RFQ AS A SECOND SECTION OF FRONT END OF ION LINAC

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There is a problem of low accelerating efficiency at front end part of ion linac. Conventional RFQ doesn't allow effective accelerating at energies higher than 3 MeV. The paper presents one of the possible ways to modify an RFQ for ion acceleration up to 15 MeV with reasonable energy gain rate. Conventional RFQ electrodes and modified electrodes are compared. Results of beam dynamics simulation are presented and discussed. RF design of the resonator of second section has been carried out. Main RF parameters of the resonator are presented.

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INTRODUCTION

The front end part of ion linacs consists of several sections. First section is usually presented by an RFQ. Conventional RFQ is a structure provides effective bunching, matching and focusing of ion beams. But it doesn't allow effective acceleration at energies higher than 3 MeV because energy gain rate decreases rapidly with energy. Therefore drift tube structures are used for acceleration in following sections of linac. In this case focusing is provided by compact magnetic quadrupole lenses placed inside drift tubes (Alvarez-type DTL [1]) or between chains of drift tubes (IH-DTL, CH-DTL [2]). The usage of magnetic focusing is complicated due to low efficiency for heavy ion beams and high cost of compact magnetic quadrupoles.

There is a structure which provides spatially periodic RF quadrupole focusing [3]. It is useful for acceleration and focusing of light or heavy ion beams. But it is very complicated at design, manufacturing and tuning, as compared with RFQ.

This paper describes one of the possible ways [4] to modify an RFQ for effective usage as a second section of ion linac. Problem of acceleration of intensive proton beam is considered as an example. Design of high intensity proton linac is presented. Main parameters of the linac are taken similar to parameters of URAL-30M linac [5] (Institute for High Energy Physics, Protvino). These parameters are shown in Table 1.

Table 1

Linac parameters

Parameter	Value
Initial beam energy W_{in}, MeV	1.77
Frequency f_0, MHz	148.5
Aperture radius a, mm	6
Maximum surface electric field $E_{s\,\max}$, kV/cm	300
Synchronous phase φ_s, deg	-30
Transverse phase advance at synchronous phase μ_s, deg	40
Transverse normalized input emittance (90%) ε_n, π·mm·mrad	1
Beam current I, mA	100

1. RFQ ELECTRODES

1.1. BASIC PARAMETERS

Energy gain ΔW of the particle for one cell of an RFQ is defined by voltage U and accelerating efficiency T [4, 6] as

$$\Delta W = qUT\cos\varphi, \qquad (1)$$

where q – charge of the particle, φ – phase of RF field, when the particle is in a maximum of accelerating field.

Voltage U between quadrupole electrodes is limited by maximum surface electric field $E_{s\,\max}$ as

$$U = \frac{E_{s\max}R_0}{\chi}, \qquad (2)$$

R_0 – average aperture radius of the channel, χ – field amplification factor mainly depends on electrode profile and radius of curvature of the tip R_e. Computation of χ has been performed in [7]. For modulated electrodes $\chi \approx 1.2\ldots1.5$. Let us assume $\chi \approx 1.36$ [7] for our estimation. In turn, R_0 defines transverse phase advance μ, in the smooth approximation:

$$\mu^2 = \frac{2}{\pi^2}K^4 + \pi\frac{qUT}{W_s}\sin\varphi, \qquad (3)$$

$$K^2 = \kappa\frac{qU}{4W_0}\left(\frac{\lambda}{a}\right)^2, \qquad (4)$$

κ – focusing parameter, W_0 – rest mass of the particle, λ – wavelength of RF field, a – minimum aperture radius of a channel, W_s – kinetic energy of the particle. For the ideal electrodes

$$\kappa = \frac{a^2}{R_0^2}. \qquad (5)$$

Combining (2) - (5) we get the relation between R_0, μ and U for the RFQ with sinusoidal modulation of electrodes. Fig. 1 demonstrates the relation between focusing strength and voltage.

