COMMISSIONING OF THE LINAC4 RFQ AT THE 3 MeV TEST STAND

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Abstract

Linac4, the future 160 MeV H^- injector to the CERN Proton Synchrotron Booster, is presently under construction at CERN as a first step of the planned upgrade of the LHC injectors. The low energy section of LINAC4, consisting of an ion source, a 352.2 MHz Radio Frequency Quadrupole (RFQ) and a chopper line is being commissioned in a dedicated test stand before installation in its final position in the tunnel. The RFQ is designed to accelerate a 45 keV, 70 mA, H^- beam to 3 MeV, with an efficiency of 95% while preserving the transverse emittance. The RFQ, a four-vane structure 3 m in length, has been designed in collaboration with CEA/IRFU and is has been fabricated at the CERN workshop. The precise fabrication has allowed achieving a field flatness of 1%. The completion of the accelerating structure in September 2012 was followed by a complete series of bead-pull measurements and by high-power conditioning to the nominal power of 0.39 MW corresponding to a voltage of 78 kV across the 3 meters. Measurements with beam are taking place during the first half of 2013.

This paper reports the results of the low-power and high power RF commissioning as well as the status of beam measurements.

INTRODUCTION

The fabrication of the Linac4 RFQ started in 2009 at CERN soon after the beam dynamics and RF studies were completed and the Engineering Specification report was issued [1]. The RF commissioning started at the 3 MeV Test Stand about four years later, in February 2013.

Figure 1 shows the RFQ accelerator installed and ready for beam tests.

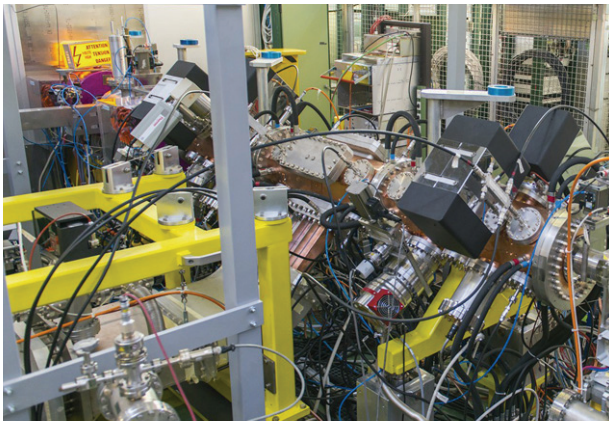

Figure 1: The Linac4 RFQ at the 3 MeV Test Stand.

A 2-solenoid Low Energy Beam Transport (LEBT) is installed between the ion source and the RFQ; the RFQ is followed by a dedicated beam diagnostics line containing Beam Current Transformers (BCT), Beam Position Monitors (BPM), profile scanners, a spectrometer and other diagnostic devices [2].

The RF operational parameters of the RFQ after the final tuning are reported in Table 1.

Table 1: RFQ Final Parameters

Parameter	Value	Unit
Operating frequency	352.2	MHz
Inter-vane Voltage	78	kV
Kilpatrick factor	1.84	-
Unloaded Quality factor	6700	-
Cavity Coupling factor β (without beam)	1.59	-
Total dissipated RF Power (without beam)	390	kW

RFQ TUNING AND RF COMMISSIONING

After completion and assembly of the RFQ in August 2012, the accelerating field was adjusted and the RF power coupler defined and built to achieve the appropriate coupling of the RF generator to the accelerating structure for a 70 mA beam current. Details concerning the tuning of the RFQ structure and the power coupling are presented in a companion paper [3].

RF Tuning

The final tuning consisted of a series of bead-pull measurements to define the penetration of the 35 pistons and of the RF power coupler that were adjusted to obtain a flat quadrupole field profile within ±1% of nominal.

Figure 2 shows the capacitance error profile of the accelerating field along the three-meter structure with final copper tuners in place.

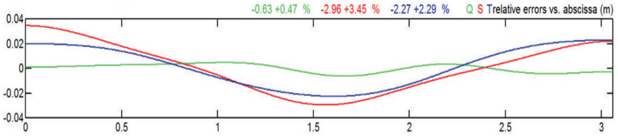

Figure 2: Capacitance errors for quadrupole (QQ, green trace) and dipole modes (SQ and TQ, red and blue traces respectively) in the RFQ structure.

A residual 3% content of dipole mode was measured after the installation of the final tuners, originated by the discrepancy between test and definitive tuners. It is foreseen to correct it when the RFQ will be transferred to its final location in the Linac4 tunnel.

RF Commissioning

The RF commissioning started on February 22nd, 2013 and progressed quite fast up to the nominal accelerating field level. The repetition frequency was set at the Linac4 value of 1 Hz and the RF pulse length to 250 µs, half the nominal 500 µs, sufficient for accelerating the 200 µs H^- beam pulse produced by the Test Stand ion source. The nominal field was reached after about 80 hours of conditioning, while after other 4 hours of conditioning the RFQ was stable at 108% higher voltage.

