BEAM DYNAMICS AND ACCELERATING CAVITY ELECTRODYNAMICS' SIMULATION OF CW 2 MEV PROTON RFQ

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Abstract

The CW proton linac has a number of important applications; serving as the initial part of a high-energy, high-power linac for an accelerator-driven system is the main of them. Its CW operation mode and a 5-10 mA beam current however are limiting factors for the accelerating field. The surface field should not exceed the Kilpatrick field by more than 1.2-1.5 times. This limitation leads to the increase in linac length and beam bunching complexity. The first results of a 2 MeV, 5 mA, CW RFQ designed for the operating frequency of 162 MHz are discussed. Beam dynamics simulation results obtained by using the BEAMDULAC-RFQ code [1] are presented. The electrodynamics of the accelerating structure based on the four-vane cavity is discussed. The accelerating cavity design uses coupling windows as was proposed earlier [2], but with windows of an elliptical form. Such form allows for better separation of quarupole and dipole modes.

INTRODUCTION

The designing of a high-power proton linac for 1.0-1.5 MeV energy is a very actual aim of accelerator technology. Such linac is useful for spallation neutron sources and drivers for accelerator driven system (ADS). Operation in the CW mode is preferable for an ADS linac.

Accelerator-driver design was done in 1999 last time in the Russian Federation. The collaboration of researchers from MEPhI, ITEP and Kurchatov Institute did the project directed to the preliminary design of such a linac in 2013. This project was supported by the Ministry of Science and Education of the Russian Federation. The linac will consist of an RFQ, RF focusing section and SC modular configuration sections. The CW mode RFQ linac section was developed as the bunching section and for low energy acceleration.

BEAM DYNAMICS' SIMULATION

By design, the CW RFQ linac section operates at 162 MHz and accelerates the beam to 2 MeV. It should be noted that accelerating potential between the RFQ electrodes will limited by 1.2-1.5 of Kilpatrick criterion value for the CW mode (~130-150 kV).

Beam dynamics' simulation was done using the BEAMDULAC-RFQ code [1]. The accelerating channel consists of three regions as was proposed in [3-4]: the dynamic matcher, the gentle buncher and the main accelerating region. The matcher needs to minimize the transverse emittance growth and to enlarge the capture coefficient. The synchronous phase is constant, channel aperture size decreases monotonously and electrodes' modulation is absent in this region. The 6D matching is realized in this region. After that the synchronous phase decreases and the modulation increases in the bunching region. The adiabatic bunching regime is used when the phase oscillation frequency is approximately constant along the channel. Beam energy has main growth in the main accelerating region, in which the modulation and the synchronous phase are constant.

Dependences of main accelerating channel parameters versus longitudinal coordinate are presented in Fig. 1. Main channel parameters and beam dynamics simulation results are presented in Table 1.

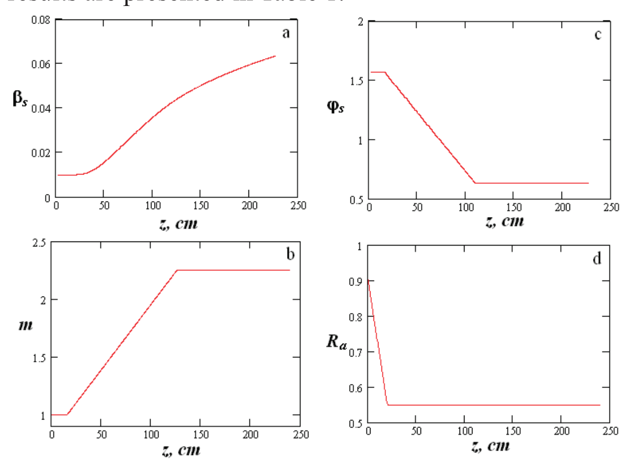

Figure 1: Main accelerating channel parameters versus longitudinal coordinate z: (a) synchronous velocity β_s, (b) electrodes modulation m, (c) synchronous phase φ_s and (d) aperture radius R_a.

The beam dynamics simulation was done to determine the optimal channel parameters that provide to low beam transverse growth and high current transmission coefficient in a wide band of injection current. Dependences of the current transmission coefficient K_T and output beam transverse emittance versus the initial beam current and transverse emittance are presented in Fig. 2. It is clear that for optimal values of the injection energy (47 keV) and the electrode potential (120 kV) current transmission decreases very slowly with injection current growth and depends not on the initial emittance.

A number of beam characteristics are illustrated in Fig. 3. Initial and output phase spaces, energy spectrum, beam envelop are presented.

