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REDESIGN OF ReA3 4-ROD RFQ*

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Abstract

The present RFQ of ReA3 reaccelerator at Michigan State University (MSU) was commissioned in 2010. This 4-rod RFQ was designed to accelerate the prebunched 80.5 MHz beams with the lowest Q/A = 1/5. However, the lack of proper cooling limited the RFQ performance to the pulsed operation with the lowest Q/A = 1/4. The design voltage for Q/A = 1/5 has never been reached even in a pulsed mode due to the sparking. In 2016 we initiated the upgrade of ReA3 RFQ to support high duty cycle (up to CW) operation with Q/A = 1/5 beams. The upgrade included the new rods with trapezoidal modulation, and new stems with improved cooling. The redesigned 80.5 MHz RFQ will consume only 65% rf power of the present RFQ for Q/A = 1/5 beam. It will provide the transmission up to 78% for 16.1 MHz beams and 86% for 80.5 MHz beams. High reliability and efficiency of the RFQ are very important for the going-on reaccelerator upgrade to ReA6 and for future operation as a part of FRIB.

The electrodes have been fabricated and installed inside the tank. The RF and beam tests started in August 2019.

INTRODUCTION

ReA was commissioned as ReA3 in 2015 [1] and currently accelerates RIBs with Q/A from 1/4 to 1/2 at the energy range from 0.3 to 6 MeV/u. The ongoing ReA3 upgrade includes: (a) replacement of the ReA3 RFQ electrodes to improve the cooling and to provide higher capture efficiency for 16.1 MHz bunches with Q/A down to 1/5, (b) adding another three cryomodules after the ReA3, (c) installation of the new electron beam ion source (EBIS) with 5 Ampere electron gun, (d) new RF controllers.

The ReA3 RFQ was commissioned in 2010, however it has never reached its design voltage for Q/A = 1/5 due to the sparking and operated in pulsed mode due the cooling system limitations.

UPGRADE STRATEGY

In order to provide the reliable CW operation of the 80.5 MHz ReA3 RFQ the electrodes were redesigned to reduce the inter-vane voltage from 86.5 kV to 70 kV, peak fields from 1.6 to 1.45 Kilpatrick units, RF power consumption from 120 kW to 80 kW. The 4-rod RFQ tank and the length of the electrodes remain the same. To gain more energy at reduced voltage we implemented the trapezoidal modulation of the electrodes in the acceleration section of the structure. We reduced the mid-cell aperture radius to keep the focusing strength. Synchronous phase changed from fixed -20° to variable from -60° to -20° to capture the prebunched 16.1 MHz beams essential for time-of-flight measurements in nuclear physics experiments. Output radial matcher of the RFQ was modified as well to provide round beam for the following superconducting linac with solenoidal focusing.

Finally, we modified the RF structure to reduce the peak surface electric fields and improve the cooling design.

MODULATION

Redesign of the modulation included analysis of the existing 4-rod ReA3 RFQ to find the reasons for sparking. Prior to the design of new electrodes we analysed possible causes of sparking in the original electrodes' geometry.

Analysis of the 4-rod Structure

A 4-rod structure is a periodical series of coupled RF cells. The periodicity creates a variation of electrode potential (voltage between the electrode and a tank) along the resonator. The variation of voltage between rods appears to be not very high – a fraction of percent. At the end of the structure we have two opposite rods with low potentials, and two other rods with high potential. The voltage between the last ones and the tank may reach 87% of the rod-to-rod voltage in the case of ReA3 RFQ, which is 1.74 times larger than in longitudinally uniform 4-vane structure. This may significantly increase the peak surface electric fields at the end of the rods (see Fig. 1).

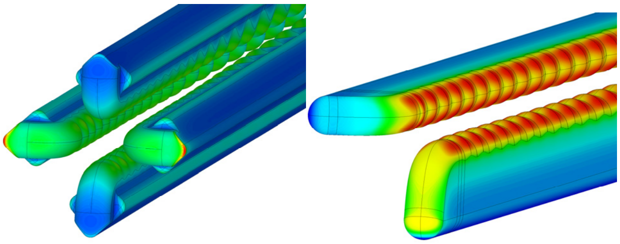

Figure 1: Surface peak electric field at the end of existing ReA3 RFQ (left) and new redesigned ReA3 RFQ (right).

