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# IFMIF/EVEDA RFQ PRELIMINARY BEAM CHARACTERIZATION

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*Abstract*

The IFMIF/EVEDA RFQ is the longest and powerful operated. Therefore, it requires a careful characterization from several aspects: beam dynamics, RF, mechanics, installation and commissioning. Due to the very large power handling, the preliminary beam operation was decided to be performed with a low proton beam current at one half of the voltage needed for deuteron acceleration, i.e. from 8 mA to 30 mA at 2.5 MeV in pulsed mode, with respect to the nominal 130-mA deuteron beam at 5 MeV in CW. In this framework, it will be presented the characterization of the RFQ in terms of simulation and measurements.

## INTRODUCTION

The Linear IFMIF Prototype Accelerator (LIPAc) is composed of an ion source, a LEBT, a RFQ, a MEBT and a SC linac and HEBT, with a final energy of 9 MeV [1].

This paper is mainly focalized on Normal Conducting linac performance. In particular RFQ is a CW linac capable of delivering 125 mA of $D^+$ beam at 5 MeV. The 10-m-long, 175-MHz RFQ structure is designed to accelerate the DC 100 keV, 130 mA $D^+$ beam from the injector with more than 90% transmission [2].

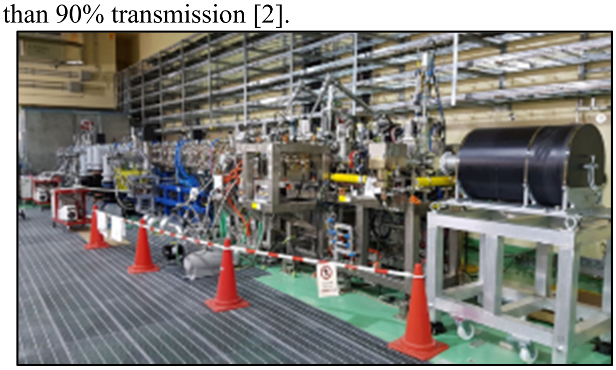

Figure 1: IFMIF/EVEDA LIPAc in Rokkasho (Japan).

RFQ is installed in IFMIF site in Rokkasho (Fig. 1) since April 2016. The low power RF characterization (bead pulling and tuning) was concluded in September 2016. We installed the 8 power couplers in December 2016, checking the field by pick-up reading. After baking and connection to the cooling system and to the 8 RF systems, RF conditioning started in July 2017. Some problems slowed down hardware conditioning and integration: the 132 kV max nominal voltage for $D^+$ beam was reached on January 2018 with very short RF pulses (20 µs/125 ms). Maximum power reached in CW was 60 kW. Until now the RFQ did not show any problem in terms of RF performances [3].

These partial results were nevertheless enough to start RFQ beam commissioning phase B1, consisting in the acceleration of a pulsed proton beam up to 2.5 MeV. On June 13th first proton beam was successfully accelerated through the RFQ. Beam operation continued until August 10th despite some trouble in one RF power supply which was then bypassed by operating with 7 over 8 RF chains only.

## LIPAC CONFIGURATION

The accelerator configuration for beam commissioning of LIPAc RFQ is shown in Fig. 2. LEBT optics includes two solenoids (Sol#) with integrated steering magnet pairs (ST#). Diagnostics include Doppler-Shift Spectroscopy, a 4 grid analyser, an Allison-Scanner, a beam stop, two CCD beam profile monitors. Three cm before RFQ matching point, there is LEBT-ACCT. RFQ input plate includes an electron repeller (-3 kV). Cavity is maintained at $10^{-8}$ mbar vacuum level by 10 cryo-pumps. For RFQ beam characterization, MEBT is equipped with an ACCT just after the gate valve separating it from the RFQ, a Fast Current Transformer (FCT) and 4 BPM's. Diagnostic-Plate next to MEBT includes 3 BPM's, 2 Slits combined with SEM-Grids for profile and emittance measurement, an ACCT-DCCT, a Residual Gas Bunch Length Monitor (RGBLM), a Fluorescence Profile Monitor (FPM) and an Ionization Profile Monitor (IPM). Lastly, a Low Power Beam Dump (LPBD) is used as Faraday Cup.

