RFQ WITH IMPROVRED ENERGY GAIN

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Abstract

RFQ structure is practically only one choice for using in front ends of ion linacs for acceleration up to energy about 3 MeV. This limit is due to its relatively low acceleration efficiency. However it isn't intrinsic feature of RFQ principle. It is defined only by vane geometry of conventional RFQ structure with sinusoidal modulation of vanes. The paper presents results of analysis RFQ with modified vane geometries that allow to reach acceleration efficiency compared with IH DTL structures. RFQ with modified vanes was used for design second section of heavy ion injector of TWAC for acceleration of ions with Z/A=0.33 up to 5 MeV/u.

INTRODUCTION

An RFQ output energy doesn't usually exceed several MeV. Using conventional RFQ structure for acceleration of particles for higher energies is impractical because RFQ energy gain decreases rapidly with energy at constant modulation.

Many DTL structures were proposed for beam acceleration following RFQ that use magnetic or radio frequency focusing. The structures are well studied, they can provide good accelerating efficiency and are realized in a number of linacs. In the framework of heavy ion injector development for TWAC facility [1] several designs of second section based on these structures have been studied. In addition it was considered option that uses conventional RFQ with relatively minor modification of RFQ electrodes and resonant structure.

81 MHz RFQ – front end of TWAC injector has been recently successfully commissioned [2]. It is designed to accelerate beam from laser ion source with Z/A = 0.33 up to energy 1.57 MeV/u.

This paper presents result of study of TWAC injector second section design based on modified RFQ. The main goal of the modification was to provide maximum energy gain at focusing sufficient for acceleration beam with current 30 mA up to 5 MeV/u.

ENERGY GAIN IN RFQ

Vanes with Sinusoidal Modulation

The energy gain of a particle in RFQ is

$$\Delta W = e\frac{Z}{A}UT\cos\varphi_s, \qquad (1)$$

e - electron charge, *Z* - charge number of the particle, *A* - mass number of the particle, *U* - voltage between adjacent vanes, *T* - accelerating efficiency, φ_s - phase of RF field, when synchronous particle is in a maximum of accelerating field.

Voltage *U* is usually chosen taking into account many different considerations. However it has to be as high as possible to increase energy gain. Its maximum value in this case is fully defined by acceptable surface electric field $E_{s\ lim}$. Most accurately voltage can be found by numerical simulation for real vane geometry and expressed as

$$U = U_{sim}\frac{E_{s\lim}}{E_{s\,sim}}, \qquad (2)$$

Here U_{sim} is voltage between vanes in computer model and $E_{s\ sim}$ is maximum field at vane surface obtained from simulation result.

Figure 1 shows results of field simulation in RFQ cell with code OPERA 3D. Simulated cell length $L_c = \beta\lambda/2$ corresponds particle energy at TWAC RFQ output. Curve 1 presents maximum field at vane surface calculated for sinusoidal modulation in $1 \le m \le 5$ range. Aperture for all modulations was constant a = 8 mm, that is average distance from axis to vane was changed as $R_0 = a(m+1)/2$. Simulation results show that for surface field limit $E_{s\ lim}$ = 250 kV/cm (about 2 Kilpatrick units for frequency f = 81 MHz) maximum voltage can reach according formula (2) $U \cong 500$ kV.

Accelerating efficiency *T* was calculated from simulated distribution of longitudinal field component E_z on axis. *T* factor for cell with sinusoidal modulation of vanes is limited by value $T \cong 0.7$. It means that the maximum effective accelerating gain per cell with studied parameters doesn't exceed $UT \cong 350$ kV.

Curve 1 shows that there is no sense to increase modulation factor more than $m = 4 \div 5$ because maximum field $E_{s\ sim}$ reduces very slowly for higher *m* while focusing efficiency rapidly decreases. Figure 2 shows transverse phase advance calculated with the following expression [3]:

$$\sigma^2 = \frac{2}{\pi^2}K^4 + \frac{\pi e UT}{W_{kin}}\sin\varphi,$$

$$K^2 = \frac{Z}{A}\frac{e\overline{G}}{4W_0}\lambda^2.$$

Here $\overline{G}$ is mean value of simulated transverse field gradient along RFQ cell, W_0 - rest mass of proton, λ - wavelength of RF field. Estimation shows that transverse motion is very close to stability border at $m \cong 4$. It defines limiting capability of conventional RFQ with sinusoidal modulation for higher energy gain acceleration.