Due to the periodicity, one of the rods is always located close to the stems holding the opposite potential. Peak fields in these areas are usually very high too (see Fig. 2).

Another feature of the 4-rod structure is a lack of quadrupole symmetry. This results in an increase of potentials of top two rods and induction of a dipole electric field component on a geometrical beam axis [2]. Peak fields increase by about 5%.

In the new design of the electrodes we applied proper curvatures and gaps as one can see in Fig. 1 and Fig. 2.

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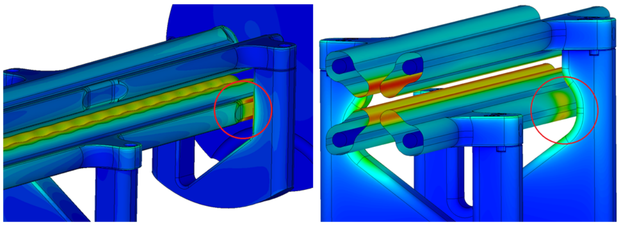

Figure 2: Peak fields in a gap between a stem and a rod in a non-optimized (left) and optimized (right) geometry.

Modulation Design

Currently, there are no RFQ code to design the electrodes with both sinusoidal and trapezoidal modulation. We developed our own approach using a computer-aided design (CAD) model is CST Studio [3]. The design procedure included two steps – preliminary design, when we roughly calculate the RFQ cells' geometry, and final design, when VBA macro in CST Studio automatically adjusts the geometry cell-by-cell to match the design law of synchronous phases. The detailed description of the approach described elsewhere [4].

Figure 3 presents the plot of RFQ parameters. One third in the RFQ length is used for the adiabatic bunching [5]. The rest part has a trapezoidal modulation with a constant accelerating gap length of 15 mm.

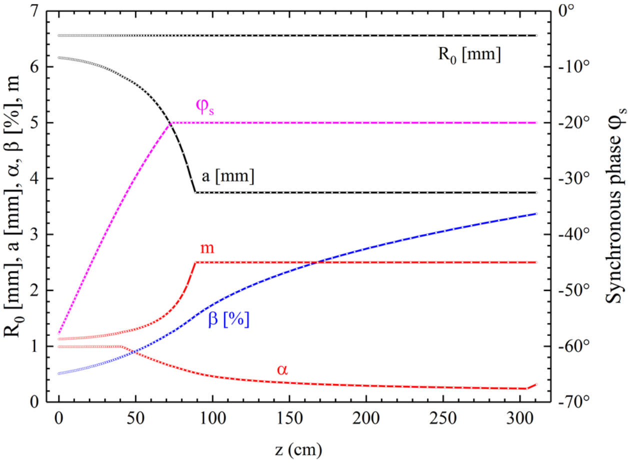

Figure 3: ReA3 RFQ cell-by-cell parameters.

In order to make a continuous and smooth electrode profile along the whole RFQ, we developed a profile for a single RFQ cell, which provides positional and tangential continuity with the adjacent cells. Figure 4 shows the transverse and longitudinal profiles of the RFQ cell. The radius of the electrode tip curvature R_v does not depend on the distance from the longitudinal axis to the electrode. The longitudinal profile of the jth cell consists of two straight parts of zero slope tangents and a sinusoidal junction of the length g_j, which is called the accelerating gap of the trapezoidal RFQ cell. The total length of the jth cell is L_j. Trapezoidal cells have $g_j < L_j$, while sinusoidal cells have $g_j = L_j$. Another two parameters define the jth cell cross section at its entrance: R_j is the average aperture radius at the jth cell entrance, and m_j is the modulation factor at the jth cell entrance. The cross section at the end of the jth cell is obviously the same as the entrance cross section of the (j+1)th cell.

