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IFMIF/EVEDA RFQ BEAM COMMISSIONING AT NOMINAL 125 mA DEUTERON BEAM IN PULSED MODE

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Abstract

In summer 2019 the IFMIF/EVEDA Radio Frequency Quadrupole (RFQ) accelerated its nominal 125 mA deuteron (D+) beam current up to 5 MeV, with 90% transmission for pulses of 1 ms at 1Hz. The Linear IFMIF Prototype Accelerator (LIPAc) is a high intensity D+ linear accelerator; it is the demonstrator of the International Fusion Material Irradiation Facility (IFMIF). In particular the RFQ is the longest and most powerful ever operated. An intense campaign of measurements has been performed in Rokkasho to characterize several performances of this complex machine: transmission, emittances, energy spectrum and beam loading. The history and the results of the commissioning until this important project milestone are here described. An overview of the foreseen activities to be carried out to reach the CW operation is also presented.

INTRODUCTION

The LIPAc RFQ is a CW linac, capable of delivering 125 mA of D+ beam at 5 MeV. The 10-m long, 175 MHz cavity is designed to accelerate a DC 100 keV, 130 mA D+ beam from the injector with transmission > 90% [1].

RFQ is installed in Rokkasho (Fig. 1) since April 2016. The low power RF characterization 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 cooling system and to the 8 RF systems, RF conditioning started in July 2017 (Fig. 2). After a first period where some hardware and integration problems have been faced, in Spring 2018 the RF operation concentrated to stabilize the conditions for the proton beam injection [2]. In June 2018 first proton (H+) beam was successfully accelerated through the RFQ [3]. After maintenance, conditioning restarted in February 2019 (Fig. 2) with the goal of reaching the conditions to accelerate D+ [4]. First D+ injection was possible in March 2019, then we reached in July 132 kV-2.5 ms-20 Hz and in July 24th we achieved a 125 mA D+ current at 1 ms/1 Hz out the RFQ, with transmission>90% (Fig. 3).

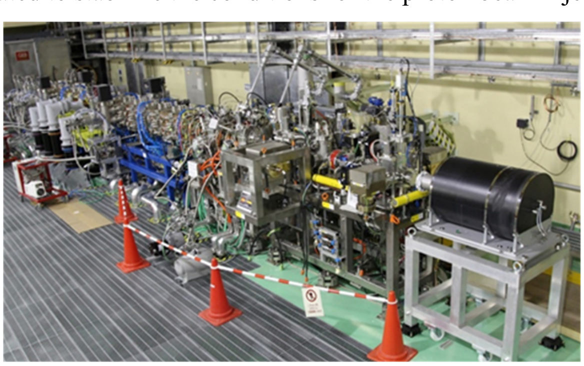

Figure 1: IFMIF/EVEDA LIPAc in Rokkasho.

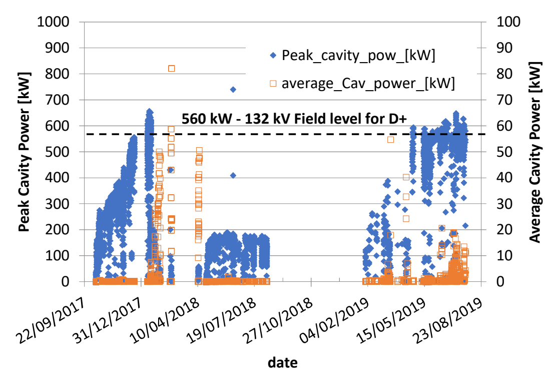

Figure 2: RF history of the RFQ (Sep. 2017 – Aug. 2019).

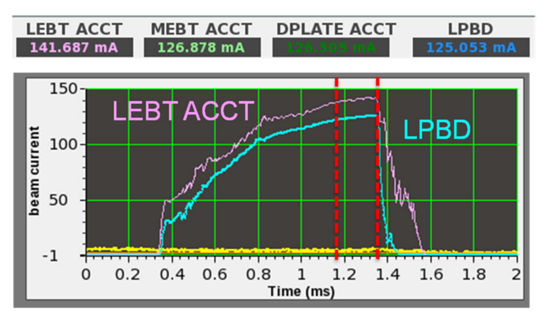

Figure 3: Image of the 125 mA D+ beam transmitted to the Low Power Beam Dump (LPBD).

