BEAM COMMISSIONING STATUS AND RESULTS OF THE FNAL PIP2IT LINEAR ACCELERATOR RFQ*

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Abstract

An H^- beam was accelerated through a continuous wave (CW) capable, 4-vane, radio frequency quadrupole (RFQ) at Fermilab that was designed and constructed at Berkeley Lab. This RFQ is designed to accelerate up to 10 mA H^- beam from 30 keV to 2.1 MeV in a test accelerator (PIP2IT). This paper presents results of specification verification and commissioning.

INTRODUCTION

Fermilab has begun to optimize its injector chain for high proton flux neutrino experiments in a program called the Proton Improvement Plan (PIP) [1]. This program was designed to satisfy the requirements for experiments that are going on-line in the current decade. It will not satisfy intensity requirements for the longer baseline detector, Deep Underground Neutrino Experiment (DUNE) [2], and a new program, Proton Improvement Plan II (PIP-II) [3], is being developed to satisfy those requirements.

The PIP-II design team has proposed building a CW beam capable, Superconducting Radio Frequency (SRF) linac, to replace the current Fermilab linac, bringing the injection energy into the Booster from 400 MeV to 800 MeV, among other improvements to be made to the rest of the accelerator complex. This will satisfy the proton flux requirement needed for DUNE's baseline experimental goal and provide enough beam for other, future proton-based experiments. To alleviate technical risks in the linac design a sub-program called the PIP-II Injector Test (PIP2IT) [4] will prototype the first 25 MeV of the accelerator chain.

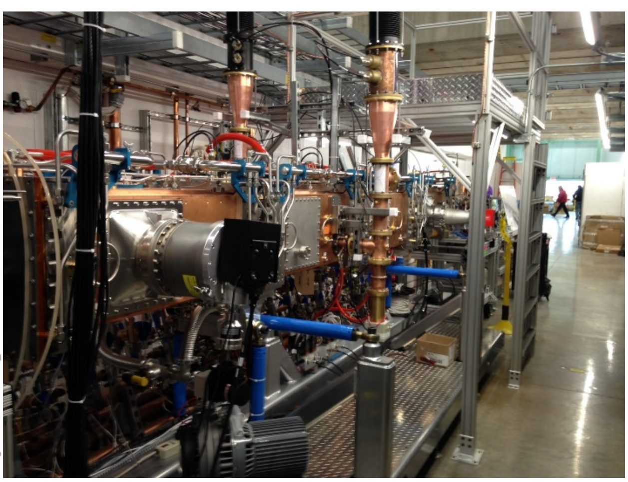

Figure 1: PIP2IT RFQ installed in beam line with support stand, water cooling manifold, and RF distribution connected to input couplers.

The PIP2IT RFQ was designed and constructed at Berkeley Lab [5]. Specifications are listed in Table 1 [6]. Two power input ports on the RFQ divide the 100kW CW load between two input couplers. Figure 1 shows the RFQ with its input couplers connected to the RF power distribution. RF power from the coupler antennas is AC coupled to ground, which allows applying a DC bias on the antennas to inhibit multipacting [7].

Table 1: RFQ Specifications

Parameter	Value	Range
Input Energy	30 keV	+/- 0.5%
Output Energy	2.1 MeV	+/- 1%
Frequency	162.5 MHz	Nominal
Beam Current	1-10 mA	Range
Vane Voltage	60 kV (peak)	Nominal
RF Power	130 kW	Max
Duty Factor	100%	
Transmission	95%	Min
Transverse Emittance	0.25 mm-mrad	Max
Longitudinal Emittance	0.8–1.0 eV-μs	Range

Cooling water temperature adjustment is the sole means of controlling the resonant frequency. Cooling channels and water manifolds were designed to separate the cooling system for the outer walls of the RFQ from the cooling system for the internal vanes [8]. While the resonant frequency response to variations of the overall temperature is weak (~2.5 kHz/°C), the response to a differential temperature between the wall and vanes is much stronger (~30 kHz/°C). Thus, the water cooling infrastructure was designed to allow separate control over the wall and vane water temperatures.

COMMISSIONING PREPARATION

Just prior to shipping to Fermilab, the RFQ was tuned for field flatness and resonant frequency at Berkeley Lab. This involved the design, construction, and testing of a 4.4-meter long bead-pull apparatus and processing system [9]. Eighty copper slug tuners and the two end-plates were adjusted and machined to give a field flatness of ~1% peak-

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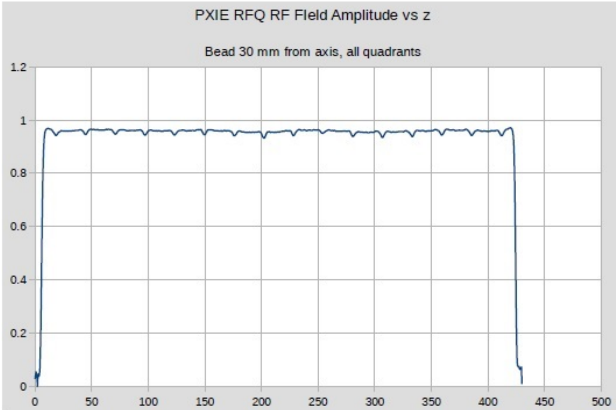

