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PROCEDURE FOR THE ALIGNMENT OF THE BEAM IN THE ELECTRICAL AXES OF THE PI-TEST RFQ*

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Abstract

The PI-Test Radio-Frequency Quadrupole (RFQ) has been in operation with beam at Fermilab since March 2016. The RFQ accelerates H^- beam from 30 keV to 2.1 MeV currently with 20 µs pulses and a maximum current of 10 mA. Once fully conditioned, the RFQ is expected to enable CW operation. Simulations with the beam dynamics code `TRACK` predict that a misalignment of the beam at the RFQ entrance can possibly deteriorate the transverse and longitudinal emittance at the RFQ exit without necessarily impacting the beam transmission. This paper discusses the procedure developed at Fermilab to align the beam in the electrical axes of the RFQ. Experimental results are shown together with predictions from `TRACK`.

INTRODUCTION

The Proton Improvement Plan II (PIP-II) is a series of upgrades for Fermilab's accelerator complex, which core is the development and construction of an H^-, 800 MeV superconducting linac with the primary goal of supporting operations for the Long-Baseline Neutrino Facility (LBNF). In order to study the feasibility of the PIP-II front-end, Fermilab has started the construction of the PIP-II Injector Test (PI-Test) which status is described in detail in Ref. [1]. In its present configuration the PI-Test linac comprises a Low-Energy Beam Transport (LEBT), a Radiofrequency Quadrupole (RFQ) and a short Medium-Energy Beam Transport (MEBT). This paper presents the procedure adopted for aligning the beam to the electrical axis of the RFQ.

PI-TEST FRONT-END LAYOUT

A layout of the PI-Test linac is presented in Figure 1. The H^- ion source is able to produce up to 15 mA DC or pulsed at an energy of 30 keV. Upon exiting the ion source, the beam is transported by a LEBT made of 3 solenoids and described in detail in Refs. [2, 3]. A set of horizontal and vertical correctors is installed within each solenoid to enable beam steering. There is a chopper downstream of the second solenoid and a movable aperture (a.k.a. LEBT scraper) is located at the LEBT/RFQ interface. The 4-vanes RFQ has been in operation at Fermilab since March 2016. Recent RFQ commissioning results in pulsed and CW mode have been reported in Ref. [4]. The beam energy exiting the RFQ has been measured to be 2.11±1% for 65 kV of inter-vane voltage. Upon exiting the RFQ, the beam is transported to a Faraday Cup by the MEBT made of 2 quadrupole doublets

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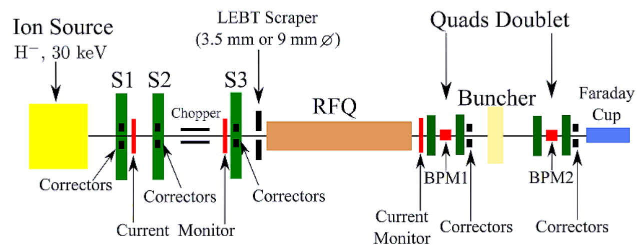

Figure 1: Layout of the PIP-II Injector Test.

with a bunching cavity located between them. BPMs are positioned between the quadrupoles inside each doublet. Using the 2 current monitors located in the LEBT and at the RFQ exit, a direct measurement indicates 98%±3% transmission through the RFQ for a 5 mA beam (short pulses) [1].

BEAM STEERING INTO THE RFQ

The solenoid and corrector fields were implemented in the codes `TRACK` [5] and `TRACEWIN` [6] as 3D fields simulated with `MWS` [7] and normalized to the measured field integrals. Using the matching procedure included in `TRACEWIN`, Solenoid 2 & Solenoid 3 correctors currents can be changed together such that, at a given position downstream (e.g.: LEBT scraper or RFQ entrance), the beam centroid angle (or position) is adjusted independently of the other degree of freedom. This tool was tested in June 2015 prior to the installation of the RFQ when an Allison scanner was positioned (in the horizontal plane) downstream of Solenoid 3. The estimated displacement accuracy is 1% between the measured and predicted horizontal position of the beam while the beam angle measurements agree to within 10% with the prediction from `TRACEWIN` [8].

