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BEAM COMMISSIONING OF THE 750 MHz PROTON RFQ FOR THE LIGHT PROTOTYPE

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Abstract

ADAM (Application of Detectors and Accelerators to Medicine), a CERN spin-off company, is developing the Linac for Image Guided Hadron Therapy, LIGHT, which will accelerate proton beams up to 230 MeV. The design of the linac will allow fast intensity and energy modulation for pencil-beam scanning during cancer treatment. The linac consists of a 40 keV Proton Injector; a 750 MHz Radio Frequency Quadrupole (RFQ) accelerating the proton beam up to 5 MeV; a 3 GHz Side Coupled Drift Tube Linac (SCDTL) up to 37.5 MeV; and a 3 GHz Cell Coupled Linac (CCL) section up to 230 MeV. A prototype of LIGHT is being commissioned progressively with the installation of the accelerating structures at a CERN site. The beam commissioning of the RFQ, which was designed and built by CERN, was completed in 2017 using a movable beam diagnostic test bench with various instruments. This paper reports on the RFQ commissioning strategy and the results of the beam measurements.

INTRODUCTION

LIGHT is a normal conducting 230 MeV medical proton linear accelerator being constructed by ADAM. The linac structures up to 70 MeV are being installed in the ADAM test facility, at a CERN site, and being commissioned progressively with the increasing beam energy [1, 2].

The first accelerating structure of the LIGHT prototype, a 750 MHz Radio Frequency Quadrupole (RFQ) [3-5], which was designed and produced by CERN, accelerates the proton beam from 40 keV to 5 MeV in only 2 meters. The RFQ is being used as an injector to the subsequent 3 GHz linac section which has strict input requirements in terms of transverse and longitudinal beam emittance. Therefore, it was crucial to determine the RF amplitude set point of the RFQ within the tolerances and measure the output beam properties to ensure high injection efficiency from 750 MHz to 3 GHz.

MEASUREMENT SETUP

Figure 1 shows the layout of the linac during the beam commissioning of the RFQ at 5 MeV. As it can be seen from the figure, the diagnostic test bench was installed downstream of the Medium Energy Beam Transport (MEBT) where the RFQ and MEBT could be commissioned together. The MEBT houses two permanent magnet quadrupoles, two steering magnets, a beam position monitor (BPM) and an AC beam current transformer. Along with the diagnostic devices on the movable test bench, the permanent diagnostics on the MEBT were also used for the beam commissioning.

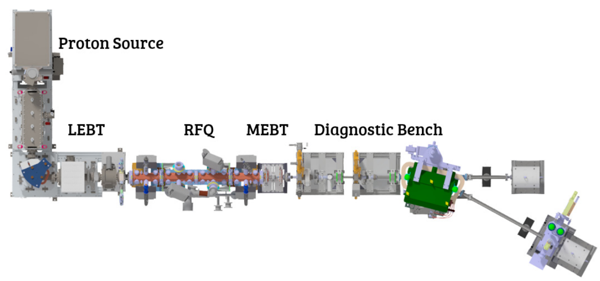

Figure 1: Layout of the LIGHT structures during the beam commissioning at 5 MeV.

Figure 2 shows the movable diagnostic test bench [6] and its components used for the beam commissioning. Each diagnostic box (Dbox) has vertical and horizontal slits followed by a Faraday Cup (FC) for beam profile and beam current measurements. The two Dboxes can be used together for transverse emittance measurements. The spectrometer line of the bench can be used for average energy and energy spread measurements (together with the electromagnetic quadrupoles). In addition, on the straight section of the test bench there are two BPMs, and three phase probes for the time of flight (ToF) measurements.

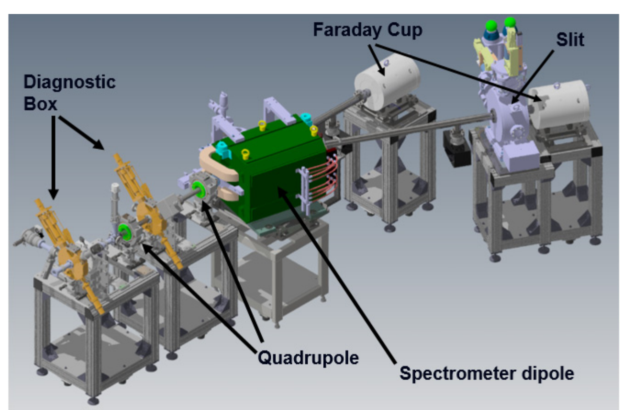

Figure 2: Diagnostic test bench with measurement instruments.

