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COMMISSIONING OF THE FRIB/NSCL NEW ReA3 4-ROD RADIO FREQUENCY QUADRUPOLE ACCELERATOR

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Abstract

The ReAccelerator facility ReA3 at the National Superconducting Cyclotron Laboratory is a state-of-the-art accelerator for ions of rare and stable isotopes. The first stage of acceleration is provided by a 4-rod radio-frequency quadrupole (RFQ) at 80.5 MHz, which accelerates ions from 12 keV/u to 530 keV/u. The internal copper acceleration structure of the RFQ was re-designed. The goal was to improve transmission while allowing to operate the RFQ in CW and accelerating ions with A/Q from 2 to 5. In this paper, we summarize the steps involved in the disassembly of the existing structure, preparation work on the retrofitted vacuum vessel, installation of the new components, and commissioning of the completed RFQ.

BACKGROUND

The original RFQ was received from the vendor in 2010. After initial commissioning tests, as well as an upgrade completed in 2011 to install improved tuning plates and internal water line clamps, the original structure has been in service to deliver beam to users up until April 2019.

Several issues with the design of the original structure became apparent upon commissioning. RF finger contact failures resulted in damage to stem O-ring vacuum seals. Additionally, clamps designed to create RF contact between the exposed electrode/rod water cooling lines and the stems failed to provide adequate contact, thus causing RF current to pass through the mounting screws vaporizing them [1]. The upgrade in 2011 addressed these two failure modes by replacing all tuning plates with versions with solid silver plates with hammered wedges to improve the stem to tuning plate connection. In addition, the electrode water line clamps were improved to create better surface contact, as well as increasing the mounting screw diameter to allow more torque to be applied to the screws.

After these modifications, average power was limited to 40 kW. This allowed for CW operation of beams with an A/Q of 2. Higher voltages, allowing for beams with an A/Q up to 4 were possible at reduced duty factors. Due to the pulsed nature of EBIT ion source, this did not represent any issue with beam operation, except for the inability to accelerate beams up to an A/Q of 5. Despite the upgrades, additional failure modes resulted in reduced operational reliability. On at least three occasions, electrode/rod water line braze joints failed resulting in in-vacuum cooling water leaks. These required that at least a portion of the structure be disassembled to make repairs to the braze joints.

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In the past few years, the original vendor of the RFQ had modified the design of their 4-rod structures with several notable improvements: electrode/rod water lines are now e-beam welded and passed through the stems, so do not see any RF current. The tuning plates no longer use RF finger contacts between plates and stems, but rather more substantial copper L-brackets held in place with screws. After seeing an example of the new design, a contract was made with the company to construct all new internal copper components to retro-fit the existing tank. Design and modelling of the new electrode/rod modulations, including a new trapezoidal design, was handled in-house by NSCL/FRIB staff [2,3,4].

DISASSEMBLY

The planned refurbishment of the RFQ was accelerated due to an in-vacuum cooling water leak which developed through the silver cap of one of the 17 RFQ cell's tuning plates. The leak was identified through helium leak checking, 5 electrode/rod segments were removed in order to access and remove the tuning plate from the RFQ tank, and the leak was repaired with silver solder. However, by this time, the new RFQ components had already shipped from the vendor, so the decision was made to proceed with the refurbishment immediately rather than reassemble the repaired components.

In total, 16 electrode/rod segments, 18 stems, 17 tuning plates, 70 water line vacuum fitting assemblies (each consisting of one Swagelok Ultra-Torr, one Swagelok tube fitting, and one Swagelok NPT O-Seal fitting), nylon tubing for 30 cooling water circuits and their related tube fittings, and 30 return water line temperature sensors were removed. This left only the tank/vacuum vessel with input coupler, two movable tuners, two copper end plates, and vacuum systems attached.

VACUUM VESSEL PREPARATION

Cooling Water Line Vacuum Fittings

After disassembly of the old structure, it was necessary to re-tap the tank with British Standard Parallel Pipe (BSPP) threads to accommodate the new custom vacuum fittings for the cooling water line penetrations. The new fittings are a significant improvement, as only one fitting is required between the tank and water lines, as opposed to the previous assembly of 3 fittings. The tank was previously tapped with shallow National Pipe Taper (NPT) threads to accept the previous Swagelok NPT O-Seal fittings.

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Significant scratching to the BSPP fitting O-ring sealing surfaces on the aluminum tank was also observed. This resulted in several vacuum leaks after assembly that required the fittings to be removed from the back and the aluminum surfaces polished with a flexible shaft rotary tool with silicon carbide impregnated polishing wheels, and then subsequently cleaned with acetone and alcohol.