PREDICTED MISALIGNMENT IMPACT

The RFQ has been implemented in `TRACK` using 3D fields from a `MWS` model. Figure 2 shows `TRACK` predicted emittance and transmission at the RFQ exit for different beam position or angle at the RFQ entrance. For these simulations, a matched 4D-Waterbag distribution with 5×10^4 macro-particles at 5 mA has been used at the RFQ entrance. The space charge effects were simulated using the 3D space charge routine. Figure 2(a) shows that a horizontal beam excursion at the RFQ entrance of ±1 mm with respect to the axis has a negligible impact on the beam transmission but nevertheless increases the output transverse emittance by ~ 25% and the longitudinal emittance by ~10%. The same observation applies to Fig. 2(b) for a beam entering the RFQ on axis with a horizontal angle of ±10 mrad. These simulations confirm the importance of properly aligning the

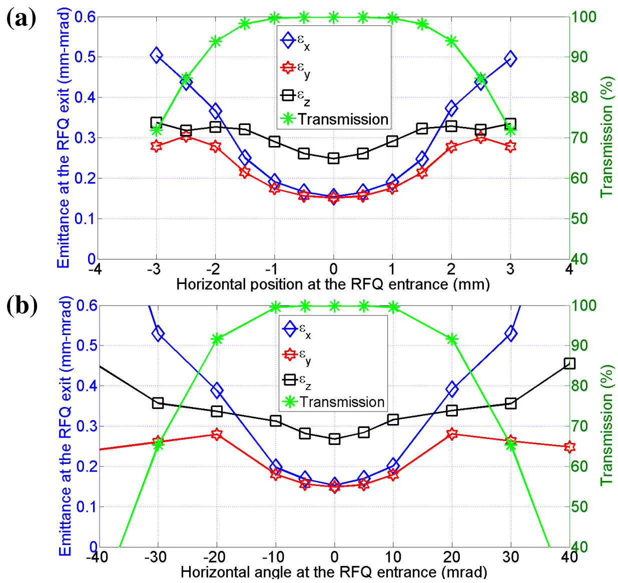

Figure 2: Predicted impact on the RFQ transmission and output transverse and longitudinal emittance of (a) Horizontal beam position and (b) Horizontal beam angle at the RFQ entrance. For a 5 mA beam from TRACK.

beam at the RFQ entrance in order to minimize the output transverse and longitudinal emittance.

RFQ BEAM ALIGNMENT PROCEDURE

The motion in the x plane for a particle of charge q and mass m_0 in an RFQ in the smooth approximation is a Mathieu equation of the form Refs. [9, 10]:

$$x(t) = (A\cos\Omega t + B\sin\Omega t)\left(1 + \frac{qXV_0}{m_0\omega^2 a^2}\sin\omega t\right) \quad (1)$$

with A and B being constants, Ω the betatron frequency, $\omega/2\pi$ the RF frequency, a the minimum vane radius, X a dimensionless parameter that depends only on the RFQ geometry and V_0 the inter-vane voltage. The betatron frequency is given by Ref. [9]:

$$\Omega^2 \simeq \frac{1}{2}\left(\frac{qXV_0}{m_0\omega a^2}\right)^2 + \frac{qk^2V_0A\sin\phi}{8m_0} \quad (2)$$

where $k = 2\pi/\beta_s\lambda$ and β_s is the normalized velocity of the synchronized particle and λ the RF wavelength. Equation (1) and Eq. (2) depend on the RFQ geometry, the beam energy and the inter-vane voltage. Hence, as long as the beam energy does not vary significantly, the beam motion and betatron frequency in an RFQ depend only on the inter-vane voltage for a given beam offset at the RFQ entrance. Therefore the procedure for aligning the beam at the entrance of the PI-Test RFQ consists in measuring the beam motion at the RFQ exit while scanning the inter-vane voltage for different beam horizontal and vertical position and angle at the RFQ entrance. The beam position or angle at the RFQ entrance leading to a minimum beam motion at the RFQ exit measured during the inter-vane scan corresponds to the nominal alignment.

