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CONDITIONING OF ROD-STYLE RFQ IN SUPPORT OF LANSCE FRONT-END UPGRADE*

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Abstract

The Los Alamos Neutron Science Center (LANSCE) front-end injection scheme is expecting an upgrade to a Radio-Frequency Quadrupole (RFQ) in order to replace the obsolete Cockroft-Walton accelerators used in present operation. A test stand using a rod-style RFQ is under development in support of this upgrade, and conditioning of the RFQ to the expected peak and average power levels was completed to ensure its feasibility. The RFQ conditioning also revealed thermal issues with the RF power coupler and issues in managing the power reflected from the RFQ. These issues and their mitigation will be discussed in light of the capability of the test stand, and future plans will also be discussed.

INTRODUCTION

The Los Alamos Neutron Science Center (LANSCE) at present depends on two 750 keV Cockroft-Walton accelerators (C-W) to inject both H^+ and H^- beam into the drift tube linear accelerator (DTL). This is a vulnerability in the ability of LANSCE to produce beams as the approximately 50 year old design has multiple components without proper spares. This vulnerability was exposed during the 2023 run cycle as the H^+ C-W was down for multiple months to correct issues with arcing in its column. One issue that has led to the obsolescence of C-Ws is the prevalence of radio-frequency quadrupole (RFQ) accelerators, and work is under way at LANSCE to replace the C-W with an RFQ.

The development of an RFQ for LANSCE has been underway for over a decade [1,2], and the LANSCE Modernization Project (LAMP) requires a test stand to develop H^+ and H^- sources, the RFQ, and other beamline components to accomplish its goal of replacing the LANSCE front end. An RFQ had previously been developed in coordination with Institute of Applied Physics in Goethe University in Frankfurt, Germany, and it was built by Kress, GmbH in 2014. RFQ conditioning is a necessary step for the test stand, and ultimately any RFQ-based upgrade, as we must prove that the RFQ is capable of sustaining high RF fields and heating of the designed 50 kV intervane voltage at 15% duty factor [1-3].

PROCEDURE

The RFQ has been using the intermediate power amplifier (IPA) of an existing test stand used to test the various RF amplifier equipment in use at LANSCE. Conditioning of the RFQ is a special use case, and some issues have arisen during the conditioning process. Overall, however, the test stand has been able to provide RF power up to the levels predicted for the next step of accelerating beam.

The RF test stand has certain features for testing spare LANSCE equipment that must be taken into account for RFQ conditioning. A TH781 tetrode IPA normally drives a final power amplifier, but for RFQ conditioning, the IPA runs power through air-insulated cable to the station with the RFQ. The IPA will see reflected power spiking at the beginning and end of the RF pulse, and much less reflected power is tolerable during FPA testing than with the RFQ. The reflected power tolerance was not changed for RFQ operation because they could be overlooked when changing to FPA test operation, risking equipment damage. This resulted in a higher rate of interlock trips during RFQ operation but not its overall conditioning.

There were additional modifications to run the IPA to the RFQ. First, there were interlocks added for RFQ water and vacuum, as well as kill switches located at the RFQ because of its distance from the RF amplifier. In addition, a waveform generator was used to ramp the power at the beginning and end of the RF pulse to reduce the reflected power. An NI cRIO-9045 was used to control resonance and collect data on the power, vacuum, and temperature of the transmission line. A diagram of the test set-up is shown in Fig. 1.

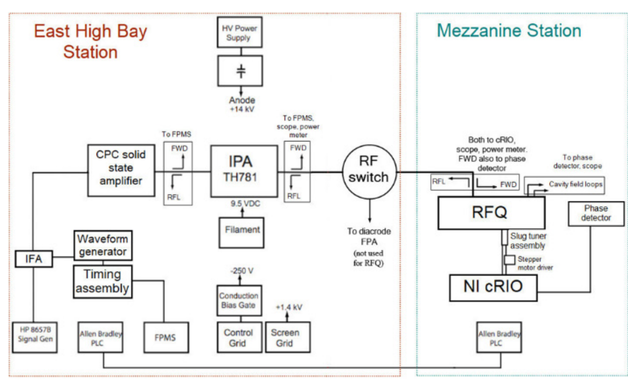

Figure 1: Diagram of the conditioning set-up. The East High Bay Station is the temporary RF source for the RFQ in the Mezzanine Station.

The goal of the RFQ conditioning was to apply the levels of RF power that would demonstrate its ability to accelerate beam. Initial simulations of the RFQ showed that it would need about 77 kW peak power to achieve the designed intervane voltage of 50 kV, but these simulations also showed that the unloaded Q-factor of the cavity was about 5300 [3]. The measured Q-factor of the cavity was actually 3000, so the power needed was then expected to be 135 kW without beam. A 20 mA beam would require an

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additional 14.3 kW to accelerate it from 35 keV to 750 keV, for a total power of 150 kW. After the RFQ was retuned to run at 201.25 MHz, the Q-factor was 2600, so 155 kW would be needed (170 kW for beam). The typical duty factor for LANSCE is 12% (120 Hz, 1000 µs), and 15% is the upper limit, so the goals for average power were 22.5 kW and 25.5 kW for the two tunings.

