THE PARAMETERS OF RADIO FREQUENCY QUADRUPOLE LINEAR ACCELERATOR FOR DARIA PROJECT

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Abstract

The new proton linear accelerator (linac) with output energy 13 MeV and 100 mA current is under development at NRC “Kurchatov Institute” - ITEP for DARIA project. The linac consists of Radio-Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) with operating frequency 162.5 MHz.

The RFQ is based on 4-vanes structure with shifted coupling windows. DTL has a modular structure and consists of separated individually phased cavities with focusing magnetic quadrupoles located between the cavities. The DTL is based on interdigital H-mode (IH-DTL) 5-gaps cavities. The 6D beam matching between RFQ and DTL is provided by magnetic quadrupole lenses and RF-bunchers.

The paper presents results of the radio-frequency (RF) design, thermal analyses and RF tuning of RFQ linac accelerating structure.

Key words

DARIA, Linac, RFQ, neutron source, compact neutron generators.

1 Introduction

The 13 MeV 162.5 MHz linac for acceleration of 100 mA pulsed (pulse length is 100 μs and repetition rate is 100 pps) proton beam is under development at ITEP. The linac is designed for the DARIA project (neutron source Dedicated to Applied Research and Industrial Applications) directed to the development of compact neutron generators for Universities, Scientific Centers and Industry [Grigoriev et al., 2019].

The proton linac consists of $\approx$ 5.4 m long RFQ with operating frequency 162.5 MHz and $\approx$ 5.9 m long DTL with the same operating frequency. The RFQ is based on 4-vanes structure with shifted coupling windows The DTL consists of 6 separate individual phased interdigital H-mode (IH-DTL) 5-gaps cavities (see Fig. 1).

The low energy beam transport (LEBT) line provides the proton beams delivering from the ion source to the input of RFQ with minimal losses and with parameters providing the best proton capture into acceleration process. The medium energy beam transport (MEBT) line provides the transport and 6D matching of proton beam accelerated in RFQ to the input of IH-DTL.

According to beam dynamics simulation the RFQ‘s vanes length should be equal to 5446 mm, average aperture radius $R_0 = 9$ mm, vane tip radius $Re = 0.8R_0 = 7.2$ mm. The resonator is operated at frequency 162.5 MHz.

The RFQ cavity consists of 778 mm long 7 sections. Central five regular sections from RF point of view are identical; meanwhile the first and last ones have some

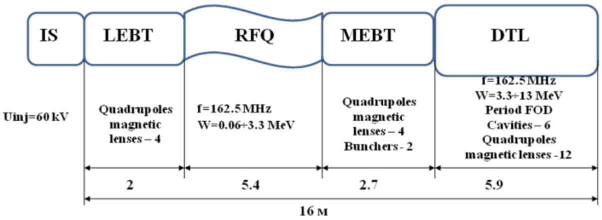

Figure 1. The general scheme of proton linac structure.

speciality. In the article the results of the central resonators development are presented and discussed.

2 RF RFQ design

The principles of operation of the RFQ were first presented by the inventors, I.M.Kapchinskiy and V.A.Teplyakov in [Kapchinskiy and Teplyakov, 1970a; Kapchinskiy and Teplyakov, 1970b]. The RFQ accelerates and focuses the ion beam by electric field at the same time. It achieves by special shape of the electrodes (vanes or rods) which located near the axis of the accelerator and form the acceleration channel. Electrodes are shaped to have a periodically varying gap that matches the RF frequency to the beam velocity at that point in the accelerator. This cause the particles to form bunches in step with the exciting frequency, such that they pass through each region as the local field is near the acceleration maxima.

The RFQ structures subdividing to two main branches: 4-vane structure and 4-rod structure. The 4-vane RFQ consists of a cylindrical cavity divided longitudinally into four quadrants by partitions called vanes. The vanes originate at an inner wall of the cavity and protrude toward the centerline axis. Each quadrant of the RFQ is a separate RF resonator and the combination of the four is used to provide an RF electric quadrupole field at the axis. Since the 4-vane RFQ is an RF cavity, the wavelength of the desired resonant frequency determines the physical dimensions of the cavity.

