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UPGRADE OF THE RADIO FREQUENCY QUADRUPOLE OF THE REACCELERATOR AT NSCL / FRIB*

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Abstract

The ReA-RFQ is a four-rod radio frequency quadrupole (RFQ) structure of the MSU rare isotope Reaccelerator.

Since the commissioning in 2010 the original ReA RFQ experienced some operational problems. The design voltage was never reached, and continuous wave (CW) operation was never achieved due to cooling issues. In 2016, a new design including trapezoidal modulation was proposed, which permitted achieving increased reliability, and would allow reaching the original required specifications. The new rods were built, installed and commissioned in 2019. Since then, the RFQ has been working successfully, and recently it was opened for inspection and verification of its internal status. No damage and discoloration were observed.

This paper describes the RFQ rebuild process, involving specific RF protections and other technical aspects related to the assembly of the structure.

INTRODUCTION

The MSU reaccelerator started user operation as ReA3 in 2015 [1]. The facility is being continuously upgraded to enhance its scientific capabilities and reliability. Recent upgrades include: (a) replacement of the ReA3 RFQ electrodes to improve their cooling and provide high capture of pre-bunched 16.1 MHz beams with $A/Q = 5$ [2], as well as CW operation, (b) installation of a room-temperature rebuncher cavity and another superconducting RF (SRF) cryomodules after the ReA3 linac, (c) installation of the new high-current electron-beam ion source (EBIS) for stable and rare-isotope beams, (d) installation of the new RF controllers.

Although the nominal range of mass-to-charge ratios is from 2 to 4, the operation with ions of $A/Q = 5$ is considered to best match the EBIT performance [3]. The original ReA3 RFQ was commissioned in 2010 and has been in service until April 2019. Several issues related to the RF contacts between various parts of the structure became apparent upon commissioning. After the modification of the tuning plates, their RF contacts, and the electrodes' water line clamps, we had to limit the average power to 40 kW. This could provide the CW operation only with beams of $A/Q = 2$. Higher voltages, required for the beams with A/Q above 4, were possible at reduced duty factors. Thanks to the natural pulsed operation of the EBIT, this was not a problem for the facility, except for the inability to accelerate beams of $A/Q = 5$ due to the sparking issues. Despite the multiple upgrades and improvements, the operational reliability of the RFQ was gradually reducing.

The CW operation of the reaccelerator facility is essential for its future multi-user upgrade, when pulsed rare-isotope and stable beams will be simultaneously accelerated in the linac and delivered to different users in an alternate manner [4,5]. Until recently, the RFQ has been the only part limiting the CW performance of the facility.

UPGRADE STRATEGY

In 2016, the original vendor of the ReA3 RFQ proposed a new design of the electrodes' stems. The proposal included the modification of cooling channels, tuning plates, and the angle brackets connecting the tuning plates to the vertical stems of the four-rod RF structure.

The FRIB/NCSL scientists also proposed to re-designed the quadrupole electrodes in order to reduce the inter-electrode voltage. First, this allowed for the reduction of the RF power consumption. Second, the peak surface electric fields also decreased. To recover some energy gain after the voltage got reduced, a trapezoidal modulation of the electrodes was employed [6]. Table 1 summarizes the main design parameters that have been changed. Some design considerations are presented in [2].

Table 1: Modifications of the RFQ (for $A/Q = 5$ beam)

Parameter	Original RFQ [7]	New RFQ
Output energy	600 keV/u	538 keV/u
Voltage	86.5 kV	70.0 kV
Average radius R_0	7.3 mm	6.56 mm
RF power	120 kW	80 kW
Peak surface field	1.6 Kp	1.4 Kp
Synch. phase	−20°	−60° to −20°
Modulation	1.15 – 2.6	1.13 – 2.5
Transmission of:		
80.5-MHz beam	82%	89%
16.1-MHz beam	N/A	78%

SIMULATIONS

Analysis of the Four-rod RF Structure

The design upgrade started from analysis of the original four-rod ReA3 RFQ to find reasons for sparking. It required an accurate simulation of the electric field distribution on the surfaces of the electrodes. Rather than simulating the whole four-rod RF structure, we created an electrostatic model of

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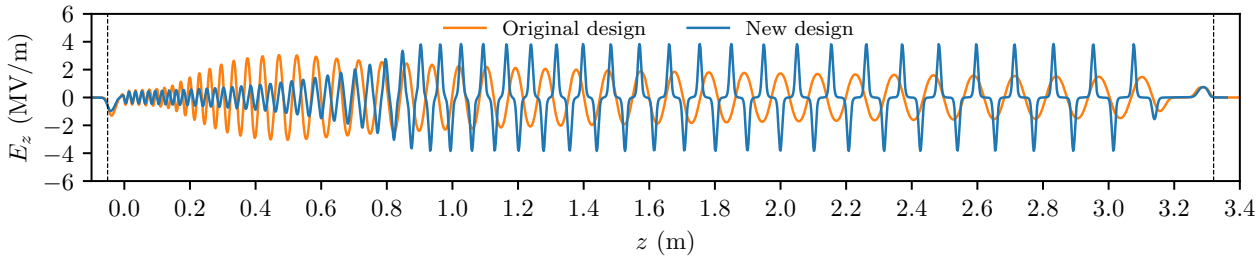