RESULTS

The RFQ has now been conditioned twice to the full peak and average power goals. A previous conditioning was also attempted in 2021 before vacuum issues required correction. As previously identified, the reflected power must be very carefully dealt with, and there were additional considerations with this that arose during conditioning. There were also concerns with the heating of the transmission line that were addressed. Retuning the RFQ was required for it to operate at the design frequency. An overview of the results of conditioning are shown in Table 1.

Table 1: Overview of Conditioning

Parameter	1st Conditioning	2nd Conditioning
Operating Frequency (MHz)	201.45	201.25
Unloaded Q-Factor	3000	2600
Power Required For 20 Ma Beam (kW)	150	170
Highest Peak Power Achieved (kW)	165	180
Average Power Required for 15% Duty Factor (kW)	22.5	25.5
Highest Average Power Achieved (kW)	17	19

Low Power Conditioning

The initial conditioning was done at low RF power. This was first done using a continuous wave solid state amplifier at 50 W, then pulsed up to 500 W peak at 15% duty factor. This low power conditioning was essential after the RFQ had been open for months as there was significant outgassing at even this low power. After the RFQ was retuned, conditioning was required at peak power < 1 kW over several hours before power could be increased.

In addition to the vacuum response at low power, the low power conditioning was also needed to condition through the low power multipactor bands. The RF pulses must have ramps at the beginning and end to reduce the reflected power spikes inherent with the resonant RFQ structure so as to not surpass the strict reflected power thresholds of the IPA. Multipactor can cause strong reflected power spikes during these ramps as the multipactor power levels are passed through. Conditioning of multipactor at these power levels then also helped to alleviate these reflected power spikes to more easily achieve high power, and Fig. 2 shows RF pulses as multipactor conditions and breaks in the middle of the pulse.

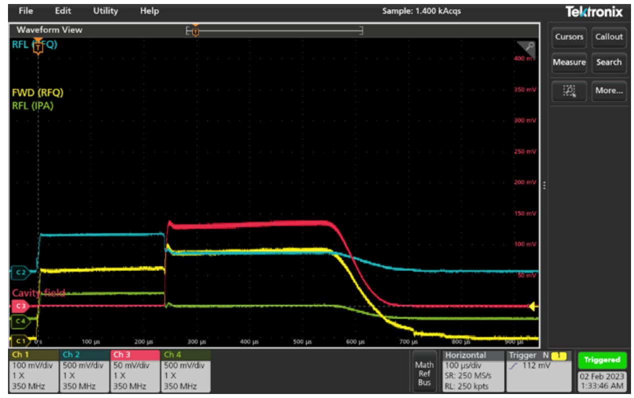

Figure 2: Forward power (Ch 1), reflected power as measured at the RFQ (Ch 2) and IPA (Ch 4), and cavity fields (Ch 3) as multipactor is breaking during a pulse.

Achieving Peak Power

Ultimately, the conditioning of the RFQ has been successful in reaching the highest peak and average power possible during both conditioning sessions. The initial conditioning at 201.45 MHz identified many issues that allowed a more seamless second conditioning once the RFQ was retuned to operate at 201.25 MHz. The estimated peak power for beam acceleration was achieved.

The achievement of high peak power into the RFQ was an important milestone to show the required 50 kV intervane voltage could be attained without arcing. The conditioning at both tunings achieved a peak power level of about 165 kW for over an hour, and the retuned cavity achieved up to 180 kW of peak power for a few minutes. Getting to 180 kW was only sustained for a short time because it required adjusting the gain of the amplifier, which made operation unstable. Reaching the peak power required for beam increases the RF fields past the required 50 kV, providing some overhead.

Achieving Average Power

The RFQ also must handle a significant amount heating due to average power. The importance of putting high RF power was demonstrated in 2021 when one of the vanes developed a vacuum leak at 2.5 kW average power. Applying high average power into the RFQ to expose any further issues was desired, so testing the RFQ to the limit of the RF amplifier was necessary. A thermal issue in the transmission line and power coupler was also addressed.

Application of high average power was limited by the capabilities of the test stand. The power supply of the IPA has a limit 2.2 A of charging current before it will overheat, so the power supply can only be run at 10% duty factor as the anode current is about 20 A at high power. The RFQ ran over 17 kW average power for over half an hour originally, and after retuning it ran at 15 kW for over an hour and at 19 kW for 10 minutes.

