A SPATIALLY PERIODIC RFQ ACCELERATING STRUCTURE BASED ON E_{010} MODE CAVITY

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Abstract

Tera Watt Accumulator (TWAC) accelerator/storage ring complex with the laser ion source is in progress at ITEP. A spatially periodic RFQ structure is considered for the second stage of the new intense injector linac behind of conventional spatially uniform RFQ. The cavity based on the operating mode of E_{010} type at the frequency of 81 MHz is studied in order to create the rf focused accelerating channel with the focusing period comprising two rf oscillations. In the frame of the simple analytic theory, the ideal electrode geometry and parameters of the channel have been preliminary defined. The numerical simulations of beam dynamics in the 6 m long section give the average accelerating gradient of around 3 MV/m for the ion beam with the nominal current of 40 mA and normalised transverse emittance of 4.4*π mm*mrad.

1 INTRODUCTION

The efficient and simple accelerating structure without focusing magnets behind of conventional RFQ is the subject of investigation for this paper. A spatially periodic RFQ (SP RFQ) structure [1] is proposed as the second stage of the new injector linac for ITEP-TWAC project [2]. Since the laser ion source delivers the intense beam with the enlarged emittance, high acceptance and current capability are really necessary in this case for both first and second stages of acceleration.

A theory of spatially periodic RFQ is developed in the Ref.[1], being applied to the focusing period with the length of $2\beta\lambda$. Good parameters have been demonstrated for π-mode (or Wideroe type) accelerating channel, where symmetric plus-minus rf voltage is assumed. But in practice, rf amplitude should grow along with the particle velocity in order to keep the accelerating efficiency from the beginning to the end. Such an increasing rf voltage could be realised in the cavity based on H_{11} mode by means of variation of the inductance and capacitance. Unfortunately, the structure gets complicated in this case, dissipating more rf power as well because of additional capacitance. On the other hand, accelerating field is naturally constant along the Alvarez structure based on E_{010} mode cavity. If the structure is properly tuned, the stored energy is distributed uniformly as well as the magnetic field; therefore rf voltage applied to the accelerating cell is automatically proportional to the cell length. This feature makes E_{010} mode attractive for accelerating structures of different type including those focused by rf field. As a known example, RFD and "chain-like" structures described in the Refs. [3], [4], respectively, can be mentioned.

Starting from the theory and results given by the Ref.[1], present work is aiming to realise the principle of SP RFQ focusing in the modified Alvarez cavity. Unlike the known rf focused structures supplied with the "horns" or "fingers", accelerating channel is shaped in terms of ideal geometry, corresponding to the main accelerating and focusing spatial harmonics of rf potential.

2 RF POTENTIAL DISTRIBUTION AND CHANNEL GEOMETRY

The ideal distribution of rf potential in the rf quadrupole focused channel of 2π-mode (or Alvarez) type with the focusing period length of $2\beta\lambda$ can be represented by three main spatial components:

$$U(r,\theta,z)=U_0\left[A(r,z)+F(r,\theta,z)+L(z)\right]; \qquad \textbf{(1)}$$

$$A(r,z)=A_2 I_0(k\,r)\sin(k\,z); \qquad \textbf{(2)}$$

$$F(r,\theta,z)=F_1 I_2\left(\frac{k}{2}r\right)\cos(2\theta)\sin\left(\frac{k}{2}z\right), \qquad \textbf{(3)}$$

$$L(z)=\frac{k}{\pi}z-1, \qquad \textbf{(4)}$$

where r, θ, z are cylindrical co-ordinates; U_0 is the potential amplitude; $k=2\pi/\beta\lambda$ is the longitudinal wave number; β, λ are normalized particle velocity and rf wavelength, respectively. Two of these terms, $A(r, z)$ and $F(r, \theta, z)$, are second axisymmetric (accelerating) and first quadrupole (focusing) spatial harmonics, respectively, which are similar to the main components in the π-mode SP RFQ channel [1]; A_2 and F_1 are their amplitudes. Third potential term $L(z)$ appears only in the 2π-mode structure, where linear potential component always exists.

The longitudinal distribution of potential components is qualitatively illustrated by upper part of Fig. 1. Lower part of this figure shows the longitudinal profile of ideal equipotential surface $U(r, 0, z)=1$, as well as possible profile of the realistic electrode (finger).

Suppose that the distance from the axis to the electrode surface is a_1 at the maximum potential of accelerating harmonic, $z=\beta\lambda/4$, and a_2 at the maximum of the quadrupole harmonic, $z=\beta\lambda/2$, as Fig. 1 shows. Than the amplitudes of accelerating and focusing harmonics can be found from two boundary equations $U(a_1, 0, \beta\lambda/4)=U_0$, $U(a_2, 0, \beta\lambda/2)=U_0$ as follows:

$$F_1 = \frac{1}{I_2\left(\frac{k}{2}a_2\right)}; \quad \textbf{(5)}$$

$$A_2 = \frac{1}{2I_0(ka_2)}\left(3 - \frac{\sqrt{2}\cdot I_2\left(\frac{k}{2}a_1\right)}{I_2\left(\frac{k}{2}a_2\right)}\right). \quad \textbf{(6)}$$