Figure 1: Accelerating field distribution along the RFQ.

the quadrupole channel with fine mesh. In this model, all solids may only be equipotential, which does not match well with the nature of periodical distributed accelerating structures, such as a four-rod one. Therefore we defined the electrostatic potentials by comparing the local field distributions with those of the electromagnetic RF model. We concluded that the longitudinal periodical potential variation of the rods does not effect the field strength between the rods. The fields at the ends of the RF structure, however, required a significant difference of the rod potentials. For example, the voltage between a high-potential rod and the tank increases by a factor of 1.74 compared to a spatially uniform RF structure, such as a four-vane.

The lack of the quadrupole symmetry in the RF structure induces a dipole electric field component on the geometrical beam axis [8] which in the static model was created by assigning a potential difference between two top and two bottom electrodes. The final normalized potentials of the four rods are the following: +0.895 (top-left), −0.155 (top-right), +0.845 (bottom-right), −0.105 (bottom-left). The potentials of the tank walls remain zero. While the peak fields between the quadrupole rods do not depend much on the above-mentioned effects, the peak fields at the ends (i.e. between the RF structure and the end walls of the tank) greatly increase in presence of the longitudinal variation of the rods' potentials and the dipole field component [2].

Trapezoidal Modulation

Following a practical design approach developed in this project [2, 6], we built a CAD model of the new RFQ electrodes. The main feature of the new rods is their trapezoidal modulation. It increases the transit-time factor compared to the conventional sinusoidal electrodes. Similar to the drift-tube accelerating structures - the shorter gap provides higher transit-time factor. The distributions of the accelerating field along the RFQ for the original and the new design are shown in Fig. 1. One third of the RFQ length is used for the adiabatic bunching. The remainder has the trapezoidal modulation with a constant accelerating gap length of 15 mm. Careful design allows increasing of the RFQ efficiency and energy gain rate while keeping the peak fields low, which also remain the same in every cell of the accelerating section of the RFQ.

After the operational voltage reduction, the RFQ output energy would drop from 600 keV/u to about 470 keV/u, while trapezoidal modulation partly recovered it to 538 keV/u.

HARDWARE IMPLEMENTATION

Component Cooling

The water cooling of the copper components was optimized to ensure adequate cooling during high duty factor and CW operation, as well as to address reliability issues with the original design.

The majority of the cooling improvements pertain to the rods which experienced several failures during operation due to routing of the water lines and use of braze joints. The original design supplied water to the rods via copper tubing running in-vacuum along the vertical support stems, exposing them to the RF fields. These were attached to the stems using copper clamps to facilitate proper flow of the RF currents. However, in some cases, the screws attaching the clamps ended up carrying the currents, causing them to melt. Additionally, the in-vacuum copper tubing connections to the rods were brazed, and several developed in-vacuum pin-hole water leaks during operation, which required repair. The new design solves both of these issues. The supply and return water lines are routed through the middle of the support stems, avoiding exposure to RF currents. The connections of the stainless supply and return water lines, as well as the copper plugs in the coaxial water channels in the rods, are electron beam welded rather than brazed to reduce the likelihood of in-vacuum leaks at these connection points.

The original tuning plates for the RF cells had been replaced during a previous upgrade to a design that incorporated S-shaped channels under a solid silver plate which was brazed on top. These had begun to develop in-vacuum pin-hole water leaks through the silver due to water erosion at the locations where the inlet water was supplied perpendicular to the silver plate and was required to undergo a 90° directional change. The new cooling design of the plates mimics the original, which is a single copper U-shaped tube with radius bends brazed into a slot in the bottom of the plates.

The cooling of the vertical stems still consists of a V-shaped channel drilled into the atmosphere-side of the components to allow supply and return water flow, but the depth of the channels was increased to distribute cooling and lower the peak temperature of the stem. Another major improvement is a BSPP threaded interface, allowing for more secure plumbing connections than the original, which consisted of short stubs of brazed copper tubing with push-to-connect tubing fittings.

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Tuning Plate Modifications

After initial assembly and tuning of the new RF structure, it was observed that the tuning plates needed to be nearly bottomed out on the floor of the RFQ vacuum vessel in order to achieve the desired resonant frequency of 80.5 MHz, while maintaining a reasonable RF cell flatness, and allowing adequate range on the movable tuners to accommodate frequency shifts due to thermal changes. To address this issue, pockets shown in Fig. 2 (left) were cut into the tuning plates to lower the frequency range.