LIPAC CONFIGURATION

The configuration for beam commissioning of LIPAc RFQ is shown in Fig. 4. 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 from RFQ matching point, there is LEBT-ACCT. RFQ input plate includes an electron repeller (-3 kV). Cavity is maintained at 10^{-8} mbar vacuum

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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 BPMs. Diagnostic-Plate (D-Plate) next to MEBT includes 3 BPMs, 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). Low Power Beam Dump (LPBD) is used as Faraday Cup.

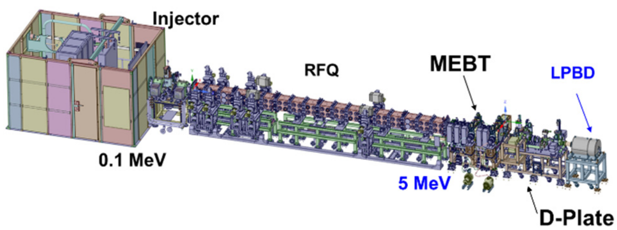

Figure 4: LIPAc configuration showing main systems.

CRITERIA AND PROCEDURE FOR RFQ INPUT BEAM

The beam injection into the RF has been prepared in the previous years by a detailed characterization of the Ion Source (IS) and LEBT beam [5]. The Twiss parameters were measured moving the Allison Scanner at the IS exit, between the 2 Sol# and after the RFQ injection cone. The large number of measurements have been used to benchmark a model of the line, based on WARP for space charge compensation patterns and LEBT transport, IBISIMU for the IS extraction, Tracewin for matching routines and outputs and Toutatis for the RFQ model "as built", i.e. containing mechanical and voltage errors measured on the real cavity.

Since during RFQ operation the Allison Scanner would be located in the box between the two LEBT Sol#, we wanted to determine a fast experimental criteria to define if a certain IS beam is acceptable for the RFQ injection, looking to the emittance just after Sol1.

The practical result is that, in order to limit the emittance growth in the second half of the LEBT for any couple of Sol#, the emittance after Sol1 must be $\varepsilon < 0.2\ \pi$ mm mrad normalized rms (Fig. 5). This should ensure a transmission of at least 90% accelerated particles through the RFQ at full current. It should be noticed here that in 2018 [6] we reported 0.15 π mm mrad as limit for RFQ input match; a successive analysis showed that this number was affected by an error on the Allison Scanner gap that caused underestimation of the emittance [5].

After the first H+ beam injection, the procedure applied to each RFQ injection point has been:

1. Study of the point at the injector level, in particular check if the emittance between the two Sol# is compliant with the criteria
2. Solenoid set to theoretical value.
3. Rough ST# optimization, to maximize LPBD current.
4. Sol# scan and ST# refinement with a dedicated routine.
5. Slight MEBT quadrupoles tuning.

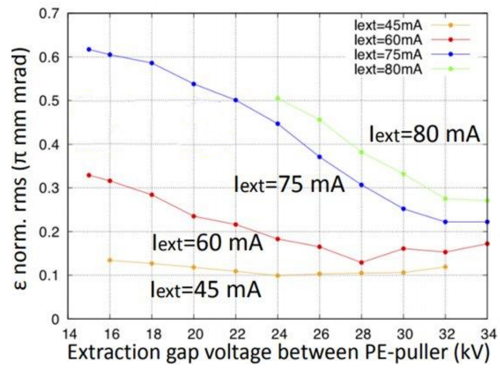

Figure 5: Limit for the emittance between two Sol#, here for H+ as function of the voltage between plasma electrode (PE) and puller electrode.

BEAM COMMISSIONING RESULTS

We report now some significant results of the H+ and D+ beam campaigns.

A technical problem limited the use of the chopper for the high current D+ experiments (Summer 2019). Therefore, we injected the full un-chopped IS pulse into the RFQ. Because of the LPBD power limit, the IS beam pulse was kept around 1.3 ms. Normally, high perveance operation from the IS requires pulse of at least 3 ms, in order to have a stable plasma at the end of the pulse. Two main effects follow such short, un-chopped pulse:

- The IS pulse was unstable. Therefore, the current was oscillating with a σ = 2 mA, increasing the error on the current measurements.
- The D+ fraction was around 80%, lower than the nominal IS tuning, where D+ ≈ 90 % for IS pulses > 3 ms. This caused an overestimation of the current at the RFQ input, given by the presence of other molecular species extracted from the IS.