Figure 3: Final RFQ bead pull measurement showing the average field perturbation of the four quadrants. Field is flat to +/-1% pk-pk and frequency in air at 25°C is 162.440 MHz. Bead was pulled 30 mm from the center and a 45° angle from the axes defined by the vane tips. Disturbance from pi-mode rods is amplified away from the center as shown by the small dips in the plot. It does not affect the field flatness on the beam line axis.

to-peak. Figure 2 shows the final bead-pull results. Forty-eight field pick-up loops were calibrated after the tuning was complete, and the relative amplitude of these loops was verified upon arrival at Fermilab to ensure that no internal components were disturbed during transport.

Input couplers were installed and coupling adjusted for best match into the RFQ when the couplers are driven in phase with each other. Two, 75 kW, CW RF power amplifiers are connected to the RFQ. Each amplifier is protected by an external, 75 kW, CW circulator, tuned to 162.5 MHz. High power directional couplers are connected to the amplifier, just before the input couplers, to provide Low Level RF (LLRF) forward and reflected power diagnostic signals at each input.

RF CONDITIONING

Pulsed Conditioning

The RFQ was first brought up to operational field settings in a low duty, pulsed mode. The LLRF signal calibrations were verified relative to precise power meter readings over the full operating range of the RFQ field. Each amplifier is driven by a separate output of the LLRF system [10]. These signals are derived from the same reference signal and can be attenuated and phase shifted relative to each other. The attenuation and phase shift were set to minimize the reflected power from the RFQ, and consequently optimized for driving in perfect sum mode. The RFQ vane potentials were also verified to within 10% accuracy using an x-ray detector.

The water cooling system used to tune the resonant frequency of the RFQ does not have an external heat source besides the RF power itself. During conditioning in pulsed mode, the duty cycle was limited to 5%. This did not generate enough heat to allow compensating for a 60 kHz offset in the resonant frequency using differential temperature between the wall and the vane cooling water. However, the offset is small enough not to have a noticeable effect on the beam properties coming out of the RFQ.

The RFQ conditioned very quickly with little incident with help from the RF interlock system that can disable RF quickly upon detection of high reflected power. The conditioning rate was fundamentally limited by the pumping rate from adsorption on the copper as the field and duty cycle were increased. The vacuum level was controlled to below 2-3 e-6 Torr with a trip limit of 1 e-5 Torr. The RFQ couplers experienced multipacting at low power, but this was remedied by a 1 kV bias on the coupler antenna.

Pulsed conditioning concluded with operating the RFQ with a vane tip voltage of up to 72 kV set point, pulse width of 0.45 ms, and repetition rate of 10 Hz.

CW Conditioning

The main challenge for CW conditioning and operation is the large thermal relaxation of the RFQ during RF trips [11]. Drifts in resonant frequency while in pulsed mode were small and slow enough to be handled manually. When operating CW, the resonant frequency of the RFQ after RF trips changes quickly and is relatively largely. Figure 3 shows a plot illustrating the RFQ resonant frequency response to a series of RF trips. As a result, the

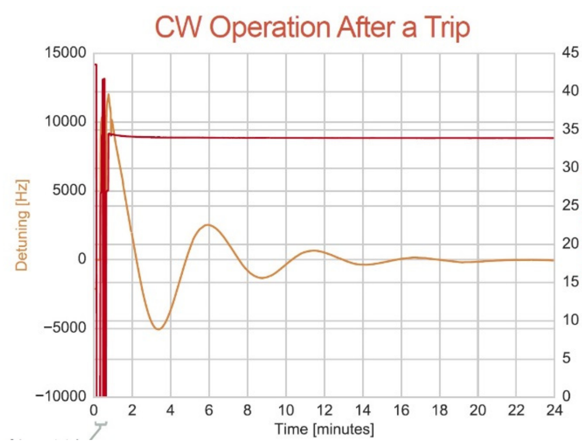

Figure 2: Plot showing RFQ resonant frequency detuning after 30 seconds of RF trips during CW conditioning. RFQ detunes by about 12.5 kHz in seconds and requires lowering the operational field to recover RF stability while the resonant control system stabilizes the resonant frequency.

LLRF system needs to track that frequency in order to keep power into the RFQ and stabilize the water temperature system. Experts adjusting cooling water valves manually are able to reduce the interruption time due to RF trips down to as low as one minute. An automated proportional and integral feedback loop was commissioned, but its settling time is an order of magnitude slower than nonlinear tuning. There is work underway to implement a more advanced automated tuning algorithm [12].

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CW conditioning was performed up to 62 kV of vane potential, shy of the 65 kV nominal set point, the operating voltage for pulsed mode operation. This tested the viability of the RFQ and input couplers in CW regime, but it was not urgent to condition to full field until being ready for CW beam operation and studies.