Tank Polishing

The interior of the tank was discolored in many places due to the evaporation of several in-vacuum screws as well as RF discharge and heating issues which had occurred throughout its operational period. To better identify any new problem areas that might arise with the new RF structure, the tank interior was polished/wet sanded (Fig. 1) with deionized water and progressively finer grit silicon carbide embedded foam pads designed specifically for cleaning vacuum evaporation and deposition equipment in cleanrooms.

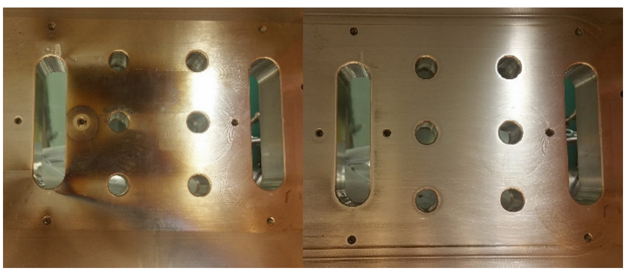

Figure 1: An area of the tank surface before and after the polishing procedure.

Cleaning

Due to the RFQ's one meter proximity to the downstream superconducting radio-frequency (SRF) LINAC cavities, the tank and all components needed to be cleaned to Federal Standard 209E Class 1000 or better cleanroom particulate levels. In addition, as only one vacuum pumping station separates the RFQ from the next downstream SRF cavity, the lowest possible vacuum pressures were desired to minimize cryo-pumping of any residual gases onto the SRF cavity surfaces.

All new parts supplied by the vendor were put through the lab's standard ultra-high vacuum (UHV) cleaning process, consisting of wiping with acetone and alcohol, steam cleaning with deionized water, a heated ultrasonic bath in Citranox acid based detergent, followed by a rinse and second ultrasonic bath in deionized water, and then drying with a nitrogen gas purge.

Due to the size of the vacuum vessel, after the polishing procedure, it was cleaned in situ: first by vacuuming to remove any loose debris, then with 65 PSI deionized steam, followed by cleanroom polyester wipes saturated first with acetone, and followed by alcohol. Laser particle counts were completed after these steps, as well as during assembly.

ASSEMBLY

Assembly was approached in the order of stems, followed by tuning plates, then electrodes, and finally water line vacuum fittings (Fig. 2). All new Viton fluoroelastomer O-rings (174 in total) were used for vacuum seals during the refurbishment to extend the operational lifespan as much as possible.

After installation of the stems and tuning plates, it was observed that the electrode/rod sections did not align properly with their mounting holes and grooves on the supporting stems. Measurements done with a laser tracker and CMM arm indicated deviations from a straight line of 0.4 mm in the vertical and <1 mm in the horizontal direction. It was necessary to loosen the clamps holding the stems into position in order to attach the electrodes, and then afterward tighten the stems. CMM arm measurements done after this step showed straight line deviations of <1.1 mm for the screw head locations attaching the electrodes.

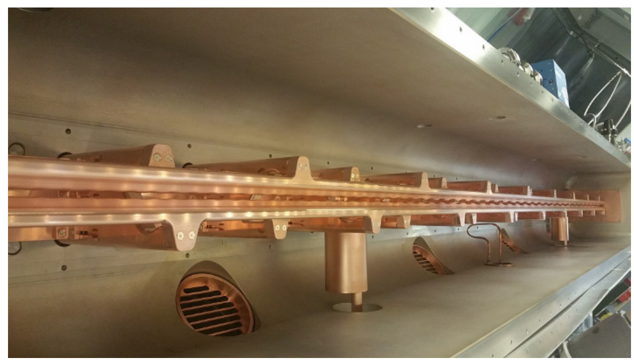

Figure 2: Copper components of the RFQ structure after installation.

RF TUNING

The initial iterative process of RF cell flatness tuning was completed by representatives of the RFQ vendor over a several day period. A 1 pF perturbation capacitor was used across the electrode gap of each RF cell. The resulting frequency shift, with versus without the capacitor, as measured on a vector network analyzer, was used to determine the overall voltage distribution on the electrodes, as was done with the previous RFQ structure [5]. Tuning plate heights were adjusted as necessary to reduce the variation between cells and to achieve the desired overall frequency. A 2.3% flatness was obtained at the end of the process and screws of all tuning plates torqued down.

Next, measurements of the RF resonant frequency versus the movable tuning plunger insertion depth were made. This active tuner range was determined to be 80.465 to 80.719 MHz at 32 °C (80.5 MHz is the nominal operating frequency). Optimization of the input coupler loop position was completed in order to improve coupling and minimize the S11 value to -20 dB. RF pickup loops were then sized and rotated to achieve the desired S21 value for the LLRF system feedback loop. The loaded Q value of the cavity was measured to be between 1851 and 1886. After completion of all necessary measurements, the transmission line was reconnected to the RF amplifier, which had undergone

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simultaneous independent testing and repairs throughout the RFQ assembly process using a dummy load.