This high average power caused significant heating in the transmission line and the power coupler. While running

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at 201.45 MHz and 8.6 kW average power, the transmission line was hot to the touch, and the highest measured temperatures were 55°C at the vacuum window and 48°C in the center of the bellows. The bellows was replaced with a more rigid version, and this improved its temperature. The cooling channel of the power coupler was found to be getting almost no flow due to the large number of parallel cooling circuits. The cooling water for the power coupler was moved to its own chiller, with the supply side set to 15°C. After these two changes, the highest temperature on both the bellows and the outer conductor at the window was about 50°C for the highest average power as shown in Fig. 3. Additional average power is not predicted to heat this to a point of damage.

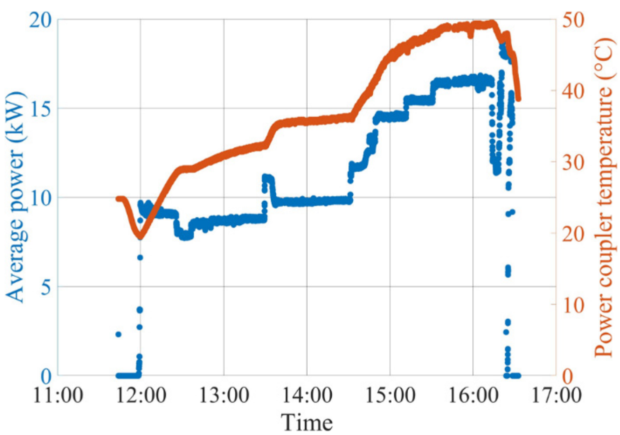

Figure 3: Average power and power coupler temperature versus time near the highest average power recorded for the retuned RFQ.

Tuning to 201.25 MHz

The tuning of the RFQ should also be briefly explained due to its necessity and importance. The tuning needed to first be adjusted so that the RFQ could be run at 201.25 MHz with the slug tuner capable of adjusting from cold to full average power. Then the tuning cells had to be individually adjusted to ensure field flatness, and the Q-factor of the RFQ needed to be measured.

The RFQ was initially tuned under the assumption that the slug tuner would move in as RF power heated the tuning circuits, but the opposite was found to be true upon the first conditioning. The resonance of the RFQ is maintained by a slug tuner that adjusts the resonant frequency within about 300 kHz, and for larger shifts in the resonant frequency, the RFQ must be opened to adjust the heights of the individual tuning cells [4,5]. From the RFQ being cold to heated with full average power, the slug tuner extracted by about 30% of its range. Additionally, moving from having the RFQ opened for tuning to closed and under vacuum increased the frequency by about 70 kHz. Considering these two factors, the tuning was done with the slug tuner inserted to 75% of its range, and the frequency was adjusted to be 201.18 MHz.

Once the frequency was adjusted to the right value, smaller changes were made to adjust the field flatness. This is performed by placing a 1 pF capacitor across the vanes at each of the tuning cells. This acts as a perturbation, and the intervane voltage at the location where the capacitor is placed is proportional to the square root of the frequency shift. Expressing that value for each cell as a percentage of the average of the square root of the frequency shift for all tuning cells is the relative voltage. The achieved flatness was ±1.5% of relative voltage for the slug position at full power, and this is within what is expected based on similar RFQs [6,7]. Figure 4 shows the field flatness and plate heights of the final tuning configuration

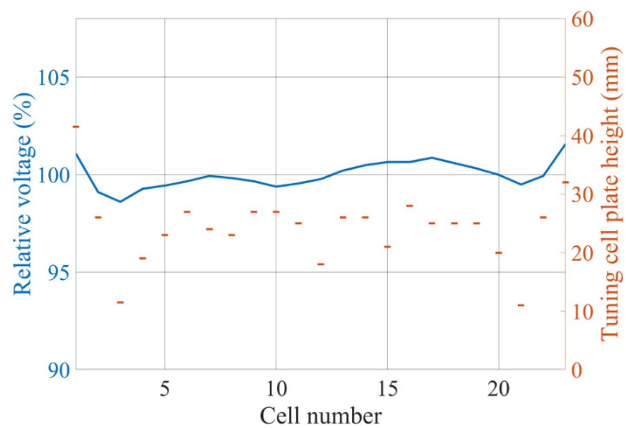

Figure 4: Relative voltage and tuning cell plate height for the final configuration at 201.25 MHz when the slug tuner is 20% inserted.

CONCLUSSIONS

The RFQ was tested to ensure it will be able to sustain the fields required for acceleration. This was initially done at a different frequency from what was designed, and the tuning was then adjusted for operation at 201.25 MHz. This retuning also achieved sufficiently flat fields for any slug tuner location, allowing the RFQ to operate at many duty factors. The RFQ was conditioned to a voltage higher than required by conditioning to an extra 10 kW past the power required for beam. The average power has only been tested to 10% of the peak power, but this cannot be increased until the power supply is upgraded. The issues with reflected power and low power multipactor will be mitigated by using a circulator to protect the IPA.

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