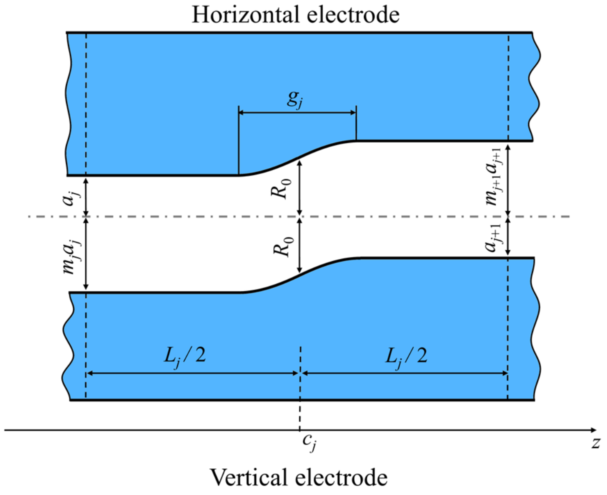

Figure 4: Electrode profile.

The advantage of the trapezoidal modulation is the increased transit-time factor compared to the sinusoidal electrodes. Similar to the drift-tube accelerating structures the shorter gap provides higher transit-time factor (see Fig. 5).

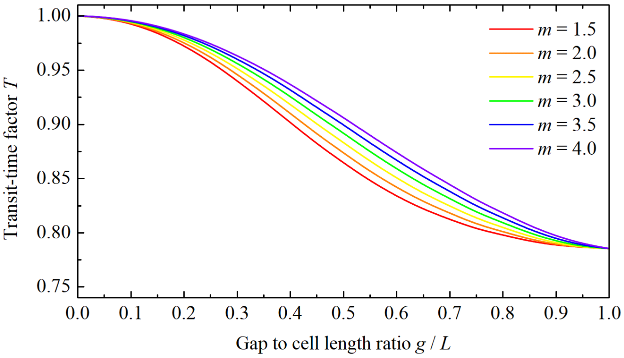

Figure 5: Transit-time factor of a trapezoidal cell.

Careful design allows increasing of the RFQ efficiency and energy gain rate while keeping the peak fields low. Figure 6 shows the peak field distribution in the new ReA3 RFQ. Constant accelerating gap along the structure, equal to g = 2.6R_0 or 15 mm, makes peak fields the same in every cell of the accelerating section of the RFQ.

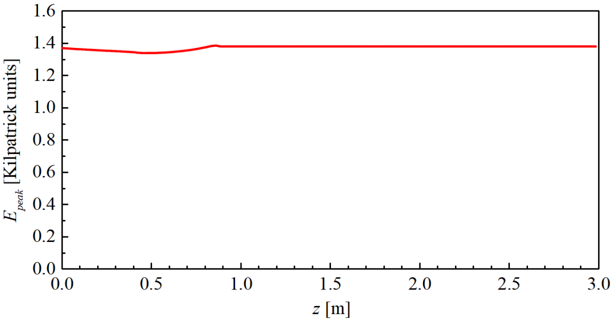

Figure 6: Surface peak field distribution along the RFQ.

The total gain from the trapezoidal modulation is presented in Fig. 7. After we reduced the design operational voltage, the RFQ output energy dropped from 600 keV/u to about 470 keV/u, while trapezoidal modulation partly recovered it to 535 keV/u.

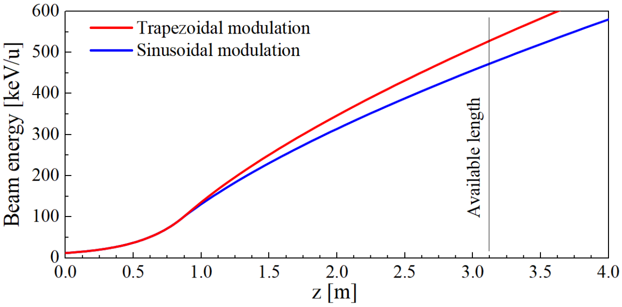

Figure 7: Energy gain in RFQs with trapezoidal and sinusoidal modulation.