The behaviour of the vacuum in the accelerating cavity (violet) and in the RF coupler (green) during a typical conditioning session are shown in Figure 3. The traces show the vacuum activity produced by each pulse and the recovery from a breakdown event.

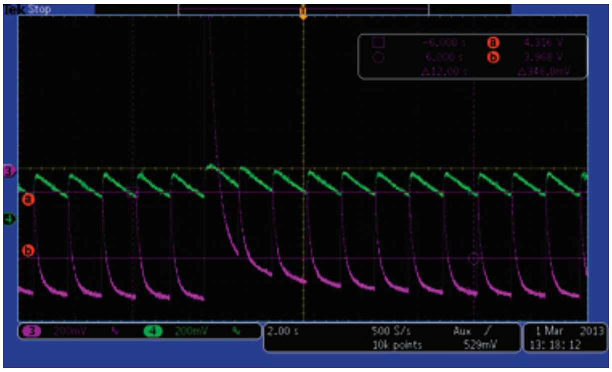

Figure 3: Vacuum level in the RFQ cavity (violet) and in the RF coupler (green).

The effect of the RF conditioning is visible also on the mass spectrum of the residual gas in the RFQ (Figure 4).

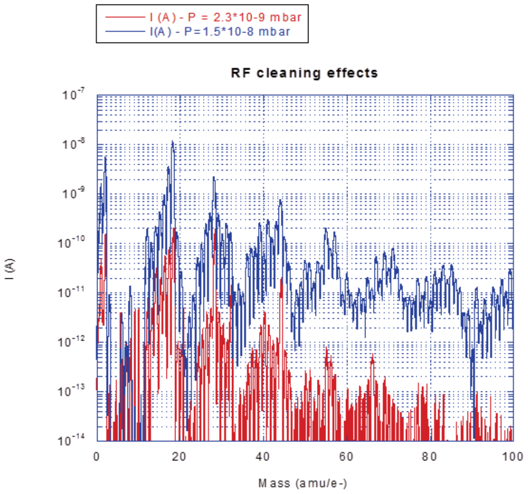

Figure 4: Mass spectrum of the residual gas in the RFQ cavity measured before (blue trace) and after (red trace) three weeks of RF conditioning.

In Figure 4 the heaviest masses are considerably reduced after three weeks of RF operation (red trace). The peaks associated to well-defined masses reveal the presence of a small leak in correspondence of one of the RF pick-ups, which was hidden in the background during the first leak detection.

RFQ BEAM COMMISSIONING

During January and February 2013 the Test Stand operation was dedicated to the characterization of the H^- beam at 45 keV.

A slit-and-grid emittance meter was located after the first solenoid and measurements for different source tuning, varying solenoid settings and varying gas pressure in the LEBT, were taken.

Finally the settings providing a 16-18 mA H^- beam over for a duration of 200 µs were retained. The emittance of the beam turned out to be higher than the nominal one (0.25 π mm mrad rms) and an optimised beam matched at the RFQ turned out to exceed the zero current RFQ acceptance by 15%. An algorithm to reconstruct the beam distribution from emittance measurement, developed especially for Linac4, has been used to find the optimised solenoid settings for matching to the RFQ and no further empirical optimisation was necessary.

Once the RFQ RF conditioning and the 45 keV beam characterization were completed, the second LEBT solenoid was installed, the RFQ and diagnostics test bench connected and the RFQ beam commissioning could start.

The first beam was successfully transported through the RFQ and accelerated to 3 MeV on March 13th.

Beam transmission was measured by comparing BCT readings on the monitors located upstream and downstream of the RFQ and cross-checked with BPM intensity readings. A beam transmission of 75% was measured at nominal RFQ settings (equivalent applied RF power of 390 kW at standard pressure of $5 \cdot 10^{-8}$ mbar), with very good agreement between measurements and simulations.

The transmission through the RFQ was measured also as a function of the applied RF power and compared to simulations. The results are shown in Figure 5.

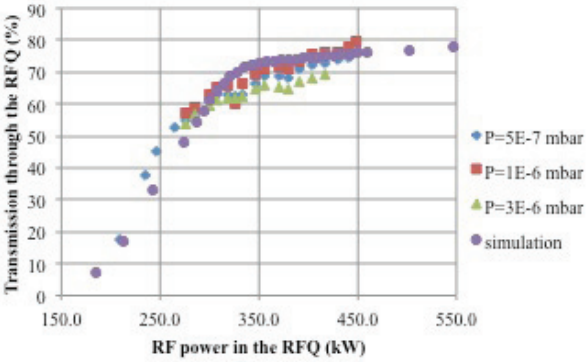

Figure 5: RFQ beam transmission as a function of the RF power and with different H_2 gas pressure in the LEBT.

