig. 9. It was essential that the L-shaped transmission line in the vault remained rigidly fixed to avoid excessive stressed applied on the coupler, which holds a fragile RF window. If a non-negligible mismatch was observed between two interface flange positions, the bolts on rotatable flanges were loosened in the pit for an increase of the degrees of freedom. In this way, 10–15 mm of mismatch were acceptable at the connection, and succeeded in completing the installation of the

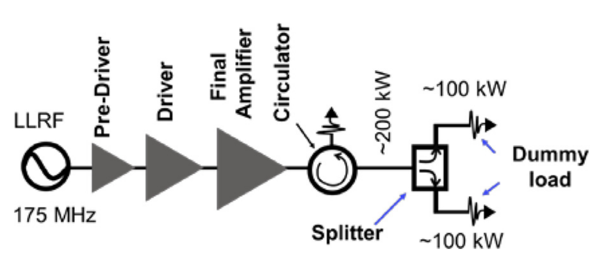

Fig. 7. Schematic of the high power test setup [15].

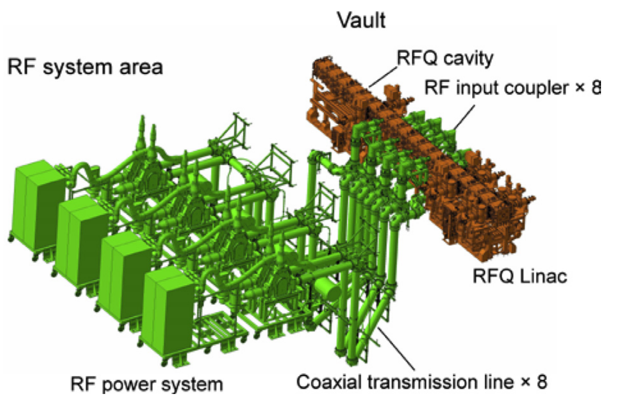

Fig. 8. 3D-model of the eight coaxial transmission lines connecting the RF power system in the RF system area to the RFQ Linac in the vault.

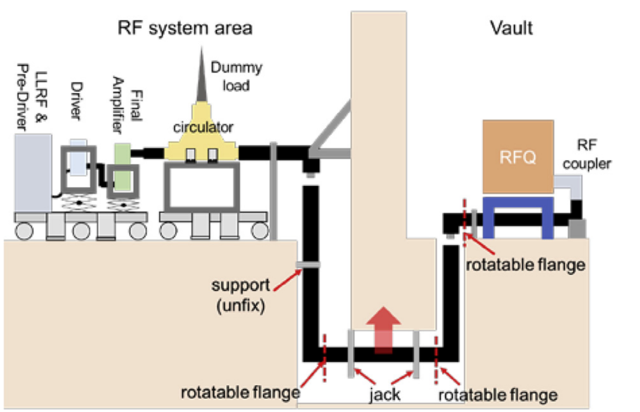

Fig. 9. Schematic of the procedure of the installation of the transmission lines.

transmission line without relevant mechanical stresses on the RF couplers.

4. RF conditioning of the RFQ linac

The RF conditioning of the RFQ cavity aims at achieving 600 kW in CW stored in the cavity, which corresponds approximately to the required electric field to accelerate deuteron beam. The water and gases remaining adsorbed on the cavity surface can be eliminated through the high power RF conditioning. In addition, electrically unsmooth surfaces become smooth through electrical sparks in the conditioning.

After adjusting the input frequency and relative phases between the RF chains, we injected RF power from all the eight chains into the RFQ cavity in pulsed mode with the feedback loop and the synchronization system. The pulse length and period were adjusted by monitoring the pressure in the RFQ cavity and the electrical spark rate. The spark occurs in the cavity or on RF couplers typically due to multipacting, etc. Such sparks are the essential process for the conditioning, but we need to carefully control the power, the spark duration and rate not to damage the surface by strong or long duration sparks. The RF system stops the RF output immediately when it receives the light signal through optical fibers installed to the RF couplers and the both end sections of the RFQ cavity. As shown in Fig. 10, RF power injected to the cavity was switched-off as soon as sparks were detected, or when the increased pressure through the released gas was above the vacuum threshold of 10^{-6} mbar.

One of the milestones on the RF conditioning was achieved by October 2017 with a peak power in the cavity of 150 kW in pulsed mode, which corresponds approximately to the required electric field to accelerate proton beam. In November 2017, the peak power achieved

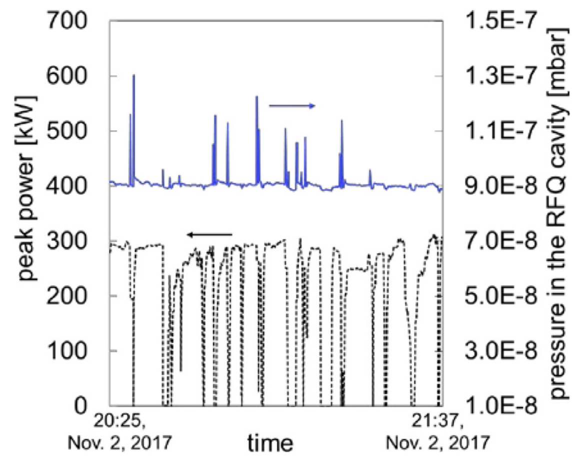

Fig. 10. One of the typical evolutions during the RF conditioning. The peak power (dotted curve) and pressure (solid curve) in the cavity are shown. The pulse width and period were 60 μs and 0.5 s, and the resonance frequency was 175.005 MHz.

300 kW as shown in Fig. 10. In the experiment, pulse width and period were 60 μs and 0.5 s, and the resonance frequency was 175.005 MHz.

5. Conclusions

The RFQ cavity was assembled and tuned under the cleanliness of ISO 8-9 in the vault, in Japan. During the water piping installation, the RFQ cavity was protected from dust using a tent covering it completely. The baking of the cavity during one week improved the vacuum values. After the high power test of the RF system up to 200 kW in CW, the transmission lines were installed from the eight RF chains to the eight ports of the RF couplers without damage induced by excessive stresses on the RF couplers. It was confirmed that the RF power system provided the balanced RF power to the RFQ cavity in-phase using the feedback loop and the synchronization system. As one of the milestones of the RF conditioning, the peak power in the cavity was achieved by reaching 150 kW in pulsed mode, which corresponds to the required electric field to accelerate proton beam. As the present status, the peak power has achieved 300 kW so far. We continue the RF conditioning to achieve the peak power of 600 kW required for deuteron beam operation.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nme.2018.04.001.

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