In this first beam commissioning period, profile diagnostics and Doppler-Shift diagnostic were not operational yet. Hence, results presented in the following are based on the ACCTs, LPBD and BPMs diagnostics.

## COMMISSIONING PLAN AND SIMULATIONS

Beam operation represents the first integrated test of LIPAc systems. In the followed approach, beam intensity was gradually increased while verifying and debugging each sub-system and their interfaces. This constitutes a safe operation mode with respect to starting directly at nominal proton current (65 mA). Low current and so low power beam operation allows using interceptive diagnostics while increasing RFQ acceptance with respect to the input mismatch.

For a better extraction conditions at low currents, injector was equipped with a 3 mm radius extraction hole instead of the original 6 mm.

* The views and opinions expressed herein do not necessarily reflect those of the author's home institutions or research funders.
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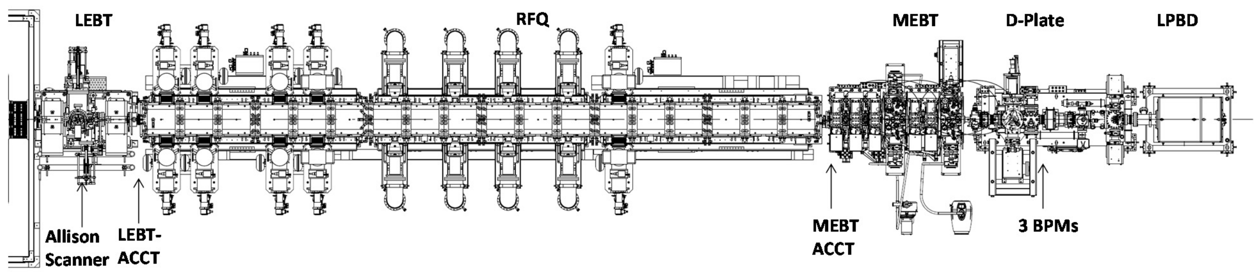


Figure 2: LIPAc configuration showing main systems and diagnostics mentioned in this paper.

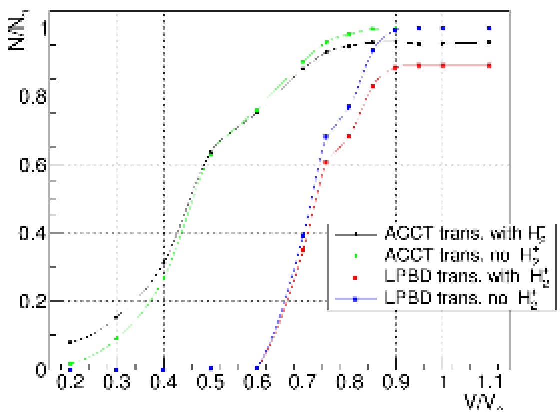


Figure 3: simulated transmission trough RFQ with/without contaminants for 8 mA input current [4].

Commissioning began in a pulsed low–power mode defined by: repetition rate = 1 Hz, injector RF pulse = 1.3 ms, RFQ RF pulse = 500 µs, beam chopper pulse = 300 µs, and injected beam current = 7 mA.

The MEBT quadrupoles (one triplet and one doublet) were set as for the matched beam, and as further protection for equipment, two scrapers at the MEBT input are both placed to a square of 20 mm side seen by the beam.

Performances of the RFQ were reproduced with an advanced simulation model of the system [4], which contains the measured geometry of the cavity and the voltage profile obtained from bead-pull measurements. Simulations were particularly useful in order to interpret effects of the input conditions and effects of contaminants on RFQ transmission (Fig. 3).

Once performances of subsystems were verified, commissioning was focused on beam current increase up to the maximum current obtainable with the 3 mm hole extraction electrode ($I_{extr}$=40 mA), without changing pulse length or period.

## EXPERIMENTAL RESULTS

### *Transmission Optimization*

For the very first injection, on June 13th, the RFQ was in amplitude open-loop, with voltage oscillating between 70-75 kV. Source total extracted current was 13 mA with a large $H_2^+$ contamination. With LEBT magnets at nominal values, no beam was extracted from RFQ.

