SPACE CHARGE EFFECTS AND RF FOCUSING OF RIBBON BEAM IN ION LINAC

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Version of the plane structure ion linac which is designed for intensive low energy ribbon beams bunching and acceleration is considered. Transverse stability is achieved by the use of nonsynchronous field harmonic focusing influence (RF focusing concept). Investigation of intensive ribbon beam dynamics features is carried out. The space charge effects are studied numerically by means of ″super particles″ approach. The proposal of 80% transmission 1 A limit current ribbon beam accelerator for the ITER neutral injection system and some another applications is presented.

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1 INTRODUCTION

Using of a neutral injection system (NIS) is known to be effective way to heat thermonuclear plasmas. It can be realized as a combination of a high intensive ion beam linac with funneling and stripping systems. Applying of the well-known RFQ linac is not suitable for this purpose because of the insufficient output beam current. Early in [1] it was suggested to use the undulator linear accelerator of a ribbon D^- beam. Applying of plane structures with ribbon beams has the following specific features: 1) large value of bunch cross-section allows to increase greatly the output current; 2) large beam surface is convenient for effective neutralization; 3) it is suitable to combine the plane channel and high-intensity ion source. The most of aspects of the undulator accelerator design was investigated in [1]. In the paper [2] studying intensive ribbon beam dynamics was carried out in the 2D model. In this paper concept of the RF focusing intensive ribbon beam accelerator is discussed. Space charge effects are investigated in 3D model. Differences between this kind of accelerator and the undulator accelerator are considered.

2 PARTICLE MOTION EQUATION

The acceleration system discussed is supposed to be realize as an interdigital H-type structure. It consists of a cavity, some vanes inside it and a number of electrodes alternatively connected to the vanes. Usually only the ribbon beam thickness keeping is investigated To create the RF field components which can provide the transverse focusing along the ribbon width it is suggested [1] to apply the curved electrodes of a special form (see Fig. 1). Let us assume the beam to interact with only two space harmonics of the RF field. Then the field potential can be presented as

$$U = \sum_{p=s,n} U_p \,\mathrm{ch}(k_x^p x)\,\mathrm{ch}(k_y^p y)\sin\left(\int h_p dz\right)\cos(\omega t) \,. \quad (1)$$

Here s, n are numbers of synchronous and nonsynchronous harmonics respectively; U_p are harmonic amplitudes; k_x^p, k_y^p, h_p are wave numbers; $h_p = (\mu + 2\pi p)/D$, μ is the phase advance per period of the structure D. Formula (1) determines the RF field of the structure considered. The motion equation in this field in a smooth approximation can be obtained using the averaging method [1]. In the single particle approach does not taking into account the space charge field it gives

$$\frac{d^2\mathbf{R}}{d\tau^2} = -\frac{\partial}{\partial \mathbf{R}} U_{eff} \;, \quad (2)$$

where U_{eff} is the effective potential function which can be expressed as

$$U_{eff} = U_0 + U_1 \,,$$

$$U_0 = -\frac{1}{2} e_z^s\left[\mathrm{ch}(\rho)\,\mathrm{ch}(\eta)\sin(\psi + \chi) - \chi\cos\psi\right] \,, \quad (3)$$

$$U_1 = \frac{1}{16}\frac{{e_n}^2 - 1}{{\Delta^-_{s,n}}^2} + \frac{1}{16}\sum_{p=s,n}\frac{{e_p}^2 - 1}{{\Delta^+_{s,p}}^2} \,.$$