These two experimental uncertainties are taken into account on the transmission calculation and they are as well applied to the assumptions withstanding the simulations.

Moreover, because of the chopper unavailability with high D+ currents in this campaign, the D-Plate emittance measurement unit was not usable with such a long pulse. For the RFQ emittance analysis we report the results for H+ at 1/3 perveance of the beam (23 mA, 2.5 MeV) [6].

Transmission vs. Voltage Curve

The Transmission-Voltage curve is a key characteristic to validate the RFQ design. The current transmission is given between RFQ Input (I_{LEBT}) and the LPBD (I_{LPBD}), in order to use the MEBT quadrupoles as filters for off-momentum particles. Such measurement scans the longitudinal and transverse dynamics of the RFQ, supplying a good insight of the machine performances.

Before scanning the RFQ voltage, input conditions are optimized looking for the values of LEBT Sol# and ST# that maximize I_{LPBD} (Fig. 6). Three points of the Sol# scan at I_{LPBD} = 125 mA have been simulated, showing a good agreement with measurement (Table 1). The higher error

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of point 1 of Table 1 (10%) is due to the larger approximation of the LEBT model, when describing beams with important losses on the metallic walls of the line.

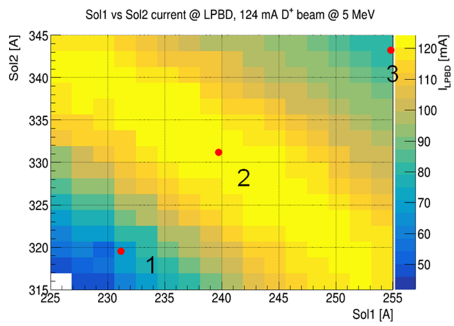

Figure 6: I_{LPBD} as function of Sol1/Sol2 currents, for I_{LEBT}=137 mA D+.

Table 1: Sim./Meas. Comparison of the Sol Scan in Fig. 6

Sol1-Sol2 point	ILPBD meas. ILEBT = 137±2 mA	ILPBD sim. ILEBT = 135 mA
1	82 mA	86±8 mA
2	124 mA	122.5±0.5 mA
3	64 mA	70.5±0.5 mA

Figure 7 shows the RFQ transmission-voltage scan for three different H+ currents compared with simulation of 24 mA H+ beam current, recorded in Summer 2018 and described in [7]. We only observe here that:

- small discrepancies at I_{LEBT}=21.7 mA and 27 mA are due to contaminant species at RFQ input;
- The larger discrepancy for I_{LEBT} = 29.3 mA is due to the non-compliancy of the input conditions with the criteria of 0.2 π mm mrad.

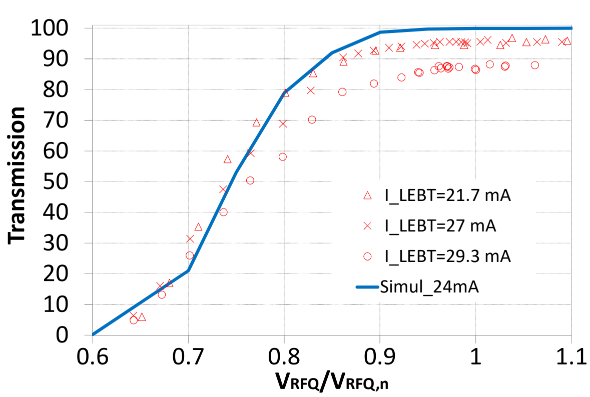

Figure 7: Transm.-Voltage curve for some H+ beams.

Figure 8 shows transmission-voltage scan for D+ beam at I_{LEBT} = 137 mA, performed with input conditions reported at point 2 of Table1. Simulation error are calculated by uncertainties of the input values used, for example slightly variations on the beam input current and Twiss parameters that can in any case fit the experimental data. The experimental results are compatible with the model.

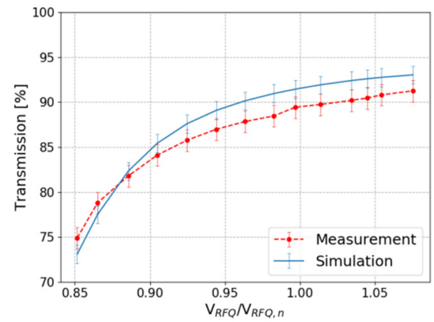

Figure 8: Transm.-Voltage curve for 125 mA D+ beam.