WATER COOLING

The new RFQ structure contains 53 individual water cooled components. In order to determine required cooling water flow rates, a nominal flow velocity of 2 m/s was selected. Volumetric flow rates were calculated per component using this velocity based on the diameter of the water cooling channels. In cases where the cooling channel diameter varied, the largest diameter (highest flow rate) was used in the calculation. Components were distributed amongst the existing 8 low-conductivity water (LCW) manifolds in a manner to ensure balanced water flow (Fig. 3).

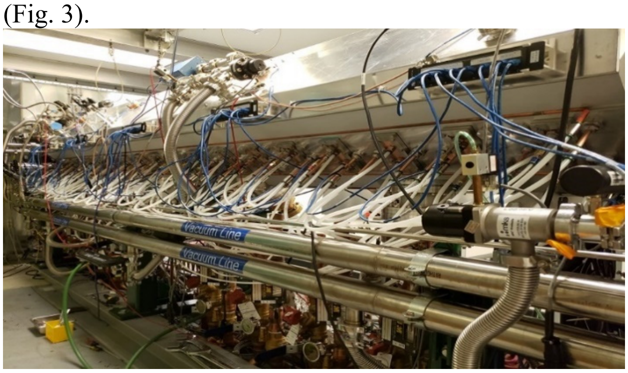

Figure 3: View of the back of the RFQ tank showing water cooling lines and return water temperature sensors.

Due to the new assembly having longer and fewer electrode sections, as well as different diameter tubing interfaces, plumbing fittings on the LCW manifolds had to be replaced. The original push-to-connect tube fittings that were used on all copper water lines on the original RFQ would not grip properly on the stainless steel tubing of the new electrodes. A compression style fitting using a rubber ferrule was selected as a suitable replacement, as a standard compression fitting with metal ferrule would not allow for the later removal of the electrode sections if necessary.

INITIAL COMMISSIONING

Conditioning of the structure with RF power proceeded quickly. Vacuum pressure was initially the limiting factor: the RF amplitude was raised slowly to keep the pressure under 1.0 x 10^{-5} Torr to avoid any possible glow discharge effects. After 50 hours of operation, a pressure below 1.0 x 10^{-7} Torr during RF operation was obtained.

The next limiting factor became the movable tuning plungers: the tuning range is not sufficient to counteract the frequency shift due to the heating of the tank during CW operation. It is currently limited to about 12 kW average power due to this effect, although it was conditioned to 25 kW CW in self-excited loop. The structure has been conditioned up to 90 kW peak power at 13% duty factor, limited by the RF amplifier. Measured X-ray dose rates appear significantly lower than the previous cavity, indicating less field emission activity from the structure.

Acceleration of a $^{14}N^{6+}$ beam was successful with a measured 84% transport efficiency using pre-bunched beam from the upstream multi-harmonic buncher (MHB). Measurements of beam transmission versus RF amplitude were completed to determine the optimal setpoint (Fig. 4). Beam energy measurements completed with a calibrated dipole magnet indicate a measured exit energy of 540 keV/u.

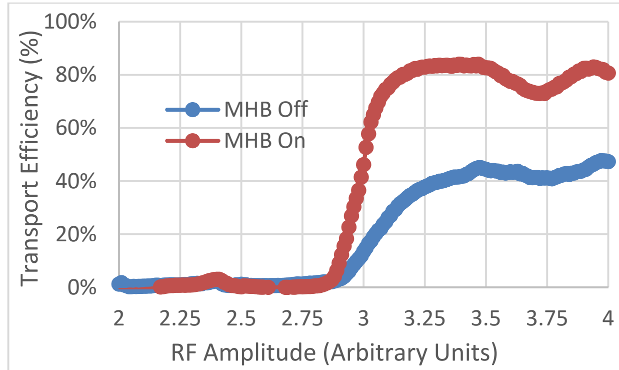

Figure 4: RFQ transport efficiency as a function of RF amplitude, with and without the multi-harmonic buncher.

CONCLUSION

The commissioning results thus far in terms of transport efficiency and exit energy agree with the simulated values (86% and 535 keV/u). The peak power reached with the new structure should allow for acceleration of ions with an A/Q up to 4.37, which is already higher than the previous structure. Additional conditioning and amplifier tests are required to increase the peak power to the level required for acceleration of beams with an A/Q of 5.

Within two weeks of initially applying power, the RFQ is already being operated in pulsed mode to deliver beams to user experiments. Future plans to address the tuning for higher duty factor operation include replacing the plungers at the end of the active tuners to lower the frequency, and possibly adding water cooled plates to the tank exterior.

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