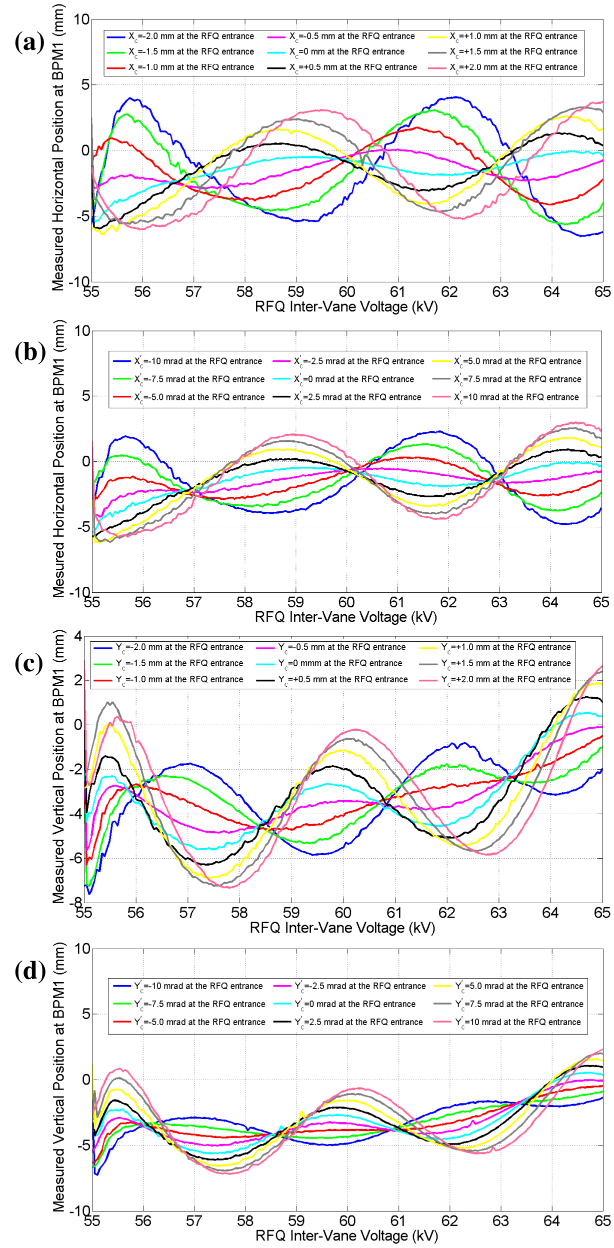

Figure 3: Measured beam motion at BPM1 as a function of the RFQ inter-vane voltage for different horizontal and vertical beam position and angle at the RFQ entrance.

Figure 3 shows the measured beam motion at BPM1 as a function of the inter-vane voltage for different beam position and angle at the RFQ entrance. The RFQ voltage was scanned from 55 kV to 65 kV corresponding to an energy variation of about 2% according to TRACK. The horizontal and vertical beam positions (Fig. 3(a) and Fig. 3(c)) were scanned from -2 mm to +2 mm in 0.5 mm steps and the horizontal and vertical angle (Fig. 3(b) and Fig. 3(d)) were scanned from -10 mrad to +10 mrad with 2.5 mrad steps. The measured RMS beam motion has been deduced from each scan and a quadratic fit of the RMS motion squared Vs beam position or angle performed. Table 1 lists the estimated beam offset in position and angle resulting from the minimum of each fit. The fact that the vertical motion tends