The measured transmission is lower than the 95% RFQ design value due to the emittance produced by the H^- source.

The LEBT H_2 gas pressure was changed to study the effect of space charge neutralisation at low energy on the matching. For each pressure a different setting of the LEBT solenoid had to be applied to rematch the beam and to recover the transmission. The best results were obtained for a pressure in the LEBT of $1\cdot10^{-6}$ mbar. The phenomenon of space charge neutralization in the LEBT necessitates further studies.

The diagnostic bench after the RFQ is equipped with a 28 degrees bending magnet for spectrometry. Although the energy spread could not be measured due to a technical problem with the spectrometer profile, it could nevertheless be verified that 95% of the outcoming beam is at the correct energy, by measuring the beam intensity in a beam current transformer after the bending.

Two different techniques were then used to measure transverse beam profiles: in one case by scraping the beam using the slit blade and in the other by moving the slit aperture through the beam and by directly measuring the transmitted current. Results agree fairly well when compared to each other and with simulations.

DIAGNOSTIC LINE COMMISSIONING

A large fraction of the commissioning with beam consisted in the commissioning of the beam instrumentation in the diagnostics line [3]. The two Beam Current Transformers, equipped with a 10 MHz readout electronics, were used to characterize the transmission along the line as well as through the RFQ, by comparison to the LEBT BCT. The transformers were also used during slit scans to reconstruct the transverse beam profiles by monitoring the current passing through the slit aperture, as in Figure 6.

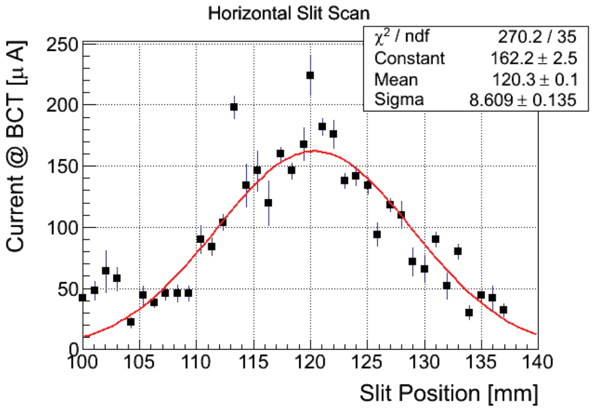

Figure 6: Beam profile during a slits scan, measuring the beam current passing through the slit 200μm gap.

The three Beam Position Monitors are meant to measure i) the absolute beam position, ii) the relative beam current among monitors, iii) the absolute beam current after calibration with the BCTs, and iv) the average beam energy via the time-of-flight between two monitors. The systems are based on strip line detectors [4]. So far the relative beam intensity was calibrated w.r.t. BCTs, as shown in Figure 7, and the beam position data analyzed to reconstruct the beam trajectory in the line.

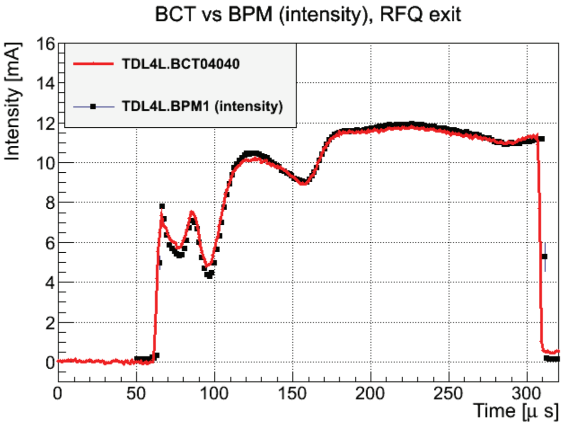

Figure 7: H^- beam current as measured by BCT and BPM, after cross-calibrating the BPM intensity signal to the BCT.

CONCLUSION

The fabrication and assembly of the Linac4 RFQ in 2012 was followed by the beam commissioning during the first months of 2013. In spite of difficulties with the characterization of the RFQ transfer function due to the characteristics of the H^- beam delivered by the ion source, a precise enough definition of the beam parameters was obtained at the RFQ output; the measurement program is now progressing at the 3 MeV Test Stand with the installation and testing of the chopper system, a crucial device for the operation of the Linac4 as injector, and with the progressive commissioning of all diagnostics equipment.

The very first measurements have already demonstrated that the chopper system is able to completely chop the beam sent into the line; the test was performed by chopping 100 μs of a 250 μs beam pulse.

After the completion of the beam measurements, at the end of May, the Linac4 front end will be moved into the Linac4 tunnel where it will undergo its final commissioning.

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