It is possible to improve accelerating efficiency using trapezoidal modulation proposed in [4]. Cell with this modulation type is shown in Figure 3. The trapezoidal modulation allows 15 ÷ 20% higher accelerating efficiency *T* due to better of longitudinal field component distribution along axis. It is important that this distribution is kept constant along the RFQ so *T* rises with particle energy at constant voltage.

However maximum surface field for this modulation type in general is close to the value for sinusoidal modulation.

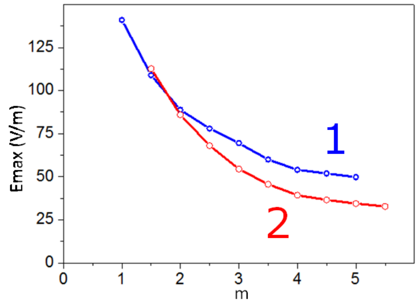

Figure 1: Calculated maximum surface electric field. Curve 1 corresponds to conventional RFQ with sinusoidal modulation, curve 2 – to RFQ with modified vanes.

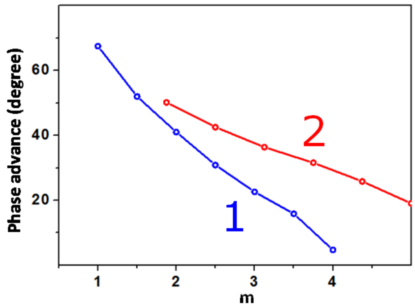

Figure 2: Calculated transverse phase advance. Curve 1 corresponds to RFQ with sinusoidal modulation, curve 2 – to RFQ with improved vanes.

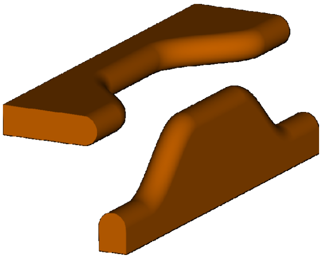

Figure 3: Adjacent vanes with trapezoidal modulation.

Improved Vanes

Whereas trapezoidal modulation considerably improves accelerating efficiency the higher voltage *U* is required for further energy gain increase. It can be provided if vane geometry allows reducing maximum surface field. Maximum field is reached at vane cross section with exact quadrupole symmetry for RFQ cells with conventional modulation and with parameters corresponding TWAC RFQ output. It was proposed to change vane profile at this cross section to increase distance between adjacent vanes. This can be achieved by transformation of the trapezoidal profile to almost "rectangular" one. Distribution of longitudinal component of field along axis is formed for this profile by "gap" between "rectangles" of adjacent vanes. Vane tips near axis are flat and have about the same curvature radius R_e as the vanes with conventional modulation.

Removing part of vane near axis decreases focusing efficiency. To compensate it more thick flat vanes with curved unmodulated pole are placed at distance from axis $R_q >> a$. Curvature radius of this part of vane is $R_{eq} \cong R_q$. 3D view of improved vanes is shown in Figure 4.

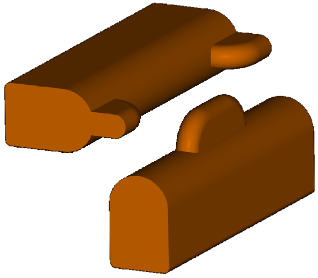

Figure 4: Adjacent vanes with improved profile.

Basic parameters of the improved geometry are shown more detailed in Figure 5. The parameters were optimized to minimize surface field, equalize it on vane surface and to increase focusing efficiency in comparison with conventional vanes with equal modulation.

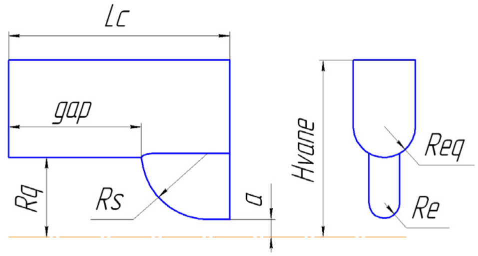

Figure 5: Basic dimensions of improved vanes.