The 4-rod RFQ consists of four rods supported by transverse structure that form an inductance of a resonant circuit. A corresponding resonant capacitance comes from rod-to-rod electric field. In general, 4-rod RFQ is less efficient than 4-vane RFQ but the physical dimensions of the 4-rod RFQ need not be related to the wavelength of the resonant frequency.

The segmented-vane RFQ (SVRFQ) or RFQ with coupling windows is a combination of the 4-vane and 4-rod RFQ configuration. It is a similar to the 4-vane RFQ but is modified by cutting windows in the solid electrodes to couple magnetic fields in the four quadrants. The effect of the windows is in increasing the frequency separation between working quadrupole mode and parasitic dipole ones. Moreover, windows allow the SVRFQ to be significantly smaller and more easily tuned than conventional RFQ. The “antisymmetric” coupling windows (each vane having windows at locations where an adjacent vane is solid) or shifted coupling windows is used to tune the electric field distribution in the first and last RFQ sections [Andreev and Parisi, 1993; Andreev and Parisi, 1994].

The RFQ structure with shifted windows (“antisymmetric”) was chosen for the project. The regular RFQ section is shown at Fig. 2. The main geometrical and radio frequency parameters for RFQ are presented at Table 1 and 2, correspondently. It should be mentioned that size of coupling windows is not final and could be modified while full RFQ structure RF simulation will be carried out.

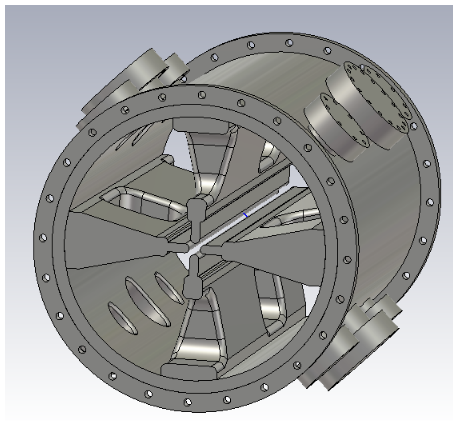

Figure 2. The regular RFQ section.

Table 1. The main dimensions of RFQ (all values in mm)

Parameter	Value
Cavity inner diameter	420
Cavity length	778
Vane base width	90
Vane base height	25
Vane top width	30
Vane window length	180
Vane window height	105
Vane tip height	34.4

The regular RFQ section has four CF100 ports and eight CF63 ports (see Fig. 2). They are used for installation of RF power feeders, RF signal antennas, movable and stationary plungers, vacuum pumps and vacuum detectors.

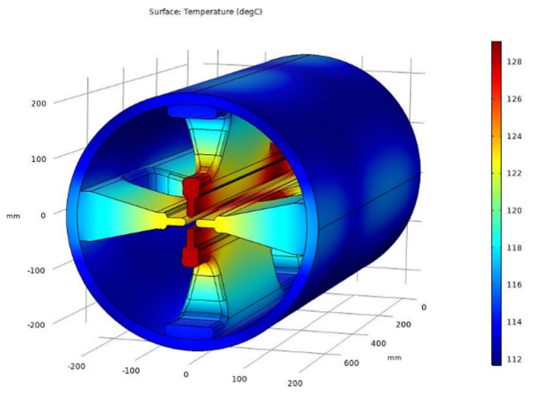

Figure 4. The RFQ section temperature (°C).