Table 1: Main Channel Parameters and Beam Dynamics Simulation Results

Parameter	Value
Particle	p^+
Operating frequency, MHz	162
Channel length, mm	2400
Matcher length, mm	160
Buncher length, mm	1100
Synchronous phase on main accelerating region, grad	36
Maximal electrodes' modulation	2.25
Maximal aperture size (on matcher start), mm	9
Maximal aperture size in main accelerating region, mm	5.5
Injection energy, MeV	0.047±1 %
Output energy, MeV	2.0
Injection beam current, mA	up to 20
Current transmission coefficient, %	96 (0 mA) 94 (20 mA)

ACCELERATING CAVITY DESIGN

The 4-vane RFQ [2] can be utilized as a first section of a high-energy, high-power linac for an accelerator-driver. The use of a segmented vane RFQ (SVRFQ) for this purpose has been proposed. This paper examines the electrodynamics model and characteristics of such a resonator. Two resonator designs different in window apertures have been compared.

The RFQ cavity has been designed to operate at 162 MHz and comprises 13 cells of length L_{cell}=185 mm each. Its main distinction from the already used SVRFQ with rectangular RFQ is the use of elliptical vane apertures. Such window geometry allows for better tuning of the resonator. 3D models of RFQ's are illustrated in Fig. 4.

To conform to the requirements put on the RFQ by apart from the operating mode frequency and its separation from higher modes – the configurations of the electric and magnetic fields, it had to be optimized by six parameters: the shell radius, the transverse and conjugate diameters of windows, the transverse diameter of the endmost windows (EWs) and the lengths of both end regions. Below in Table 2 are presented the dimensions found to be optimal, normalized to the cell length (L_{cell}) or shell radius (R_{shell}).

As the design of the RFQ utilizes coupling windows of geometry different from the traditionally used one, it had to be compared with one such resonator (see Fig. 4). Table 3 summarizes the main electrodynamics

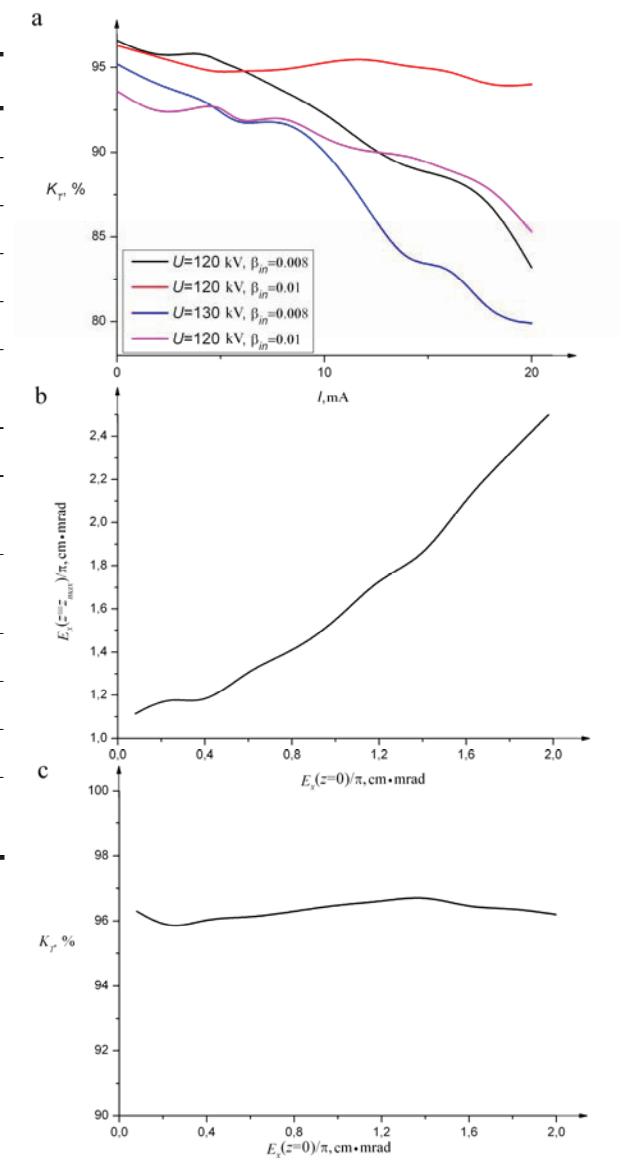

Figure 2: (a) Current transmission coefficient K_T versus initial beam current, (b) output beam transverse emittance versus initial one, (c) K_T versus initial beam transverse emittance.

Table 2: Optimal Geometry for Both SVRFQ Designs

Parameter	Elliptical aperture	Rectangular aperture
Shell radius, mm	210.716	208.042
Transverse window length, $\%L_{cell}$	130.811	123.440
Transverse EW length, $\%L_{cell}$	139.000	134.725
Conjugate window length, $\%R_{shell}$	34.549	33.388
1^{st} end region length, $\%L_{cell}$	72.757	70.380
2^{nd} end region length, $\%L_{cell}$	65.941	66.857

