RF DESIGN OF THE NUCLOTRON-NICA 145.2 MHz RFQ

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Abstract

ITEP has designed the Radio-Frequency Quadrupole (RFQ) linac for the JINR NICA Complex (Dubna, Russia) to provide ion beams ($q/A \geq 0.3$) with energy of 156 keV/u for further acceleration by existing Alvarez-type linac. The RFQ is based on a 4-vane structure with magnetic coupling windows in order to avoid a risk of excitation of dipole field components inherent in a conventional 4-vane resonator. The paper presents results of the radio-frequency (RF) design and capabilities used for coarse and fine tuning of the field distribution and resonant frequency during manufacturing and finalizing of the RFQ.

INTRODUCTION

In a framework of the Nuclotron-based Ion Collider fAcility (NICA) project [1] at Joint Institute for Nuclear Research (JINR, Dubna, Russia) upgrade of the accelerating complex front-end is being performed [2]. The upgrade includes replacement of the 700-kV accelerating tube for the LU-20 drift-tube linac (DTL) with an RFQ [3] and development of a brand new heavy ion injector based on a 4-rod RFQ and IH-DTL sections [4].

LU-20 is a conventional Alvarez-type DTL used for acceleration of proton and ion ($q/A \geq 0.3$) beams at the frequency of 145.2 MHz. The RFQ designed by ITEP provides 156 keV/u ion beams for following acceleration by the DTL at 2βλ-mode to the energy of 5 MeV/u [3].

The 145.2-MHz RFQ is based on a 4-vane resonator with magnetic coupling windows [5]. The structure provides both reliable dipole-free range and compactness compared to a conventional 4-vane. Higher RF power losses of the structure is not an issue for the RFQ injector since it operates in a pulsed mode at RF pulse width less than 150 µs and repetition rate not higher than 1 Hz.

RESONATOR DESIGN

The 2-meter long RFQ is built from 3 segments (see Figure 1) or 4.5 periods of the RF structure (see Figure 2). Each segment has a length of 690 mm and tank inner diameter of 400 mm. The average aperture radius $R_0 = 6.5$ mm and the vane tip radius $R_e = 5.2$ mm remain constant along the resonator. The cost-effective mechanical design of the RFQ has assumed vanes made of carbon steel and fastened to stainless steel tanks with screws. The whole resonator (except the vane tips) has been copper-plated after the fine machining. Photograph of the resonator segment #1 with installed vanes is shown in Figure 3.

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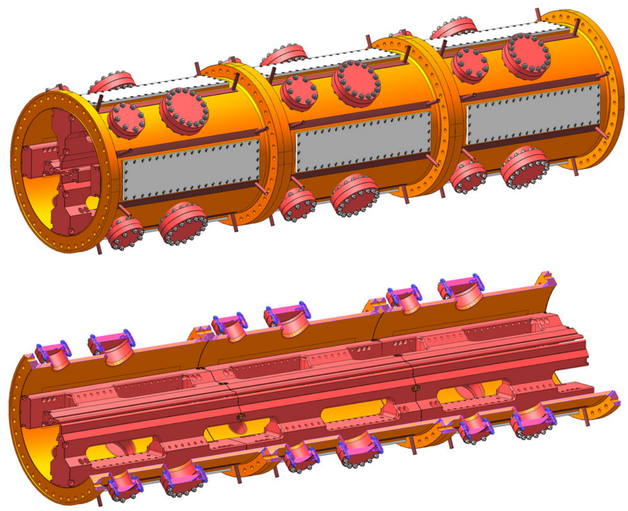

Figure 1: 3D model of the RFQ resonator.

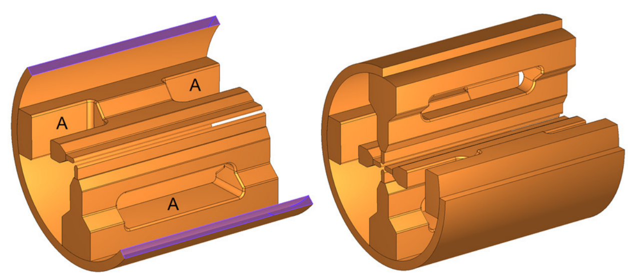

Figure 2: 3D model for the RF period of the 4-vane resonator with coupling windows.

Coupling Windows

Dimensions of the coupling windows have been adjusted in order to provide both reliable frequency range between the operating and nearest dipole modes, and convenient mechanical design. The dipole-free frequency range is required to get proper distribution of the electric field components in the accelerating channel. Dipole field components are suppressed by moving dipole modes of the resonator far away (about 10 MHz higher) from the band of the operational quadrupole mode [6]. This task as well as the whole RF design of the RFQ has been done with CST STUDIO SUITE [7].