BEAM COMMISSIONING

Current Status

Transmission efficiency measurements are carried out in pulsed mode. For that purpose, the beam line incorporates two, identical, and cross-calibrated current transformers (a.k.a. toroids) before the last solenoid in the Low Energy Beam Transport (LEBT) and at the exit of the RFQ [13]. The measured transmission is ~98% for beam currents of 5 mA (nominal) and 10 mA (max), definitely above the 95% specified. This is illustrated on Figure 4, where the beam current measured by the 2 toroids are plotted against time.

The beam energy out of the RFQ has been measured using a movable, Time-Of-Flight (TOF) BPM system [14]. At 65 kV vane potential, it was verified to be 2.11 MeV +/- 1%, again within specifications.

Future Commissioning Plans

It is expected that RFQ commissioning will be complete by the end of the calendar year (2016). In pulsed mode only, transverse emittance measurements will be carried out using a water-cooled Allison-type emittance scanner currently under construction. Also, the RF distribution, beam line, and beam line enclosure are currently being upgraded for CW beam operations, for which the primary focus will be to investigate the RFQ reliability.

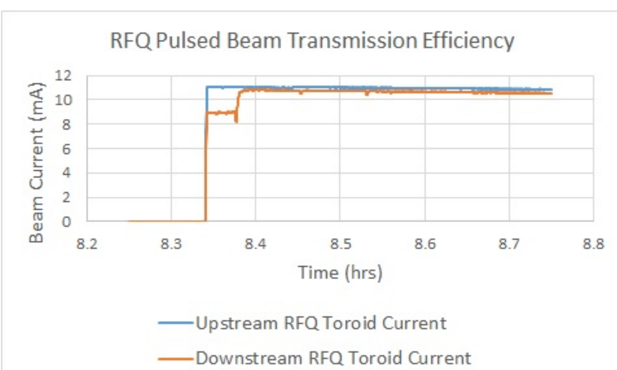

Figure 4: Plot showing the RFQ transmission efficiency at 10 mA. The pulse width is 20 µs and the repetition rate is 10 Hz. The bump in efficiency corresponds to tuning of the upstream solenoid.

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REFERENCES

[1] W. Pellico , *et al.*, “FNAL - The Proton Improvement Plan (PIP),” in *Proc. IPAC'14*, Dresden, Germany, 2014.

[2] Fermilab, “DUNE Deep Underground Neutrino Experiment,” Fermilab, 2016. [Online]. Available: www.dunescience.org. [Accessed 16 September 2016].

[3] S. Brice, “Proton Improvement Plan II: An 800 MeV Superconducting Linac to Support Megawatt Proton Beams at Fermilab,” in *37th International Conference on High Energy Physics (ICHEP)*, Valencia, Spain, 2016.

[4] A. Shemyakin, *et al.*, “Project X Injector Experiment: Goals, Plan, and Status,” in *Proc. IPAC'13*, Shanghai, China, 2013.

[5] S. Virostek, *et al.*, “Final Design of a CW Radio-Frequency Quadrupole (RFQ) for the Project X Injector Experiment (PXIE),” in *Proc. NAPAC'13*, Pasadena, CA, 2013.

[6] J. Steimel and S. Nagaitsev, “Project X RFQ: functional physics requirements, Doc#894,” 12 Feb 2013. [Online] `http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=894` [Accessed 11 11 2013].

[7] S. Kazakov, *et al.*, “Design of RFQ Coupler for PXIE Project,” in *Proc. IPAC'13*, Shanghai, China, 2013.

[8] A. Lambert, *et al.*, “RF, Thermal, and Structural Finite Element Analysis of the Project X Injector Experiment (PXIE) CW Radio-Frequency Quadrupole (RFQ),” in *Proc. NAPAC'13*, Pasadena, CA, 2013.

[9] T. Khabiboulline, “Bead Pull Measurements of Module #2 of the PXIE RFQ in April 2014,” PIP-II Document Database, 2014.

[10] J. Edelen, *et al.*, “Low Level RF Control for the PIP-II Injector Test RFQ and Bunching Cavity,” in *Proc. NAPAC'16*, Chicago, 2016.

[11] D. Bowring, *et al.*, “Resonance Control of Fermilab's PIP-II Injector Test RFQ in Pulsed and CW Modes,” in *Proc. NAPAC'16*, Chicago, 2016.

[12] A. Edelen, *et al.*, “Machine Learning and Artificial Intelligence Based Controls for Particle Accelerators,” in *Proc. NAPAC'16*, Chicago, 2016.

[13] N. Liu and N. Eddy, “The Beam Intensity Monitoring System for the PIP-II Injector Test Accelerator,” in *Proc. NAPAC'16*, Chicago, 2016.

[14] N. Patel and N. Eddy, “The Beam Position Monitoring System for the PIP-II Injector Test Accelerator,” *in Proc. NAPAC'16*, Chicago, 2016.