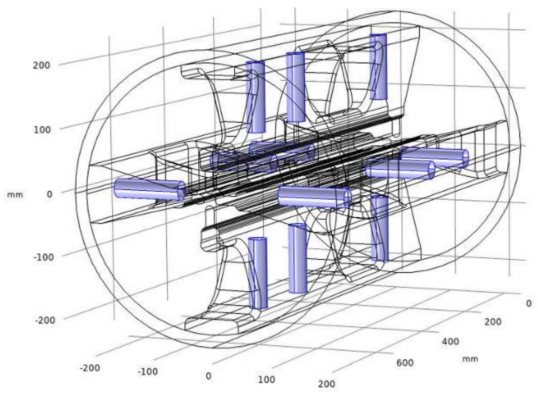

Figure 5. The water channels in RFQ section.

Table 2. The main RF RFQ parameters

Parameter	Value
Resonant frequency, MHz	162.5
Inter-vane voltage, kV	173
Self quality factor	13000
RF power losses, kW/m	125
Full RF power losses, kW	680

3 Thermal RFQ simulation

As it was mentioned above, the linac duty factor is 1%. All elements of the RFQ section were made by coppered stainless steel. The typical surface current distribution at RFQ regular section is shown on Fig. 3.

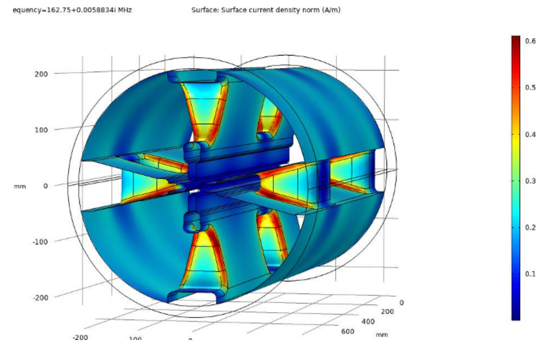

Figure 3. Surface current on RFQ regular section.

From Fig. 3 one can see that maximal current density and therefore the maximal heating is located along surface of coupling windows. The thermal simulation for regular RFQ section with duty factor 1% was carried out by using COMSOL code [COMSOL, 2022]. It was postulated that the output surface of the RFQ cavity has an emissivity coefficient 0.7 with free air convection. The results of thermal analyzes of the RFQ regular section with external air convectional cooling is shown on Fig. 4.

From Fig. 4 one can see that some parts of RFQ section (electrodes) have a temperature up to 120 °C which is not acceptable for linac operation. Therefore the additional cooling of electrodes is needed.

The cooling water channels were designed in electrode as it is shown in Fig. 5. The cooling channels consist of two coaxial tubes: inner one is used for cooling water input meanwhile the outer tube is used as a water output. The diameter of outer tube which characterizes the cooling capability is equal to 30 mm while inner has a diameter 10 mm. During simulation the output surface of the RFQ cavity has the same emissivity coefficient 0.7 with free air convection.

The thermal simulation with various water flow velocity per cooling channel was carried out and is shown at Table 3. From Table 3 one can see that the temperature of 76 °C is reached at 0.05 m/s of water flow velocity and sharply decreases up to 40 °C at 0.1 m/s water flow velocity. The further increasing of water flow velocity doesn't lead to noticeable decreasing of maximal temperature.

Table 3. The maximal temperature vs. water flow velocity

Water flow velocity, m/s	Volume flow rate, l/min	Maximal temperature, °C
0.05	7.5	76
0.075	11.25	58
0.1	15	40
1	150	32
5	750	31
10	1500	30

with water flow velocity of 0.1 m/s is shown on Fig. 6.

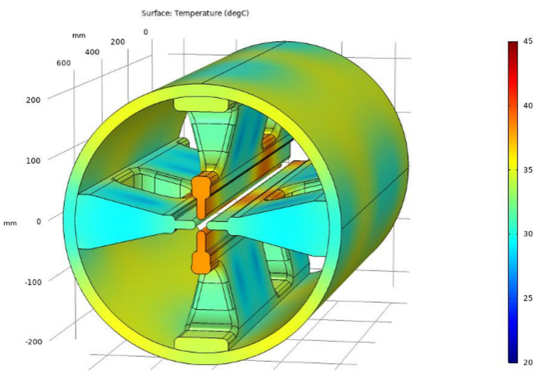

Figure 6. The result of RFQ regular section thermal simulation with cooling channels (the temperature in $^{\circ}$C).