Beam Time of Flight (TOF)

Energy of first H+ beam campaign was measured with bunchers off and detuned. The TOF between the three D-Plate BPMs was performed with oscilloscope. In absence of re-bunching, the bunches spread in phase at D-Plate position, but a structure was still present and the BPM signals were three shifted sine-like waves at 175 MHz. From phase differences we obtained an energy of 2.5 MeV within 1% error [7]. For the D+ campaign we calibrated and processed the BPM's acquired data, and the measurements were done with bunchers operative [8]. The data in Fig. 9, plotted as function of the RFQ voltage, give an output energy of 5.0 MeV within 1% error.

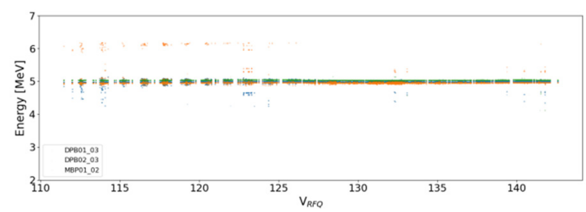

Figure 9: D+ TOF energy from different pairs of BPMs of the D-Plate and MEBT as function of the RFQ voltage.

The TOF measurements gave also an interesting result observed during the voltage scan of the RFQ (Fig. 10): the beam energy oscillates in a range of 20 keV as function of the cavity voltage. This effect can be linked to a slight RFQ input beam energy offset, that causes a synchrotron oscillation of the bunch inside the separatrix and around the nominal energy point. The amplitude of the oscillation is compatible with an injection energy 0.7 keV – 1 keV higher than nominal input energy. The effect shall be furtherly explored after the activity restarts.

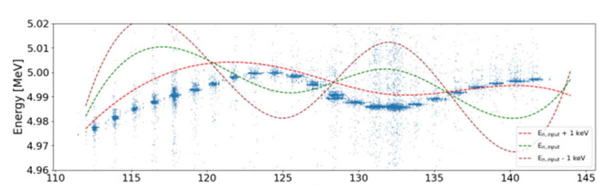

Figure 10: ToF for D+s as a function of RFQ voltage.

RFQ Beam Loading

The beam loading calculation, applied to the RFQ as a multicell cavity for 125 mA D+ (or 62.5 mA H+), gives

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+8.1 kHz detuning to be at resonance with beam. The calculations are based on the following definitions (where *i* is the cell index):

- Effective synch. phase $\phi = atan\frac{\sum_i V_i T_i sin\phi_i}{\sum_i V_i T_i cos\phi_i}$
- Effective acc. voltage $|\widetilde{V_c}| = \frac{\sum_i V_i T_i cos\phi_i}{cos\phi}$
- Effective shunt impedance $r_s = |\widetilde{V_c}|^2/P_{Cu}$

Beam operation is only possible at f_{RF} = 175 MHz, thus we measured the beam loading through two indirect effects on the forward (FWD) phase and cavity phase, compared with calculations. The experimental steps were (Fig. 11):

1. Tuning of the cavity ($f_{RF} = f_{CAV}$ = 175 MHz), adjusting the cooling water temperature to maximize the cavity voltage at 175 MHz;
2. In close loop ($f_{RF} = f_{CAV}$ = 175 MHz), measurement of FWD phase correction required at beam entrance, to be compared with $\Delta\varphi = atan\left(\frac{V_c \sin(\varphi)}{V_c\cos(\varphi)+V_b}\right) - \varphi$;
3. In amplitude and phase open loop ($f_{RF} = f_{CAV}$ = 175 MHz), measurement of the beam induced phase in cavity voltage, compared with $\Delta\psi = atan\left(-\frac{I_{beam} r_s \sin(\varphi)}{V_c(1+\beta)}\right)$.

These measurements of beam detuning include more sources of errors, with respect to the direct frequency measurement, for example a slight drop of the cavity voltage can occur in the open loop measurement. The results are satisfactory in a large range of currents (Fig. 11).