Output Radial Matcher

The input radial matcher section was kept the same as in the existing RFQ. The output radial matcher was modified for better axial symmetry of the beam, exiting the RFQ, since the RFQ is followed by a superconducting linac with a solenoidal lattice.

The profile of the matcher is defined by the equation:

$$r(z) = \frac{R_0}{\sqrt{(1-p)\cdot cos\left(\frac{\pi}{2\beta\lambda}z\right)^2 + p\cdot cos\left(\frac{3\pi}{2\beta\lambda}z\right)^2}},$$

where β is the relative beam velocity at the RFQ end, λ – wavelength of the RFQ RF field, p – geometry parameter, which was found to be equal to 0.18 for the best beam symmetry.

BEAM DYNAMICS SIMULATION

As a result of the automatic design procedure driven by the VBA macro, the electrostatic model of the RFQ was built in CST Studio. We evaluated the peaks fields and extracted the 3D field distribution for beam dynamics simulation in TRACK [6]. The tracking simulation confirmed that the design synchronous phases in each cell are the same as designed. Figure 8 presents phase-space plots of the beam at the entrance and exit of the RFQ.

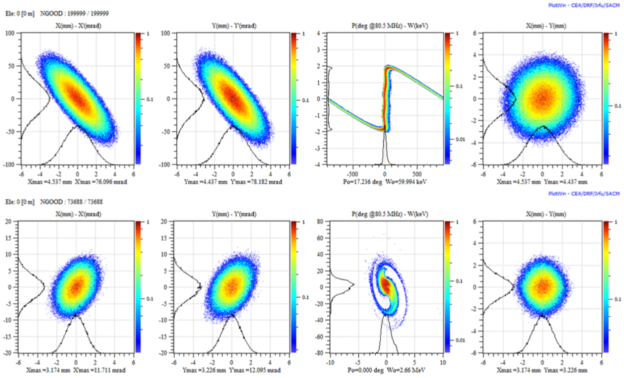

Figure 8: Input (top) and output (bottom) beam phase-space plots.

RF CONDITIONING AND BEAM COMMISSIONING

The new internal component of the RFQ were fabricated by Kress GmbH [7] and delivered to MSU in May 2019. All parts were cleaned and installed into the existing tank. Figure 9 shows the new RF structure in the tank. After the tuning of frequency and field flatness the RF conditioning and beam commissioning were started. Two days later the RFQ accelerated the first beam of $^{14}N^{6+}$ to the design energy. Beam transmission with 2-harmonic multi-harmonic buncher was 84%, while the simulated value is 86%. More details on the commissioning can be found in a separate paper [8].

Figure 9: New ReA3 RFQ structure.

REFERENCES

[1] A. C. C. Villari *et al.*, “Commissioning and First Accelerated Beams in the Reaccelerator (ReA3) of the National Superconducting Cyclotron Laboratory, MSU,” in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 1287-1290. `doi:10.18429/JACoW-IPAC2016-TUPMR024`

[2] S. S. Kurennoy, E. R. Olivas, and L. Rybarcyk, “Design Analysis of the New LANL 4-Rod RFQ,” in *Proc. North American Particle Accelerator Conf. (NAPAC'13)*, Pasadena, CA, USA, Sep.-Oct. 2013, paper MOPMA16, pp. 333-335.

[3] CST Studio Suite, `http://www.cst.com`

[4] A.S. Plastun and P.N. Ostroumov, *Phys. Rev. Accel. Beams*, vol. 21, p. 030102, 2018.

[5] T. P. Wangler, *RF Linear Accelerators*, New York: Wiley-VCH, 2008.

[6] The beam dynamics code TRACK, `http://www.phy.anl.gov/atlas/TRACK`

[7] Kress GmbH, `https://www.kress-gmbh.de/en/index.html`

[8] S. Nash *et al.*, “Commissioning of the FRIB/NSCL New ReA3 4-Rod Radio Frequency Quadrupole Accelerator,” presented at NAPAC’19, Lansing, MI, USA, Sept. 2019, paper WEPLH07, this conference.