RFQ INPUT BEAM AND SIMULATIONS

The properties of the beam at the end of the Low Energy Beam Transport (LEBT) section was fully characterized during the source commissioning in 2016. The transverse emittance of the beam was measured 1 cm away

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from the RFQ entrance. A multi-particle beam was generated using the emittance measurement data and then tracked to the RFQ matching plane for the RFQ beam dynamics simulations. Figure 3 compares the RFQ transverse acceptance, 0.25 pi.mm.mrad (normalized at 40 keV), and the measured particle distribution of a beam carrying 250 μA at the RFQ matching plane.

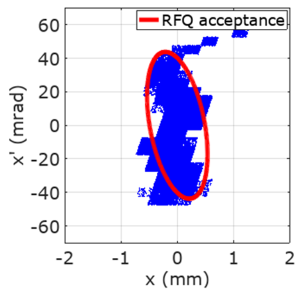

Figure 3: Measured beam distribution (blue) at the RFQ entrance and the RFQ acceptance ellipse (red).

During the design of the RFQ, the beam dynamics through the RFQ was confirmed with three independent codes [3,4], including particle tracking through the 3D field map. For the commissioning, RFQ beam dynamics simulations were performed with RF-TRACK [7] by simulating the particles through the 3D field map. Particle tracking in the LEBT, and in the diagnostic bench was performed by PATH Manager [8].

BEAM COMMISIONING RESULTS

In this section, the results of the beam measurements after the RFQ are presented along with the expected values from the simulations.

Characteristic Curve of Transmission

The calibration of the RF amplitude was confirmed by varying the field in the RFQ and measuring the transmission.

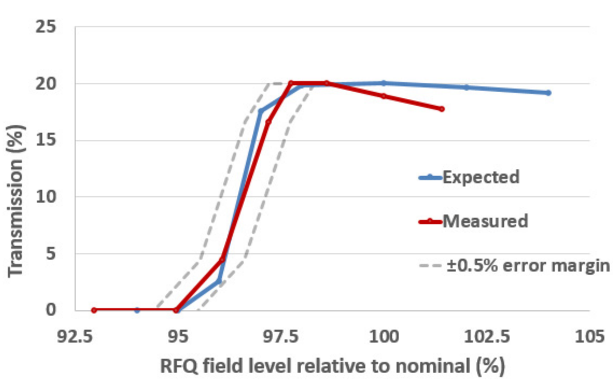

Figure 4: The expected and measured characteristic curve of transmission (only accelerated particles) of the RFQ. The dotted grey lines show the ±0.5% error margin in field relative to the measured curve.

Figure 4 shows the expected and measured curves of transmission (only accelerated particles) vs. RF field in the RFQ. As it can be seen in the figure the operational RF amplitude set point was determined with an uncertainty of better than ±0.5% where the acceptable error margin is ±1% [4]. The drop in the transmission for the field values above 98% of the nominal level is still under investigation.

The design transmission of the RFQ is 30% [3] (for a beam fitting inside the acceptance shown in Fig. 3) while the maxium measured beam transmission through the RFQ was 20% which was expected from the simulations using the measured beam shown in Fig. 3.

Average Beam Energy

The design output energy of the RFQ is 5.0 MeV [3,4]. The average energy of the beam after the RFQ was measured both with the spectrometer and the ToF system [9]. The measured average energy values are 5.07 MeV and 5.03 MeV from the spectrometer and ToF, respectively.

Energy Spread

To measure the energy spread, the electromagnet quadrupoles on the test bench (Fig. 2) were adjusted to minimize the beta function at the slit of the spectrometer where the horizontal beam profile was measured. The distribution of energy is then calculated from the measured beam profile. The comparison of measured and expected relative energy distribution is given in Fig. 5. The measured rms energy spread is 7.0 keV while the expected value is 7.5 keV.