Here $\mathbf{R} = [\rho, \eta, \chi]$,

$$\vec{e}_p = \begin{pmatrix} e_x^p\,\mathrm{sh}(k_x^p X)\,\mathrm{ch}(k_y^p Y) \\ e_y^p\,\mathrm{ch}(k_x^p X)\,\mathrm{sh}(k_y^p Y) \\ e_x^p\,\mathrm{ch}(k_x^p X)\,\mathrm{ch}(k_y^p Y) \end{pmatrix}, \quad e^p_{x,y,z} = \frac{e\lambda E^p_{x,y,z}}{2\pi mc^2\beta_c}$$

are the dimensionless field harmonic amplitudes, $\rho = \frac{2\pi}{\lambda\beta_c}X$, $\eta = \frac{2\pi}{\lambda\beta_c}Y$, $\chi = \int h_s dZ - \omega t - \psi$, X, Y, Z are the slowly varying coordinates, ψ and β_c are the synchronous particle phase and velocity respectively, $\Delta^{\pm}_{s,p} = \frac{h_p \pm h_s}{h_s}$.

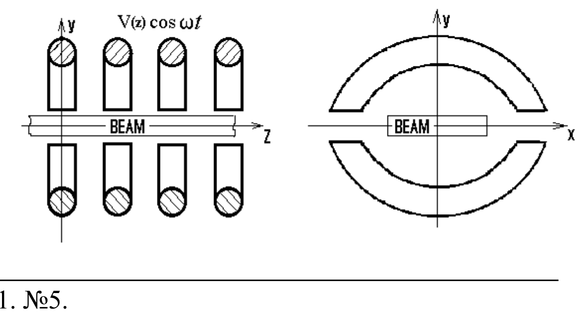

Fig. 1. The plane structure.

Effective potential function (3) determines the 3D beam motion completely. Term U_0 describes interaction of particle with synchronous harmonic accelerating and defocusing the beam. Summand U_1 evaluates only the transverse focusing and is being independent of the synchronous particle phase. The form of equation (2) allows the Hamilton analysis to be used. Existence of a total minimum of the function U_{eff} is the necessary condition of simultaneous transverse and longitudinal focusing. Expanding the U_{eff} near the synchronous particle coordinate one can formulate this condition in the form

$$\omega_\chi^2 > 0,\ \omega_\rho^2 > 0,\ \omega_\eta^2 > 0, \qquad (4)$$

where ω_χ, ω_ρ, ω_η are frequencies of small longitudinal and transverse oscillations. If the condition (4) is satisfied, the effective potential function U_{eff} is the 3D potential well in the bunch frame. Therefore, in the RF focusing ribbon beam accelerator discussed the particle energy gain is achieved by affecting the synchronous wave field. The ribbon transverse stability is achieved using the focusing influence of a nonsynchronous field harmonic (RF focusing concept).

3 CHOICE OF CAVITY PARAMETERS

3.1 RF field harmonic structure

So, for the plane structure $k_x^p << k_y^p$, one can assume $e_y^p \cong e_z^p \equiv e_p$, p=*s, n*. Because of the shielding effect (i.e. interaction between bunch space charge and channel walls) the defocusing influence of Coulomb field along the ribbon width is weak. The focusing in this direction is provided using the curved electrodes. The focusing condition $\omega_\eta^2 > 0$ can be presented in the form

$$\alpha \sin(\psi + \chi) < \frac{1}{2} e_n^2 \left(\frac{1}{\Delta_{s,n}^{-\,2}} + \frac{1}{\Delta_{s,n}^{+\,2}} \right) \left(\frac{h_n}{h_s} \right)^2 + \frac{1}{2} e_n \frac{\alpha^2}{4}, \qquad (5)$$