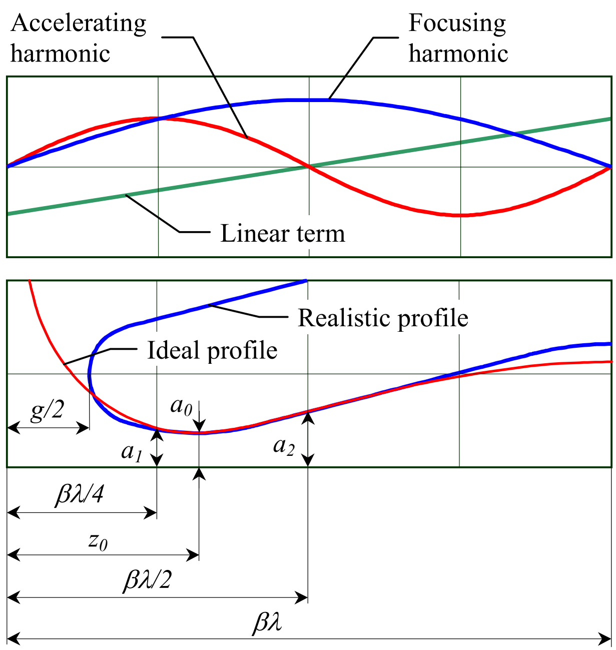

Figure 1. Potential components and electrode profile.

Unlike in the π-mode SP RFQ channel, longitudinal position of minimum aperture does not coincide with $bl/4$. One can see that both a_1 and a_2 values are larger than minimum aperture a_0.

A single focusing period of the realistic accelerating channel is shown at Fig. 2. The sequence of the rings is installed at the axis, each of them supplied with the longitudinal electrodes or "fingers". In the given design, two stems support every ring along cavity diameter; the horizontal and vertical stems being interchanged along the structure. Similar to the conventional RFQ electrodes, the fingers are assumed of semicircular shape with the fixed radii of the transverse cross-section curvature.

Since the cavity operates at E_{010} mode, rf voltage between any adjacent rings is of the same direction and amplitude U_0. One can see that the total amplitude of rf voltage between fingertips is as high as $2U_0$, whereas the focusing voltage at the symmetric quadrupole cross-section is two times lower. Axis distributions of rf potential and electric field calculated for definite electrode geometry by electrostatic solver are shown at the lower part of Fig. 2.

The space between fingertips around of $z=0$, $\beta\lambda$, $2\beta\lambda$,.. can be interpreted as the main accelerating gap, while the maximum quadrupole field occurs at the symmetric cross-sections of the channel, $z=bl/2$, $3bl/2$,.. Nevertheless, the longitudinal accelerating field exists at the symmetric cross-sections too because of finger inclination. Finally, the direction of accelerating field is alternating along the axis similar to π-mode distribution, but the amplitudes at the main accelerating gaps and focusing regions differs approximately two times. Therefore, the common field at the channel axis can be represented as some superposition of π- and 2π-modes.

In general, the "chain-like" structure [4] mentioned above looks close to the given design except the channel geometry, which is created in the present work in terms of ideal accelerating and focusing components.

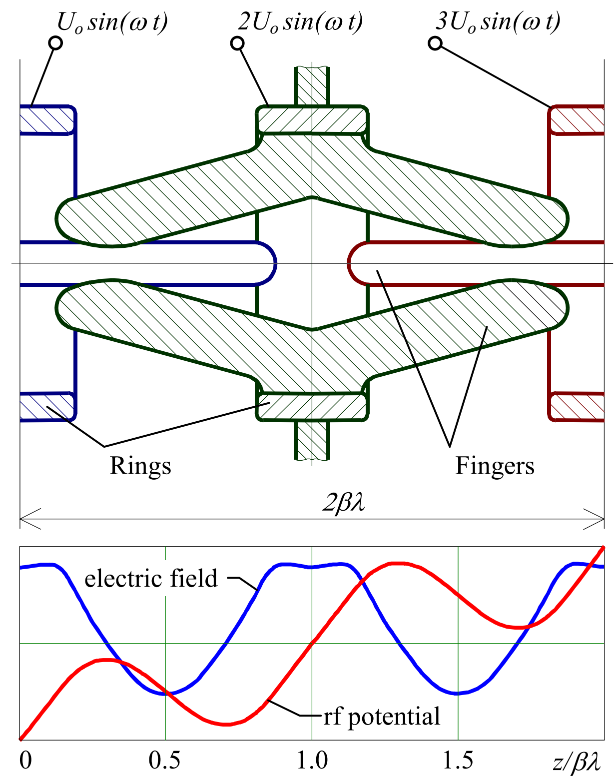

Figure 2. Electric field and rf potential calculated at the axis of the single focusing period of accelerating channel.