Frequency Adjustment

The mechanical design assumed the resonant frequency adjustment during the manufacturing by whittling down the surfaces of coupling windows (surfaces A in Figure 2)

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equally for each electrode. The windows have been designed to get the resonant frequency of 146.6 MHz, i.e 1.4 MHz higher than the operational one. Sensitivity of the resonant frequency to the transversal size of the window has been defined by 3D simulation much more precisely than the resonant frequency itself. After the fine machining and before the copper plating, the resonant frequency has been measured and new window height has been calculated. Windows have been milled by 2 mm.

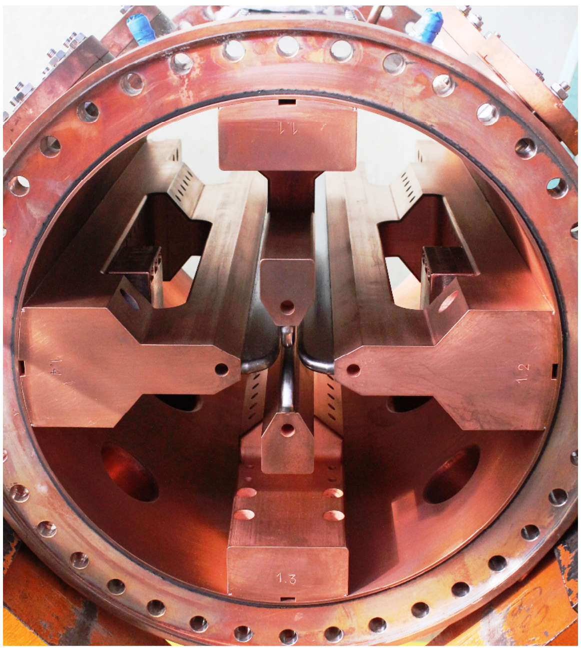

Figure 3: Resonator segment #1.

SIMULATION RESULTS

The RF design of the whole resonator is based on the simulation result for the half of an RF period of the structure (Figure 2).

Field Distribution

Unlike conventional 4-vane, a structure with adjacently displaced coupling windows has longitudinal components of the surface current, inducing the azimuthal magnetic field, which joins all four chambers of the resonator and provide better transverse stability of the field distribution.

Periodicity of the resonator structure leads to corresponding periodical deviations of the electromagnetic field. For the designed resonator such deviations don't exceed 0.5%. (see Figure 4 for unmodulated tips).

Main components of the simulated 3D electric field along the resonator with modulated tips are presented in Figure 5. Due to the absence of the strong quadrupole symmetry of the structure the RF electric field has a non-zero longitudinal component at the z-axis in the end gaps. This field component appears as two peaks of E_z at $z = 0.0$ m and $z = 2.1$ m in Figure 5. In order to suppress the effect of this field on the beam dynamics, the lengths of the end gaps are made equal to $\beta\lambda$, where $\beta = v / c$ is a normalized velocity of the beam in the gap and $\lambda = c / f$ is the wavelength of RF field.

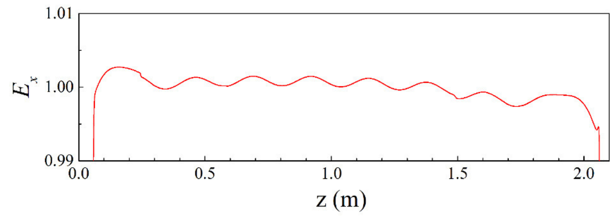

Figure 4: Normalized distribution of the electric field transverse component along the resonator (simulation).

RF Parameters

The list of RF parameters achieved with simulation and measurements is presented in Table 1. Simulation results correspond to the whole-copper 3D model which didn't include ferromagnetic losses on the steel vane tips.

Table 1: RF Parameters of the RFQ

Parameter	Value
Operating frequency	145.2 MHz
Dipole mode frequencies	156 MHz
Inter-vane voltage	125 kV
Quality factor (sim / meas)	9500 / 4600
Shunt impedance (sim / meas)	43/21 kΩ
Wave impedance of dipole modes	~ 100j Ω
RF power losses (sim / meas)	200 kW / 420 kW
Peak surface electric field	25 MV/m (1.92 Kilp)

TUNERS & COUPLERS

Two movable tuners (see Figure 6) are installed into the central segment of the resonator through two opposite CF100 ports. These tuners are controlled remotely and used to compensate the frequency detuning caused by temperature variations of the resonator geometry.

Tuning copper bricks are installed inside the coupling windows (see Figure 3) for field adjustment and frequency tuning. One pair of bricks is installed in the front-end coupling windows, another – in the back-end windows, and third pair in the center of the resonator. Fine tuning was performed by positioning of the bricks in the windows. After the alignments all bricks were fastened by screws. This tuning approach allows getting more free CF100 ports for pumping unlike the conventional slug tuners.