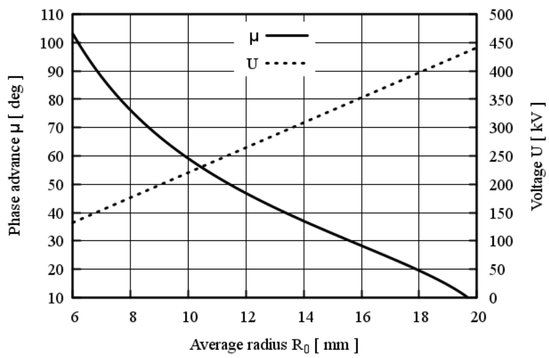


Fig. 1. Transverse phase advance μ and voltage U versus average aperture radius R_0 of the RFQ channel

To achieve the highest energy gain we have to decrease transverse phase advance μ to the lowest allowable value - 40 degrees (Table 1) at $R_0 \approx 13.2$ mm, $U \approx 280$ kV.

Average aperture radius of all electrodes discussed below is equal to 13.2 mm, initial cell length $L_{cell} = \beta\lambda/2$ is 62 mm and corresponds to W_{in}.

1.2. ELECTRODE PROFILE

The electrostatic field simulation has been performed with CST STUDIO SUITE [8] to design the RFQ electrode profile. Distribution of electric field on the surface of electrodes with sinusoidal profile at 1 V voltage is presented in Fig. 2.

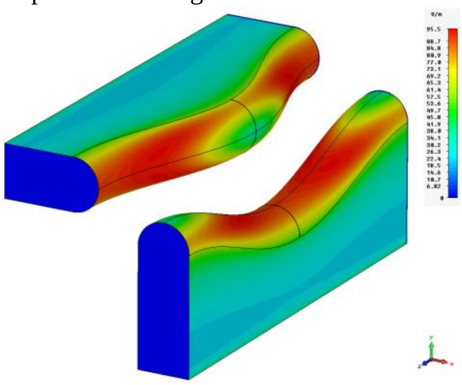


Fig. 2. Electric field on the surface of electrodes with sinusoidal profile at 1 V voltage

We can notice that highest electric field (95.7 V/m) is located on the surface where the four electrodes have equal displacements from longitudinal axis.

Distribution of electric field in an RFQ has been studied in [9] in details.

To increase accelerating efficiency T trapezoidal profile of electrodes can be applied [4, 10]. Trapezoidal profile is formed by two parts with minimum and maximum displacements from longitudinal axis connected with short sinusoidal junction, called "gap". Distribution of electric field on the surface of electrodes with trapezoidal profile at 1 V voltage is presented in Fig. 3. The highest electric field (98.0 V/m) is located on both surfaces where the four electrodes have equal and maximum displacements from longitudinal axis. This means that balance of electric field for focusing and accelerating is good enough. Moreover the main advantage of trapezoidal profile is pretty constant maximum electric field $E_{s\,\max}$ at constant gap length L_{gap}, average aperture radius R_0 and minimum aperture radius a.

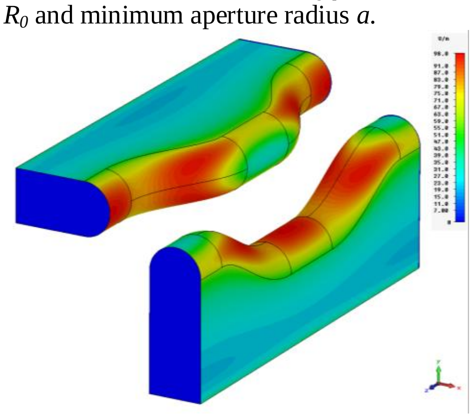


Fig. 3. Electric field on the surface of electrodes with trapezoidal profile at 1 V voltage

As a result of simulation we get corrected values of field amplification factor $\chi = 1.3$ and voltage $U = 300$ kV.

Accelerating field E_z along the RFQ cell is shown in Fig. 4 for both sinusoidal and trapezoidal electrodes with $L_{cell} = 62$ mm. Common design of an RFQ electrodes allows increasing of accelerating efficiency has been discussed in [4, 11].