After some manual LEBT adjustment, the following results were obtained: LEBT-ACCT = 5.3 mA, MEBT-ACCT = 1.7 mA (30% transmission), LPBD = 1.2 mA (20% transmission). LEBT magnets were set as: Sol1 = 90A (nominal), Sol2 = 155A (nominal=186A), ST1Hor = 0, ST1Ver = 40A, ST2Ho r= 0, ST2Ver = 0.

This was the first clue of a strong misalignment of the accelerator column and LEBT with respect to the RFQ input. Weaker Sol2 value allows filling the RFQ acceptance compensating misalignment effects, taking advantage of the increased RFQ acceptance for low current beam.

Operations were then stopped and a script for automatic scan of the 6 LEBT magnets was prepared to allow the systematic study of RFQ transmission towards LPBD, in function of input parameters.

We restarted operation on June 15th with RFQ in amplitude close-loop at voltage 70 kV. After running the scan routine only on LEBT ST1 and ST2, (solenoids set at nominal values, we obtainined the following transmission results: LEBT-ACCT = 7.4 mA, MEBT-ACCT = 6.3 mA (85%), LPBD = 5.4 mA (72%), with LEBT magnets: Sol1 = 90A (nominal), Sol2 = 186A (nominal), ST1Hor = -20A (saturated), ST1Ver = 80A, ST2Hor = -20A, ST2Ver = 20A (saturated).

Photon radiation measurements confirmed that protons with energy larger than 2.4 MeV impinged on copper.

The same procedure was repeated for different current values. Results are reported in Table 1.

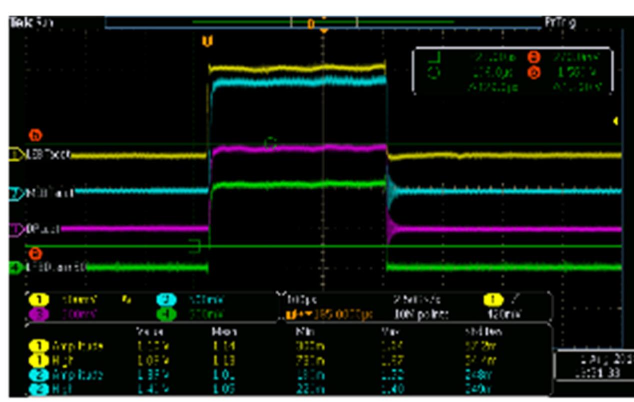

Figure 4: current signals at different points of the LIPAC for $I_{extr}$=30 mA. ($V_{scope}$~50 Ω·$I_{beam}$; only for the MEBT-ACCT $V_{scope}$~67 Ω·$I_{beam}$)

We observed that:

- The proton fraction at the RFQ input was unknown and the RFQ itself could transmit some contaminants that could not reach LPBD (Fig. 3). So we tried to maximize the transmission to LPBD.

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Table 1: Transmission values at different extracted currents. Marked magnets are saturated* or temporarily out of order†. Some inconsistency of current measurements. (i.e. MEBT < LPBD).

| $I_{extr}$ (mA) | ε (π mm.mrad) | LEBT (mA) | MEBT (mA) | LPBD (mA) | Sol1 (A) Exp/Sim | Sol2 (A) Exp/Sim | Steerers |
|---|---|---|---|---|---|---|---|
| 13 | 0.09 | 6.6 | 6.3 (95%) | 5.8 (87%) | 130/90 | 180/186 | H1*=-20A, V1=107A, H2†=0A, V2*=20A |
| 20 | 0.10 | 9.8 | N.A. | 9.4 (96%) | 130/140 | 177/153 | H1*=-20A, V1=105A, H2†=0A, V2=0A |
| 30 | 0.14 | 21.7 | 20.6 (95%) | 20.9 (96%) | 135/137 | 160/145 | H1*=-20A, V1=75A, H2†=0A, V2*=-20A |
| 35 | 0.12 | 27.0 | 25.0 (93%) | 25.7 (95%) | 140/137 | 148/145 | H1*=-20A, V1=65A, H2=-8A, V2=-10A |
| 40 | 0.20 | 29.3 | 25.8 (88%) | 26.1 (89%) | 137/N.A. | 151/N.A. | H1*=-20A, V1=63A, H2=-10A, V2=-10A |