where $\alpha \equiv e_s / e_n$. Formula (5) defines the value of the parameter α which allows the transverse stability to be achieved for all values of particle phase. It can be seen from condition (5) that a large phase capture under a good transverse focusing may be obtained if $\alpha << 1$. On the other hand, this parameter is bounded below because the acceleration gradient $dW/dz = 0.5\alpha E_n \cos\psi$ is proportional to α. Parameter e_n also defines the value of the frequency ω_η. The value of e_n is bounded above by a sparking criteria. Formula (5) also gives that the RF focusing is more effective in the case of low beam velocity. One can optimize the set {*s*, *n*, μ} calculating value of ω_η at fixed α, e_n, ψ. The system providing the most strong transverse focusing is to be chosen. It should be noted that structures with a large harmonic number are not effective. Firstly, realization of systems with $p>2$, p=*s, n* is hardly possible since it is necessary to set many electrodes per structure period. Secondly, the value of the field amplitude which corresponds to separatrices overlapping decreases fast versus growth of harmonic number. It may lead to longitudinal instability. One can see from (5) that if the inequality $\alpha << 1$ is satisfied, systems with $s>n$ are ineligible because of insufficient transverse focusing. For the cavity parameters we consider (see below) the acceleration structure {s=0, n=1, μ=π} is to be regarded as the best. The optimum ratio k_x^p / k_y^p can be obtained using a computer simulation of beam dynamics. For the cavity parameters of accelerator discussed (see below), the transmission coefficient is maximal if k_x^p / k_y^p =1/23. In this case the transverse frequency ω_ρ is very small. Actually, the beam particles do not have time to complete even one oscillation along the ribbon width. It means that such a plane structure can be considered as an analogy of multibeam system.

3.2 Acceleration channel parameters

Let the acceleration cavity consists of two subsections: the gentle buncher subsection and the acceleration one. In the gentle buncher the synchronous particle phase decreases linearly from ψ=π/2 to some nominal value and the RF field amplitude increases as a fair-curve. Here the beam is being bunched carefully and accelerated insignificantly. In the acceleration subsection these parameters are fixed making the bunch to gain the necessary energy. The approach described allows to enlarge the transmission coefficient greatly. During the bunching process the averaged separatrix is slowly deformed. In the undulator ribbon beam accelerator [1] RF field inside the channel is primary transversal. So fast oscillation amplitudes of a longitudinal coordinate and velocity are very small, and difference between the longitudinal motion in phase space and its smooth approximation is insignificant. Therefore the phase motion is not very sensitive to the slow changing of cavity parameters. In the accelerator of this type to achieve a large transmission the field amplitude versus longitudinal coordinate in the gentle buncher can be chosen as any growing function (for instance, it may be proportional to sine). In the RF focusing ribbon beam accelerator discussed here the RF field in the interaction area is primary longitudinal. In this case fast oscillation amplitudes of a longitudinal coordinate and velocity are not small, and transmission is very sensitive to the choice of the field amplitude as a function of the longitudinal coordinate. The reason is loosing of bunch particles with velocities of large fast oscillation amplitudes from within the deforming separatrix. In paper [3] a special method of gentle buncher parameter choice for the acceleration system with a primary longitudinal RF field was suggested. It is based on the concept of longitudinal limit current nondecreasing. Value of this characteristic is approximately proportional to longitudinal acceptance. To provide a high transmission the longitudinal acceptance should be increasing function. This statement defines the relationship between the field amplitude, synchronous particle phase and beam velocity in the gentle bunching subsection. Such approach can be used for cavity parameter choice in the RF ribbon beam accelerator described. The electrode form depends on the equilibrium particle velocity and is defined by relationship $(k_x^p)^2 + (k_y^p)^2 = (h_p)^2$, $p=s,\ n$, which can be derived from Maxwell's equations. The ratio k_x^p / k_y^p=const is the system parameter. Construction of the structure period is defined by the phase advance μ and harmonics number *s, n*. The form and size of electrode cross-sections should provide the necessary harmonic spectrum of the RF field. It can be obtained by computer simulation in the 2D model.

4 NUMERICAL SIMULATION

The computer simulation of high-intensity ribbon beam dynamics in the plane structure described was carried out by means of the ″superparticles″ method. The Coulomb field is calculated using the Cloud-in-Cell method. Here the space charge density is computed on the grid which is set into the bunch area. The Poisson equation on the grid is solved using the fast Fourier transform. Gentle buncher parameters (see Fig. 2) were optimized numerically by means of the component-wise descent method. The starting parameters for computer optimization were calculated by the approach described in previous chapter.