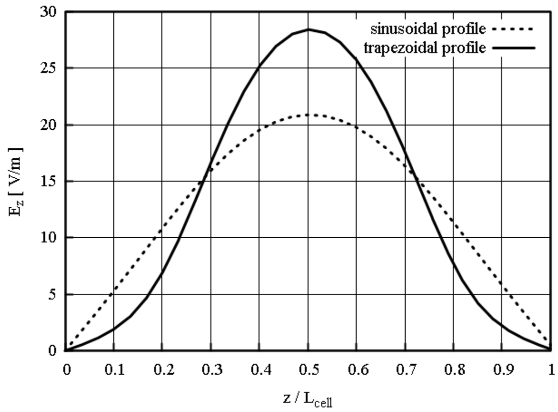


Fig. 4. Accelerating field E_z along the RFQ cell with sinusoidal profile (dot) and trapezoidal profile (solid) at 1 V voltage

Accelerating efficiency T is calculated by [9]:

$$T = \frac{\pi}{UL_{cell}} \int_0^L u(z)\cos\left(\frac{\pi}{L_{cell}} z\right) dz \,, \tag{6}$$

where $u(z)$ – electric potential distribution along the RFQ cell. By simulation and calculation we get $T = 0.62$ for sinusoidal electrodes and $T = 0.70$ for trapezoidal electrodes with $L_{cell} = 62$ mm. Fig. 5 presents increasing of accelerating efficiency T of the RFQ with trapezoidal electrodes with energy. Whereas accelerating efficiency T of the RFQ with sinusoidal electrodes remains constant with energy and equal to 0.62 (see Fig. 5 illustrates results of simulation of several RFQ cells with different L_{cell} and calculating by equation (6)).

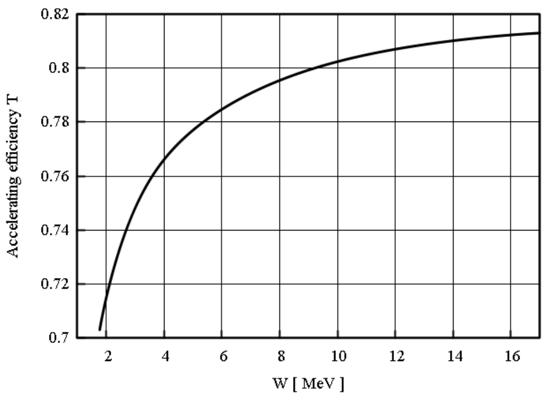


Fig. 5. Accelerating efficiency T versus beam energy W

1.3. LONGITUDINAL DYNAMICS

There are several parameters describing the channel of RFQ linac: minimum aperture radius a, average aperture radius R_0, curvature radius of the electrode tip R_e, gap length L_{gap} and length of each n-th cell $L_{cell\ n}$. Last parameter can be approximately defined as

$$L_{cell\ n} = \left(\frac{\beta_{n-1} + \beta_n}{2}\right)\frac{\lambda}{2}, \tag{7}$$

where β_n – normalized synchronous velocity at the end of the n-th cell, which is calculated from

$$\beta_n = \sqrt{1-\frac{1}{\gamma_n^2}}\,, \tag{8}$$

$$\gamma_n = 1+\frac{W_n}{W_0}\,. \tag{9}$$

Energy at the end of n-th cell W_n we can find from recursive equation

$$W_{n+1} = W_n + qUT(W_n)\cos\varphi_s\,. \tag{10}$$

Beam energy along the RFQ linac is shown in Fig. 6. While accelerating efficiency T increases the energy gain rate decreases with beam energy due to fast increasing of cell length L_{cell}. This feature is inherent for all linacs with constant voltage along the longitudinal axis.

Let us consider that the linac consists of two sections. Length of first "T1" section (1.8…7.4 MeV) is taken equal to 2.8 m and average energy gain rate for this section is 2.0 MeV/m (see Fig. 6). Length of second "T2" section (7.4…15.0 MeV) is 5.8 m and average energy gain rate for "T2" section is 1.3 MeV/m. Fig. 7 demonstrates profiles of adjacent trapezoidal electrodes of the "T1" section of the linac.