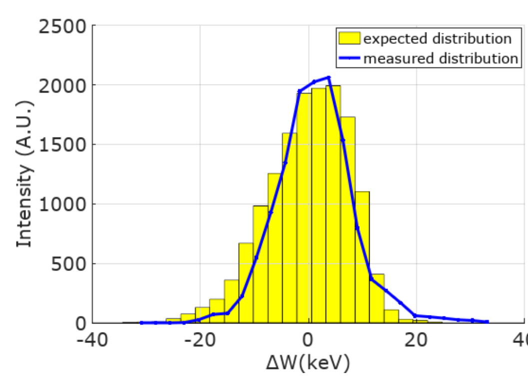

Figure 5: Measured and expected relative energy distribution.

Transverse Emittance

The transverse emittance of the beam was measured using the two Dboxes in the test bench. For the emittance measurements in each transverse plane a set of two slits and a FC was used [6].

Figure 6 shows the comparison of the measured and expected phase space plots of the beam after the RFQ for the input condition shown in Fig. 3. The measured and expected normalized rms transverse emittance values are given in Table 1. The smaller measured emittance in the vertical plane was most probably due to particle losses in the RFQ or MEBT.

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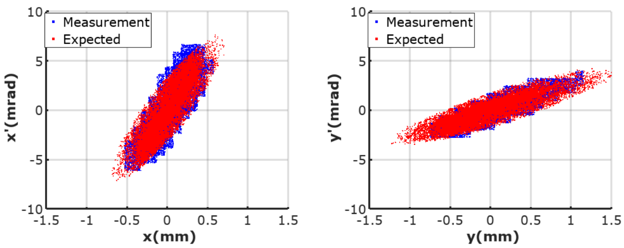

Figure 6: Comparison of measured (blue) and expected (red) phase space plots of the beam after the RFQ.

Table 1: Expected and Measured Normalized rms Transverse Emittance in the Horizontal and Vertical Planes

	Horizontal (pi.mm.mrad)	Vertical (pi.mm.mrad)
Expected	0.033	0.033
Measured	0.032	0.025

Figure 7 shows the horizontal phase space plots of the RFQ input and output beams (both expected and measured) when the beam was steered in LEBT both in the negative (first column) and positive (second column) x directions. As it can be seen from the figure, for each case, it was possible to observe the holes in the output phase spaces predicted by the RFQ simulations.

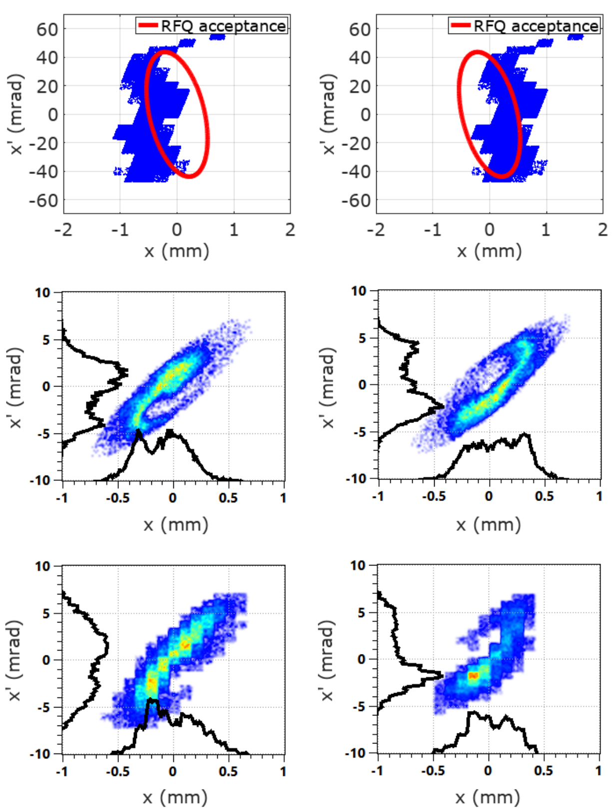

Figure 7: Horizontal phase space plots of the RFQ input beam when steered in the negative and positive x directions (first row), expected (second row) and the measured (third row) phase space plots after the RFQ for each case.

CONCLUSION

The CERN 750 MHz proton RFQ which is used as an injector to the 3 GHz structures of the LIGHT prototype was successfully commissioned at the ADAM test facility. The operational RF amplitude set point was determined with the beam measurements and the output beam parameters were characterized using a movable diagnostic test bench. The results of the beam measurements during the RFQ commissioning were taken as a reference for the commissioning of the LIGHT accelerator at higher energies.

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