The resonator uses two identical RF coupling loops (see Figure 6) installed symmetrically in CF100 ports of the middle segment of the RFQ. The area of the loops is about 870 mm^2. The non-compensated inductance of the couplers leads to a resonant frequency decrease by ~ 33 kHz. The maximum coupling is obtained with the loop rotated by 15° from vertical orientation. Fine adjustment of the input impedance is carried out by free loop rotation.

CF63 ports are used for RF voltage feedback pick-up loops, vacuum gauges and bypass vacuum line.

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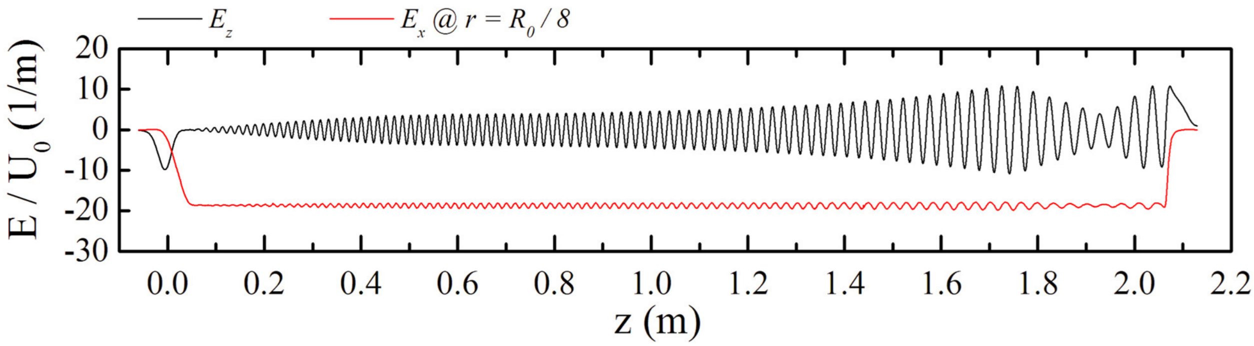

Figure 5: Components of the simulated 3D electric field along the RFQ.

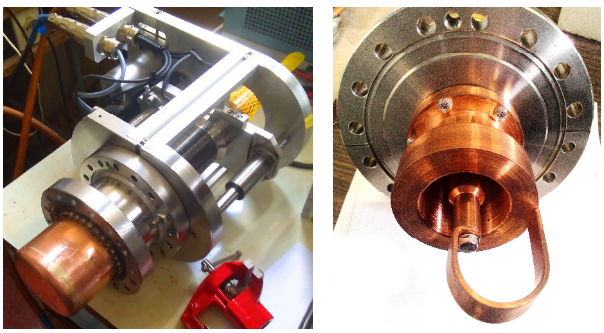

Figure 6: Frequency tuner assembly (left) and RF coupling loop (right).

MEASUREMENTS

The bead-pull measurements of the electric field distribution in each chamber of the resonator have been performed with a dielectric ball (see Figure 7). Balance between the chambers and longitudinal profile of the electric field has satisfied the requirements of the beam dynamics. Moreover, tuning by the bricks provide a good opportunity for the following improvement of the field longitudinal flatness and transverse balance.

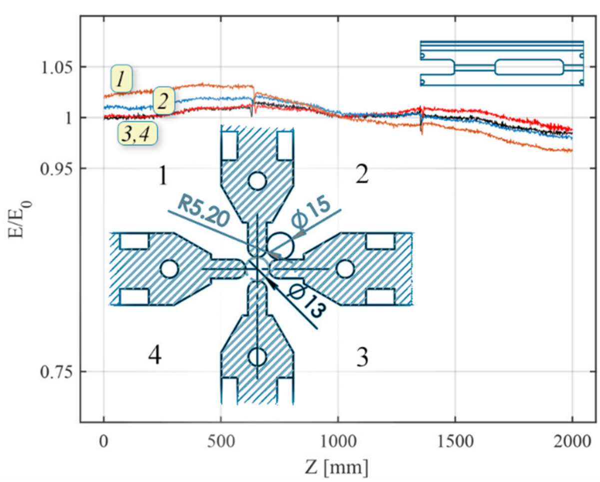

Figure 7: Measured distribution of the electric field along the RFQ chambers.

CONCLUSION

The designed RFQ has been successfully fabricated, assembled and aligned by the Zababakhin All-Russian Scientific Research Institute of Technical Physics (VNIITF). After the transportation to ITEP minor adjustments of the resonator vanes have been done. Movable frequency tuners, RF coupling loops, and frequency tuning bricks have been installed following the primary bead-pull measurements. The RFQ has successfully passed the vacuum test and high power RF commissioning had been started. The maximum available RF power has been successfully fed into the RFQ after the mechanical polishing of the vane tips and several weeks of the RF conditioning.

The RFQ has been moved to JINR in October 2015 for beam commissioning [8, 9]. In May-June 2016 the run of Nuclotron with the RFQ has been held successfully for the first time.

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