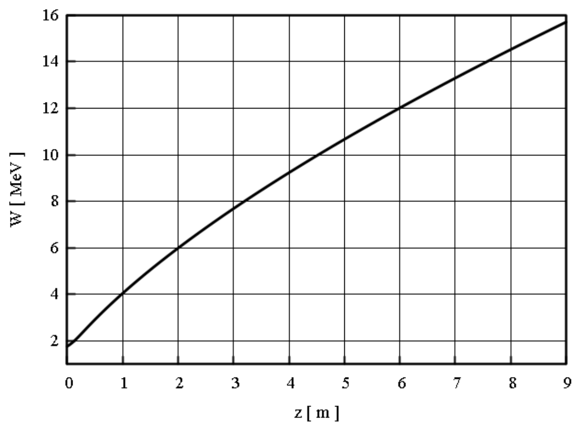


Fig. 6. Beam energy W along the RFQ linac

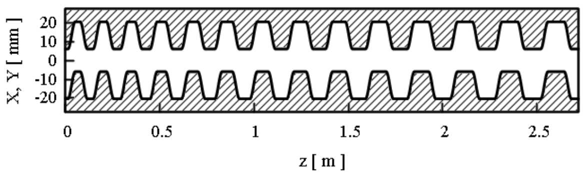


Fig. 7. Profiles of adjacent trapezoidal electrodes of 7.4 MeV RFQ

2. RFQ LINAC

2.1. RESONATOR

Resonator RF design for "T1" section has been performed with CST STUDIO SUITE. The resonator is based on 4-vane resonant structure with displaced magnetic coupling windows [12]. This structure provides good separation of quadrupole and dipole modes, perfect field and frequency stability for random perturbations of geometry due to strong coupling between all four chambers of resonator. General view of the resonator is presented in Fig. 8.

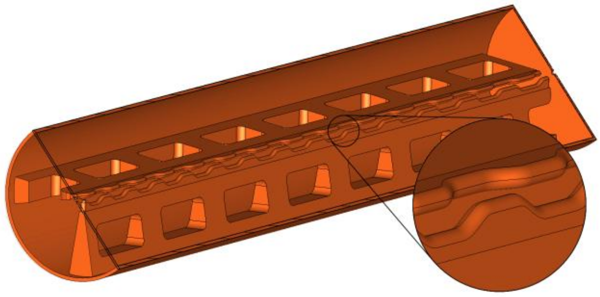


Fig. 8. Resonator of 7.4 MeV RFQ with trapezoidal electrodes (half of the resonator is cut)

Main parameters of the resonator are presented in Table 2. Effective shunt impedance ZT^2 is defined by

$$ZT^2 = \left(\frac{\Delta W_R}{\cos\varphi_s}\right)^2 \frac{1}{P_{RF} L_R}\,, \tag{11}$$

where ΔW_R is energy gain through the resonator.

Table 2

Resonator parameters

Parameter	Value
Resonant frequency f_0, MHz	148.5
Tank diameter D_R, m	0.46
Tank length L_R, m	2.78
Minimum aperture radius a, mm	6
Average aperture radius R_0, mm	13.2
Radius of curvature of the tip R_e, mm	8
Trapezoidal "gap" length L_{gap}, mm	38.8
Number of RFQ cells	28
Inter-vane voltage U, kV	300
Maximum surface electric field $E_{s\,max}$, kV/cm	300
Synchronous phase φ_s, deg	-30
Energy gain rate dW/dz, MeV/m	2.0
Quality Q	11600
RF power dissipation P_{RF}, kW	830
Normalized RF power P_{RFn}, kW/m	296
Beam power (at 100 mA) P_B, kW	560
Total power P_T, kW	1390
Effective shunt impedance ZT^2, MOhm/m	18
Voltage ripple δU, %	< 3.0

Calculated distribution of electric field components along the resonator is shown in Figs. 9 and 10.

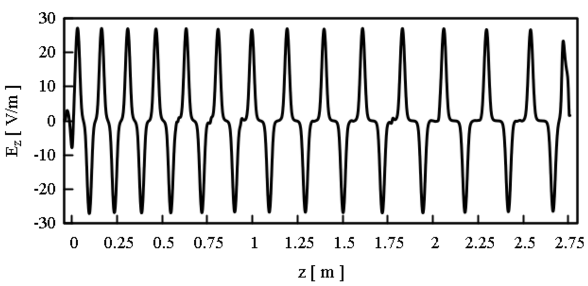


Fig. 9. Longitudinal component of electric field along the longitudinal axis (normalized to 1 V)