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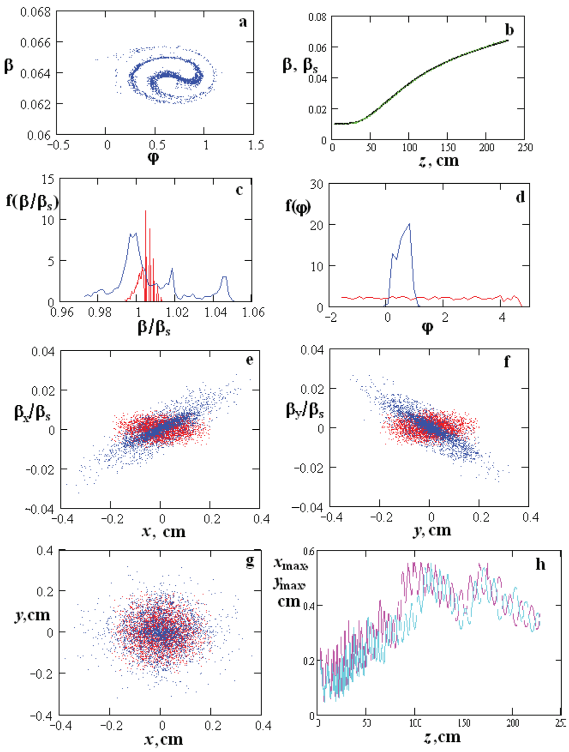

Figure 3: Beam dynamics simulation results: (a) longitudinal phase space, (b) average and synchronous velocities along channel, (c) energy spectrum, (d) phase spectrum, (e) and (f) transverse emittance, (g) beam cross-section and (h) beam envelope. Beam current 20 mA. Initial characteristics are shown by red curves, output – by blue.

Table 3: Min Electrodynamics Characteristics

Parameter	Elliptical aperture	Rectangular aperture
$H_z(z)$ top ripple, $\%H_z{}^{top}{}_{mean}$	15.972	7.639
$E_{max}/E_{RF\ breakdown}$	2.685	0.693
Power loss, kW	195.465	197.765
Q-factor, 10^4	1.182	1.169
Transverse shunt impedance, kΩ	86.461	85.455
Quadrupole and dipole modes frequency separation, MHz	2.031	1.497

characteristics of both resonator designs (U=160 kV). It is clear that the $E_{max}/E_{RF\ breakdown}$ and $H_z(z)$ top ripple needs for further optimization for elliptical windows SV RFQ. Figure 5 illustrates the magnetic and electric fields distribution uniformity for both window apertures. It is clear that both cavity designs give similar results.

CONCLUSION

Results of beam dynamics simulation in 2 MeV and 20 mA RFQ section and SVRFQ cavity electrodynamics characteristics modelling are discussed. Such linac is designing to CW mode operation. The accelerating channel characteristics provide to very slowly decrease of the current transmission with injection current growth. Novel SVRFQ cavity design with elliptical cavities provides to possibility of more flexible cavity tuning and higher quadrupole and dipole modes frequency separation than in SVRFQ or 4-vane RFQ cavities. The wall power loses are also lower for novel cavity design.

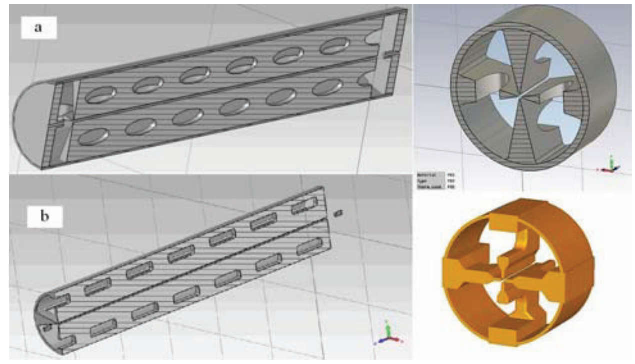

Figure 4: SVRFQ cavities design: (a) novel design with elliptical windows and (b) conventional rectangular windows.

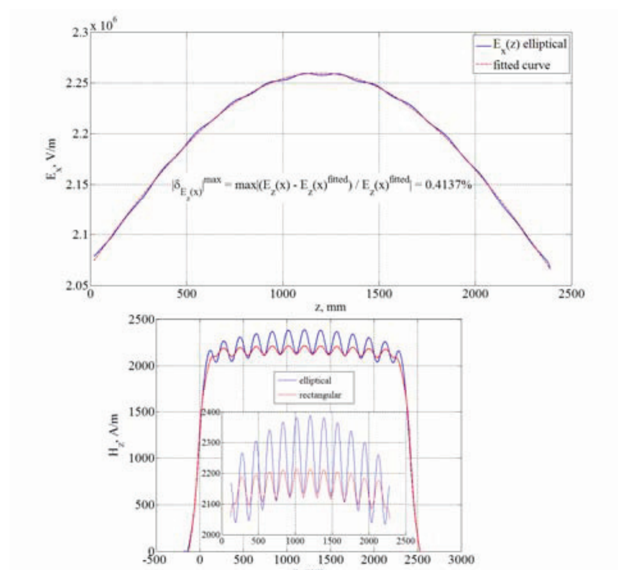

Figure 5: Magnetic and electric fields' distribution uniformity for both window apertures.

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