- The experimental reference emittance measured between two solenoids in order to match RFQ input should be ε ≤ 0.15 π mm*mrad. The point at $I_{extr}$=40 mA has a larger emittance and may have a consequent lower transmission due to emittance growth at the RFQ injection point [5].
- At very low current the fraction of $H_2^+$ extracted is larger as well as the acceptance of the RFQ for $H_2^+$. This explains the losses in the MEBT at $I_{extr}$=13mA, consistently with simulations (Fig. 3).
- The misalignment effects (Sol1 and STV1&2) decreases with increasing current, due to the different value of the source intermediate electrode.

### Voltage and Transmission

We measured the RFQ transmission as a function of the RFQ Field Amplitude for different input currents listed in Table 1 and we compared them to the simulated RFQ transmission for 24 mA input current (Fig. 5).

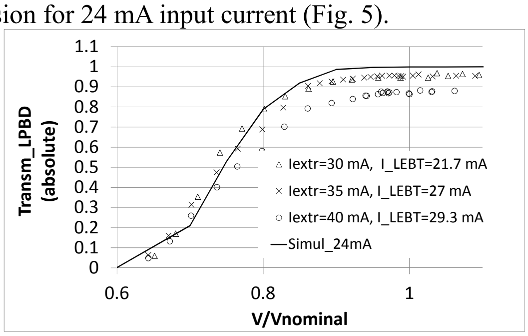


Figure 5: Absolute LPBD transmission vs RFQ voltage.

According to simulations [6], RFQ and MEBT transmission should be 100%, for proton currents up to 30 mA. Our hypothesis to explain the discrepancies shown in Fig.5 is the combination of:

- Presence of contaminants at LEBT-ACCT (Fig. 3);
- Residual misalignment at RFQ input (due to steerer saturation);
- Emittance at RFQ input (see Table 1, $I_{extr}$=40 mA).

By rescaling transmission data to maximum value, superimposition to simulation results is possible. This comparison, shown in Fig.6, confirms the expected trend.

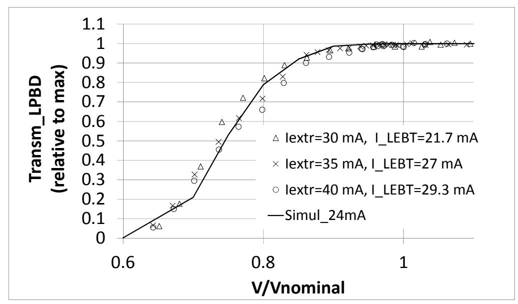


Figure 6: Relative transmission to LPBD vs RFQ voltage.

### Output Energy Measurements

The Time of Flight measurement between the three D-Plate BPMs was performed with oscilloscope. The signals are two shifted sine waves at 175 MHz. We measured the time $\delta t_{kj}$ between two adjacent peaks. Since the pulse rising edge is not sharp, we cannot determine the correspondence between bunch and signal peak. Nevertheless considering two measurements with cables swapped ($\delta t_{kj}$ and $\delta t_{jk}$), the cable delay contribution is removed [7].

Table 2 shows that the 2.5 MeV output energy protons is confirmed with an error of 1%.

Table 2: Result of ToF Measurements.

| | Distance (mm) | $\delta t_{kj}$ [ns] | $\delta t_{jk}$ [ns] | Energy [MeV] |
|---|---|---|---|---|
| BPM1-2 | 155.8 | 4.07 | 4.39 | 2.52 |
| BPM1-3 | 1265.3 | 3.13 | 4.71 | 2.48 |

## CONCLUSIONS AND PERSPECTIVES

This first month of RFQ beam commissioning confirmed the expected performances of the RFQ in terms of beam transmission and energy and this is an encouraging result. After the maintenance and realignment of the injector as well as the recovering of the profile diagnostics we should be able to have more significant comparisons with simulations after resuming the operation by the end of this year. In the meantime RF conditioning should continue up to 132 kV-CW to demonstrate the full characteristics of the cavity.

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