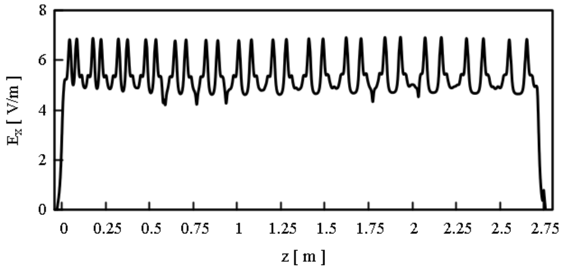


Fig. 10. Transverse component of electric field along the resonator at 1 mm displacement from longitudinal axis (normalized to 1 V)

2.2. BEAM DYNAMICS SIMULATION

Electric field exported from CST STUDIO SUITE is used to perform the beam dynamics simulation with code TRANSIT [13]. TRANSIT is a 3D beam dynamics code developed in ITEP (Moscow). 100 mA proton beam has been matched with the RFQ channel. Beam transverse envelopes are presented in Fig. 11.

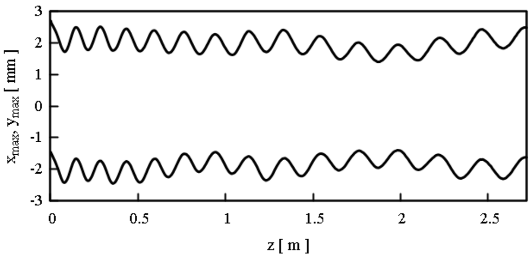


Fig. 11. Beam transverse envelopes

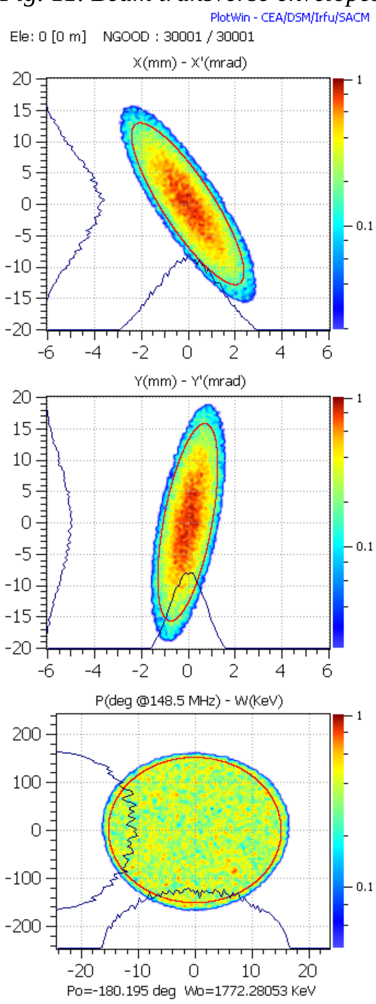
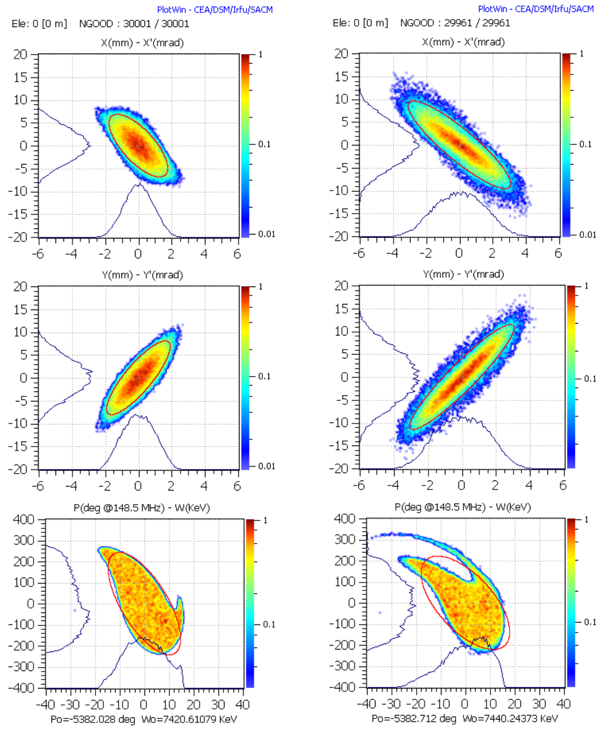


Fig. 12. Input phase-space plots of the beam

Input and output phase-space plots [14] of matched beam are shown in Figs. 12 and 13. Beam parameters are presented in Table 3.