Initial operation of the RFQ revealed an electrical contact issue with the angle brackets bridging between the stems and the tuning plates, which allowed RF current to flow under the plates and down the water lines, damaging the O-ring seals on the water line vacuum vessel feedthroughs, resulting in a vacuum leak. This also damaged and melted many of the in-vacuum screws attaching the angle bracket to the stems and tuning plates.

The primary root cause of this issue appears to be inadequate torqueing of the in-vacuum screws. This was addressed by increasing the torque on the screws from 5 to 25 in-lbs, which based on offline testing was near the maximum possible to prevent deformation of the M4 screw heads. In addition, the silver-plating on the screws was doubled in thickness to account for RF skin depth issues. Furthermore, high-purity 0.010-inch-diameter gold wire was sandwiched in between the stems, angle brackets, and tuning plates, as shown in Fig. 2 (left), to define an RF contact point, and protect the screws by preventing any RF currents from reaching the screw threads and shank.

As a doubly redundant measure, to prevent any RF from reaching the tuning plate water line feedthrough O-rings, circular RF finger rings were installed in the channels where the tuning plate water lines penetrate the vacuum vessel. The feedthrough vacuum fittings were also equipped with ring shaped canted coil springs to protect the O-rings. These two measures (Fig. 2, right), ensure that the water lines are electrically grounded to the vacuum vessel, and that no RF fields should be present at the O-ring locations.

Alignment Verification

Two measurements were completed on the RFQ copper structure: one to verify rod gap distances and another to verify the transverse position of the rods with respect to the theoretical beam axis. Micrometer measurements of the rod-to-rod distances were taken at each RF cell flats on the two outside edges of the rods. The measurements indicate that the rod distances are within 0.5 mm of their nominal values. CMM arm measurements of all rod attachment screw head positions and all accessible planar rod surfaces were also taken. The data was analysed to determine a line of best fit for the beam axis.

Commissioning of the New Design

After a short period of pulse conditioning, a $^{14}N^{6+}$ beam from the EBIT was used for initial beam commissioning. A transport efficiency of 84% was observed using pre-bunched beam from the upstream multi-harmonic buncher. The measured efficiency matched the calculated value reasonably well. The beam energy was measured using a calibrated dipole magnet and determined to be 540 keV/u.

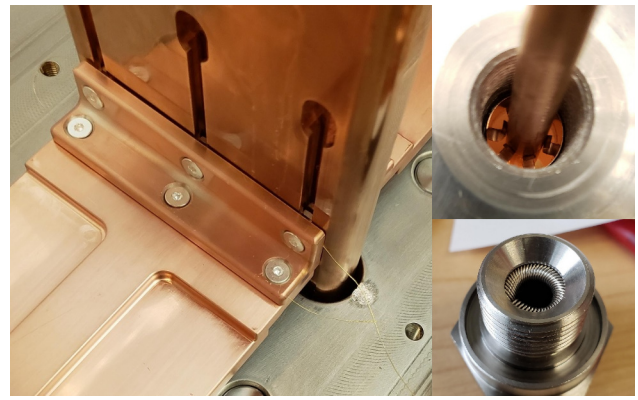

Figure 2: (Left) Gold wire being installed at angle bracket junction between tuning plate and vertical support stem. Also visible are pockets cut into the tuning plates to lower the frequency. (Right) RF finger ring and canted coil spring protecting water line O-rings from RF.

Operational Experience

The fully refurbished RFQ has been in use supporting scientific user experiments since March 2020. It has been opened twice for inspection, with the only observation that the tuning plate angle bracket screws require a slight re-torqueing, likely due to thermal expansion and contraction of the components or deformation of the gold wires in the tuning plate junctions.

The cavity has been operated in CW mode at a power of 21.5 kW for ions with an A/Q up to 2.22. Most beam operation is done in pulsed mode due to the pulsed ion beam injection and extraction in the EBIT source. The highest peak power used for beam delivery thus far was 60 kW, with a duty factor of 49%, for ions with A/Q of 3.64. RF conditioning without beam has reached 100 kW peak power, corresponding to an A/Q of 4.8 with a duty factor of 37.5%. There has been no observed evidence of issues operating at a higher amplitude or duty cycle if required.

CONCLUSION

The ReA3 RFQ upgrade mitigated the risks of water leaks into the vacuum chamber which previously resulted in unscheduled interruptions of beam delivery to our users. The trapezoidal modulation allowed reducing the RF power consumption which in turn enabled the high-power pulsed and CW operation. Thanks to the detailed analysis of the peak fields in the whole 4-rod structure including end gaps and stems, and minimization of the peak field magnitudes, the RFQ operation for ions with A/Q of at least 4.8 is reliable now.

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