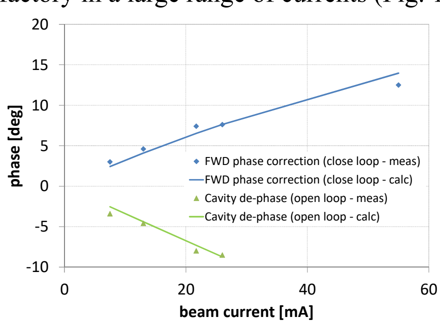

Figure 11: Beam loading induced de-phase for different H+ currents (Sim/Meas). In open loop it was impossible to measure the 55 mA H+ current because of the significant RFQ voltage drop induced by the beam.

Transverse Emittances Downstream of the RFQ

For the nominal D+ beam currents, the un-chopped IS pulse length (1.3 ms/1 Hz) overcomes the power limitation of the D-Plate slits, used for the transverse emittance measurements after the RFQ (limit = 100 µs/1 Hz at 125 mA). Then, it was impossible to measure the transverse emittance for such current. However, a benchmark measurement was performed for 22 mA of 2.5 MeV H+ beam (1/3 of the nominal perveance, equivalent to 41.6 mA of D+). Figure 12 shows an example of the reconstructed phase spaces after RFQ, simulated and measured. Table 2 shows some values of benchmarked emittances with respect to RFQ voltage and LEBT Sol#. An overall good agreement is achieved, showing that the emittance and the Twiss parameters are reproducible by the integrated simulation model (LEBT, RFQ, MEBT).

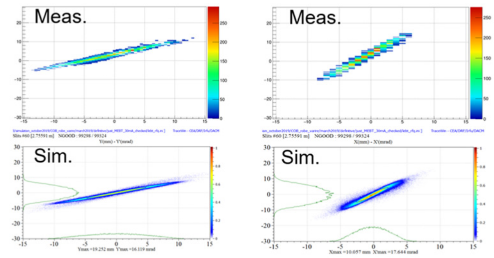

Figure 12: H+ simulated and measured emittance for xx' and yy' plane after RFQ (point 3 of Table 2).

Table 2: Sim./Meas. Comparison of RFQ H+ Emittances

Point	1	2	3	4	5	6
Sol1 [A]	131	135	135	135	135	135
Sol2 [A]	162	162	160	160	160	160
VRFQ [kV]	70	70	70	66	66	62
ILPBD [mA]	22.1	22.0	22.8	21.8	22.4	21.8
εexp/εsim [π mm mrad]	0.24 /0.28	0.22 /0.23	0.23 /0.23	0.24 /0.24	0.24 /0.24	0.24 /0.24
βexp/βsim [mm/π mrad]	6.5 /6.0	6.6 /6.3	6.9 /6.1	7.1 /7.5	7.0 /7.0	8.0 /8.1
αexp/αsim	-4.4 /-4.5	-4.3 /-4.3	-4.6 /-4.6	-4.8 /-5.5	-4.7 /-5.0	-5.4 /-6.0

CONCLUSIONS AND PERSPECTIVES

The results obtained up to now show that the RFQ works as designed, with good agreement between simulations and measurements: transmission-voltage curve, beam loading calculation, LEBT Sol# scan and RFQ transverse emittances are reproducible and benchmarked.

In future pulsed mode operations, we need to measure:

- the transverse emittance for the nominal beam intensity, with chopper now repaired;
- the longitudinal emittance;
- the x/y profiles at the nominal beam intensity.

After these last pulsed beam tests, it is essential to run the RFQ in CW mode in order to fully demonstrate its performances in terms of RF and thermal stability and verify the effects on the cavity when subjected to long run CW beam operation.

The maintenance from September 2019 to February 2020 has been dedicated to an important upgrade of the RF system in order to improve the conditioning of the cavity to CW RF operation. Moreover a dedicated beam transport extension has been installed after the MEBT (Fig. 13). The purpose of this line is to fully characterize the RFQ before installing the Superconducting Linac. The D-Plate has been shifted ahead, the HEBT is now installed and the LPBD is now replaced by the High-Power Beam Dump, able to receive up to 1.12 MW beam power.

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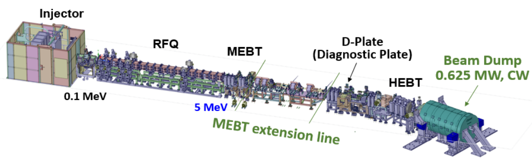

Figure 13: the present configuration (April 2020) of the IFMIF/EVEDA installation in Rokkasho.

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