a *b*

Fig. 13. Output phase-space plots of the beam. Beam current I is (a) – 1 mA, (b) – 100 mA

Table 3

Beam parameters

Parameter	Value	
	Input	**Output**
Beam energy *W*, MeV	1.77	7.44
Transverse normalized X/Y emittance (90%, I = 1 mA), ε_n, π·mm·mrad	1.0/1.0	1.05/1.04
Transverse normalized X/Y emittance (90%, I = 100 mA), ε_n, π·mm·mrad		1.68/1.58
Longitudinal normalized Z emittance (90%, I = 1 mA), ε_n, π·deg·keV	2300	2600
Longitudinal normalized Z emittance (90%, I = 100 mA), ε_n, π·deg·keV		3100
Transmission, *K* (1 mA / 100 mA), %	100/100	

One of important parameters of high intensity linacs is emittance growth. The main sources of emittance growth in the intermediate energy range are [6, 15]:

1. Influence of non-linear external focusing forces
2. Redistribution of energy between longitudinal and transverse degrees of freedom
3. Influence on non-linear beam self-field forces.

Influence of the first and the second causes has been verified with simulation of 1 mA proton beam. Results of the simulation show only 5% emittance growth.

While the simulation of 100 mA proton beam shows 60…70% emittance growth. It seems to be caused by high coulomb dispersion and insufficient beam matching with superposition of external and space-charge fields.

CONCLUSIONS

The way to use an RFQ for high intensity proton beam acceleration up to 15 MeV is presented. Main geometric parameters of trapezoidal RFQ electrodes have been calculated. These electrodes provide 13…30% higher accelerating efficiency then conventional sinusoidal electrodes (see Fig. 5). Beam energy increasing along the RFQ is calculated. The RFQ provides high average energy gain rate. Results of beam dynamics simulation with 3D fields has been presented and discussed. Proposed resonator provides adequate effective shunt impedance compared with Alverez-type DTL's one.

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УСКОРИТЕЛЬ С ПРОСТРАНСТВЕННО-ОДНОРОДНОЙ КВАДРУПОЛЬНОЙ ФОКУСИРОВКОЙ В КАЧЕСТВЕ ВТОРОЙ СЕКЦИИ НАЧАЛЬНОЙ ЧАСТИ ЛИНЕЙНОГО УСКОРИТЕЛЯ ИОНОВ

А.С. Пластун

Существует проблема, связанная с низкой эффективностью ускорения в начальной части линейного ускорителя ионов. Традиционный ускоритель с пространственно-однородной квадрупольной фокусировкой (ПОКФ) не позволяет эффективно ускорять при энергиях выше 3 МэВ. Представлен один из возможных способов модификации ускорителя с ПОКФ с целью ускорения ионов до энергии 15 МэВ при приемлемом темпе ускорения. Выполнено сравнение традиционных и модифицированных электродов. Представлены и обсуждаются результаты моделирования динамики пучка. Разработана модель высокочастотного (ВЧ) резонатора для второй секции ускорителя. Представлены основные ВЧ-параметры резонатора.

ПРИСКОРЮВАЧ З ПРОСТОРОВО-ОДНОРІДНИМ КВАДРУПОЛЬНИМ ФОКУСУВАННЯМ В ЯКОСТІ ДРУГОЇ СЕКЦІЇ ПОЧАТКОВОЇ ЧАСТИНИ ЛІНІЙНОГО ПРИСКОРЮВАЧА ІОНІВ

А.С. Пластун

Існує проблема, пов'язана з низькою ефективністю прискорення в початковій частині лінійного прискорювача іонів. Традиційний прискорювач з просторово-однорідним квадрупольним фокусуванням (ПОКФ) не дозволяє ефективно прискорювати при енергіях вище 3 МеВ. Представлено один з можливих способів модифікації прискорювача з ПОКФ з метою прискорення іонів до енергії 15 МеВ при прийнятному темпі прискорення. Виконано порівняння традиційних і модифікованих електродів. Представлено і обговорюються результати моделювання динаміки пучка. Розроблено модель високочастотного (ВЧ) резонатора для другої секції прискорювача. Представлено основні ВЧ-параметри резонатора.