Table 1 allows comparing field simulation results for sinusoidal and improved profiles. The same values for aperture *a* = 8 mm, cell length L_c = 100 mm, vane tip curvature radius R_e = 5.6 mm and modulation factor *m* = 4 were used for both cases of simulation.

Table 1: Field Simulation Results

Parameter	Sinus.	Impr.
Limit surface electric field E_{lim}, kV/cm	250	250
Maximum surface electric field $E_{s.max}$ @ 1V intervane voltage, V/cm	0.54	0.39
Voltage *U*, kV	463	636
Acceleration rate *UT*, kV	324	513
Transverse phase advance μ, deg	5	26

BEAM DYNAMICS SIMULATION

Improved vane profile was used to design RFQ with parameters corresponds the second section of TWAC injector for detailed computer simulation of beam dynamics. RFQ was designed using 3D field maps calculated by OPERA code. Basic parameters of the RFQ are shown in Table 2.

Table 2: Basic Parameters of Improved RFQ

Operating frequency, MHz	81.36
Z/A of ions	0.33
Input ion energy, MeV/u	1.57
Output energy, MeV/u	5.0
Transverse emittance, norm, π mm·mrad	1.5
Maximum surface field, kV/cm	250.
Voltage, kV	685.
Electrode modulation	4.5
Cell number	20
Total length, m	3.0

Code TRANSIT written in ITEP has been used for the beam dynamics simulation. Longitudinal and transverse field components along section calculated by OPERA 3D code that was used in TRANSIT are shown in Figure 6.

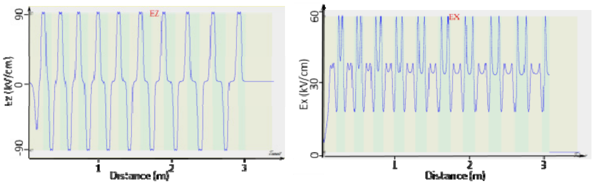

Figure 6: Longitudinal field component on axis (a) and transverse field component at r = 5 mm (b).

Figure 7 shows calculated transverse envelopes that confirm stable transverse particle motion along the section. Simulated envelope size shows that RFQ with improved vanes provides required transverse acceptance.

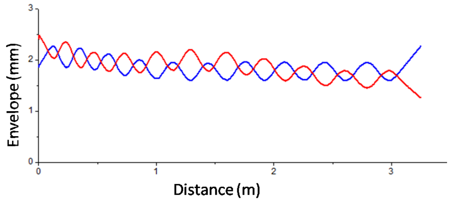

Figure 7: Transverse envelopes calculated with TRANSIT code.

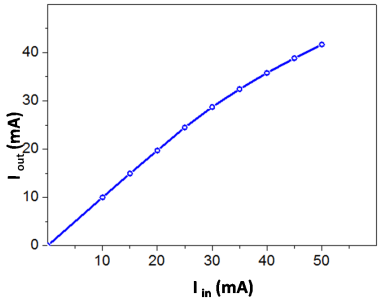

Figure 8: Calculated beam current at RFQ output in dependence on input one.

Simulation results in Figure 8 show that RFQ with improved vanes provides close to 100% beam transmission in required beam current range $0 \le I \le 30$ mA. It is important to say that in spite of complicated vane profile field has good linearity in working area that is evidenced by absence of growth of transverse and longitudinal emittances.

Table 3: Beam Transmission Parameters

Transmission, % (I = 0 / 30 mA)	100 / 98.6
Transverse rms envelope, mm (I = 0 / 30 mA)	2.0 / 3.1
Transverse emittance growth (I = 0 / 30 mA)	1.0 / 1.2
Longitudinal emittance growth (I = 0 / 30 mA)	1.0 / 1.1

CONCLUSION

RFQ structure with improved vane profile is proposed for acceleration following conventional RFQ. Computer simulation showed that new vane profile allows ≈ 30% lower maximum surface field at modulation factor $m = 3 \div 5$ comparing with conventional vanes. Accelerating efficiency of new profile is the same as provided by vanes with trapezoidal modulation.

3 m length RFQ has been designed for injector of TWAC facility. It provides about than 3.5 MeV energy gain. Computer simulations confirmed that the structure is capable to accelerate ion beam with current I = 30 mA with transmission about 100% and with only small transverse and longitudinal emittances growth.

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