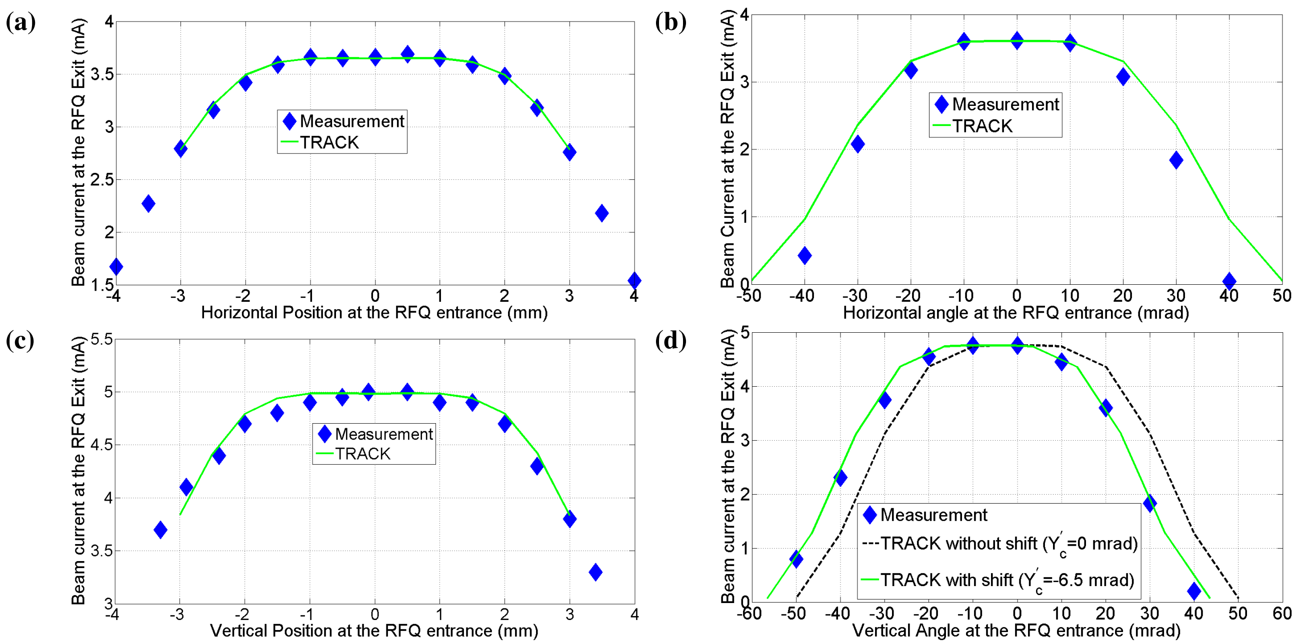

Figure 4: Measured and Simulated beam current at the RFQ exit as a function of (a) Horizontal beam position (b) Horizontal beam angle (c) Vertical beam position and (d) Vertical beam angle at the RFQ entrance. Simulations from TRACK.

to increase as a function of the inter-vane voltage in Fig. 3(c) and Fig. 3(d) suggests that the beam seems to experience a vertical dipole kick. The origin of this dipole kick is under investigation. We think that the large measured vertical angle offset may be needed to minimize this dipole kick.

Table 1: Estimated Beam Offset at the RFQ Entrance

Hor. Position	Hor. Angle	Ver. Position	Ver. Angle
-0.25 mm	-2.5 mrad	-1.12 mm	-7.72 mrad

TRANSMISSION VS BEAM ALIGNMENT

Figure 4 shows the current measured with the monitor located at the RFQ exit during the scans in position and angle described in the previous section. A fairly good agreement is observed in Fig. 4 between the measured current and the simulation from TRACK when the beam is assumed to enter the RFQ with zero position offsets and no angle in the x-direction. In addition, the disagreement between the measured and simulated transmission is almost eliminated when a -6.5 mrad vertical angle offset is assumed in TRACK (Fig. 4(d) green trace) which corroborates the observation in Table 1.

CONCLUSION

The beam in the PI-Test RFQ is aligned by scanning the RFQ inter-vane voltage and finding the position and angle at the RFQ entrance that minimizes the beam motion downstream. These measurements show that for the original nominal steering solution, the beam enters the RFQ with a ~7 mrad angle offset in the vertical direction, which is consistent with TRACK simulations of the beam transmission compared to equivalent data. An Allison scanner currently under fabrication will be installed shortly in the MEBT. It will allow a better characterization of the beam quality exiting the RFQ (e.g.: emittance) and in turn help better evaluate the alignment procedure.

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