3 BEAM DYNAMICS

Assuming that the general rf potential $U(r, \theta, z)$ oscillates in time as $sin(\omega t)$, one can analyse particle motion near the axis. Longitudinal motion in the single accelerating harmonics $A(r, z)$ is easily described by the ordinary autophased equation with the following phase advance of the small longitudinal oscillations:

$$\mu_z = 2\pi\sqrt{-\frac{eZ\cdot U_0 A_1 \sin(\phi_s)}{2m_0c^2\beta_s^2\gamma^3}}, \quad \textbf{(7)}$$

where eZ, m_0, γ are the charge, the rest mass and the relativistic factor of the ion, respectively; β_s is the synchronous particle velocity related to the speed of light c; ϕ_s, ψ are the synchronous phase and phase deviation from the synchronous position. The amplitude of the travelling wave harmonic of the electric field is the same as the effective accelerating gradient:

$$E_m = \frac{\pi U_0 A_2}{\beta_s \lambda} . \quad \textbf{(8)}$$

Introducing the time variable normalised to the focusing period $\tau = ct/2\lambda$, one can reduce the equation of the transverse motion to well known Matieu's equation:

$$\frac{d^2 x}{d\tau^2} + \pi^2 \left[a(\phi) + 2q(\phi)\sin(2\pi\tau)\right] \cdot x = 0 \quad \textbf{(9)}$$

with the coefficients:

$$a(\phi) = \frac{4eZ \cdot U_0 A_2 \sin(\phi)}{m_0 c^2 \beta_s^2 \gamma}, \qquad q(\phi) = \frac{eZ \cdot U_0 F_1}{4 m_0 c^2 \beta_s^2 \gamma} . \quad \textbf{(10)}$$

Phase advance of the transverse oscillations per focusing period may be estimated as follows:

$$\mu_r(\phi) \cong \pi \sqrt{a(\phi) + \frac{q(\phi)^2}{2}} . \quad \textbf{(11)}$$

with the accuracy of around 10% within the range of $0 < \mu_r < 90^o$. Normalized transverse acceptance of accelerating channel and beam current limitation can be evaluated directly by the formulas given in the Ref. [1].

Test beam dynamics has been simulated in the 6 m long SP RFQ section by using the specially developed computer code, where the particles are assumed as the uniformly charged clouds, each transparent for others. The resulting parameters are presented at the Table 1.

Table 1: Calculated parameters of SP RFQ channel.

Charge to mass ratio		1/3
Operating frequency	MHz	81.4
Input/output beam energy	MeV/u	1.6 / 7.1
Total length	m	6.0
Number of the $\beta\lambda/2$ cells		35
Focusing rf voltage	MV	0.4 – 0.73
Synchronous phase	deg.	-30
Transverse phase advance	deg.	50 – 32
Electrode curvature	mm	18; 21; 24
Maximum strength of the surface electric field	MV/m	28
Normalized transverse beam emittance	mm*mrad	4.4*π
Nominal beam current	mA	40

Relatively low operating frequency was chosen in order to accept large transverse emittance and high current of the different charge states mixture from the laser source to the first stage RFQ. The input parameters of the calculated SP RFQ section are matched to the output parameters of conventional RFQ.

Both accelerating and focusing voltages grow proportionally to the cell length. But the length of accelerating gap and the size of quadrupole aperture are designed increased so that the electric field is kept nearly constant. The curvature of the finger cross-section is changed by three steps along the structure as Table 1 shows. The total energy of 16.6 MeV per charge unit is gained at the length of 6 m, producing the average accelerating gradient around of 2.8 MV/m.

Fig. 3 shows the transverse x and y beam envelopes, including 95% of particles at every longitudinal position. The beam size increases a little, but neither beam losses no emittance growth was seen at the nominal current of 40 mA. If the intense beam is properly matched at the entrance, first losses of around 2-3% appear when the current is close to 200 mA.

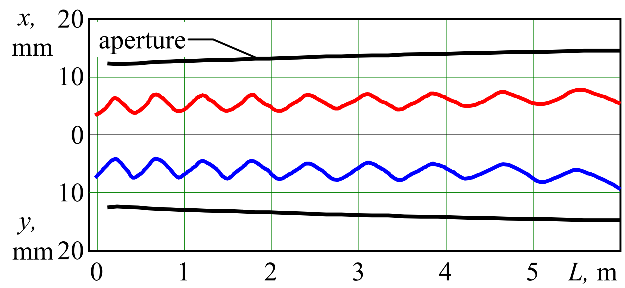

Figure 3. Transvrese beam envelope for 95% of particles.

4 CAVITY PARAMETERS

The electrodynamics parameters specified for one of $\beta\lambda$ cells from the middle of the cavity by using a standard OPERA code are sown in the Table 2.

Table 2: Calculated parameters of SP RFQ cavity cell.

Cell length	mm	344
Cavity diameter	m	1.4
Quality factor		44000
Focusing voltage	MV	0.59
RF power loss	kW/m	233

Cavity diameter of 1.4 m is approximately two times smaller that one could be expected for conventional Alvarez structure at the frequency of 81 MHz. Such a considerable reduction is mostly due to inductive loading by the long fingers. As the finger length is varied along the cavity, different inductive effect has to be compensated by capacitive loading and special inductive tuners.

5 REFERENCES

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