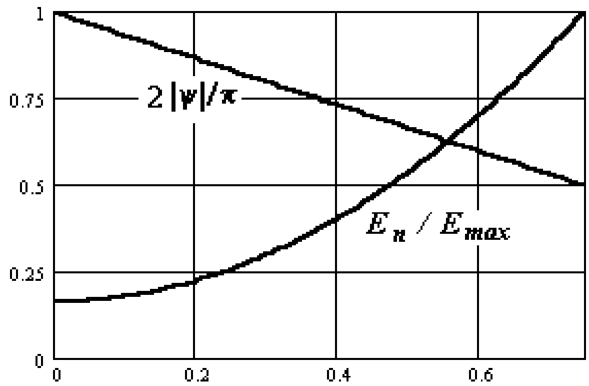

Fig. 2. Gentle bunching subsection parameters.

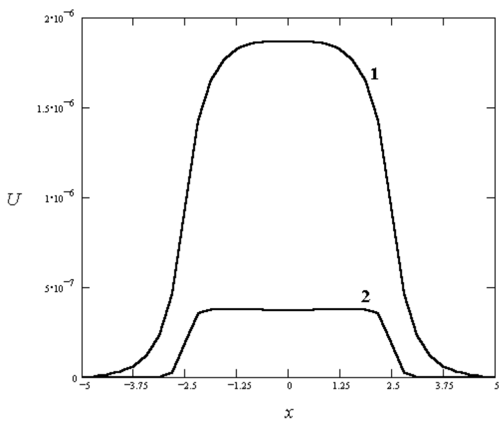

Fig.3. Dimensionless space-charge filled potential without taking into account (1) and with taking into account (2) the shielding effect.

It was shown that for acceleration of a high-intensity beam the shielding effect is significant. This circumstance is very important for large transmission obtaining. Fig. 3 shows the difference between the space charge field potential with and without shielding effect. Table 1 contains results of computer simulation. It can be seen that the RF focusing ribbon beam accelerator which is suggested in this paper provides a high transmission under a large input current. Fig. 4 shows the transmission coefficient versus input current. It proofs the efficiency of the plane structure using for high-intensity beam acceleration. To test the averaging method applicability the computer simulation was carried out for both RF field and averaged one. All results obtained in a smooth approximation and for the RF field coincide up to 5-10%.

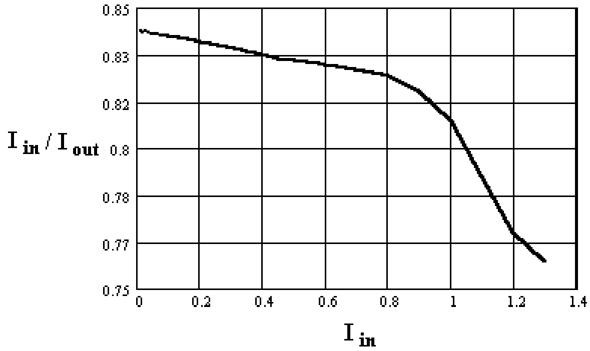

Fig. 4. Transmission versus input current, A.

Table 1. Numerical simulation results.

Parameter	Value
Operating frequency, MHz	150
Parameter α	0.1
Maximum field amplitude $E_{\max}$, kV/cm	280
Input/Output Energy, MeV	0.1/2.0
Total length, m	3
x-aperture, cm	0.2
y-aperture, cm	5

5 CONCLUSION

The RF focusing ribbon beam accelerator concept is discussed. Methods of transmission coefficient increasing are suggested. High intensity ribbon beam 3D dynamics is studied by means of computer simulations. It is shown that applying of RF focusing plane structure for intensive ion beam acceleration allows to realize a 1 A output current under more than 80% transmission.

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