From Fig. 6 one can see that the maximum temperature locates still at the top of electrodes but does not exceed 40 °C. In case if all electrodes were made by copper the maximum temperature would not exceed the 30 °C with the same water flow rate. If the water flow velocity change to 0.075 m/s then the maximum temperature of copper electrodes is increased up to 47 °C. In this case the total volume flow rate reduced from 180 l/m (for 0.1 m/s) to 135 l/m (for 0.075 m/s) per each section.

4 RFQ RF tuning

The RFQ RF tuning is aimed to:

1. Compensate fabrication and simulation errors;
2. For field adjustment;
3. Compensate the frequency detuning caused by temperature variations of the RFQ cavity geometry;

The first adjustment will be carried out during the manufacturing stage by whittling down the surfaces of the coupling windows [Plastun et al., 2017; Koshelev et al., 2017; Andreev et al., 2010]. The field adjustment could be done by mounting the brick shape plungers into the coupling windows. The size and position of the brick shape plungers will be defined after RF measurement of RFQ manufactured if it would be necessary [Plastun et al., 2017; Koshelev et al., 2017]. To compensate the frequency detuning caused by RFQ temperature variation movable plungers injected into the RFQ cavity's volume thought CF100 ports are used. These tuners are controlled remotely.

The simplest movable RFQ plunger is shown on Fig. 7. The plunger diameter is equaled to 90 mm (maximal possible size) while the plunger insertion depth is usually not bigger than the flange diameter. The dependence of frequency shift versus the plunger insertion depth is shown on Fig. 8. From Fig. 8 one can see that one plunger injected into the cavity through the CF100 port can change the resonant frequency up to 350 kHz (or ±175 kHz from intermediate position). It is enough to compensate frequency detuning caused by temperature variations of the RFQ cavity geometry.

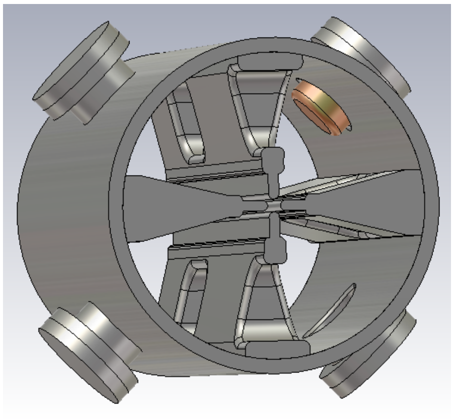

Figure 7. The plunger at RFQ section.

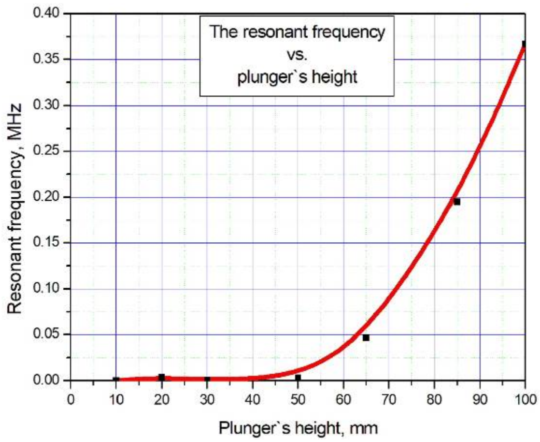

Figure 8. The resonant frequency vs. plunger's height dependence.

5 Conclusion

The new proton linac with output energy 13 MeV and 100 mA current for the DARIA project is under development at NRC "Kurchatov Institute"-ITEP. The linac consists of RFQ with operating frequency 162.5 MHz and DTL with the same operating frequency. The preliminary RFQ RF parameters and accelerator geometry which is a base point for further RFQ development as well as results of thermal simulation and RFQ RF tuning are presented in this paper.

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