FOCUSING OF RIBBON BEAM IN UNDULATOR LINEAR ACCELERATOR*

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Abstract

The possible versions of undulator linear accelerator (UNDULAC-E) using a ribbon beam is discussed. The electrodes shape for 2D transverse focusing of the ribbon beam is suggested. The influence of space charge on the beam focusing for narrow accelerating channel is investigated. Simulation results of beam dynamics and detailed study of the focusing and acceleration fields for the intensive beam are given.

1 INTRODUCTION

Early in the paper [1] it was suggested to use the compact high-frequency linear accelerators for ITER's neutral injection system (NIS), where the fast neutral deuterium atoms with energy 1.3 MeV for heating and maintenance of stationary current in tokamak's plasma are used. Among all types of the high intensity RF accelerators undulator linear accelerator of a ribbon D^- beams are suitable for NIS. The using of the ribbon beams in ITER's injector has the following features: i) high value of beam current for large width of the beam, ii) large surface for effective beam neutralization, iii) suitable combination of high current ion sources and large slot for ion extraction.

In high intensity RFQ accelerators the ribbon beam can not be accelerated because of limitations of the focusing channel aperture. In this paper the linear accelerator with the plane electrostatic undulator (UNDULAC-E) are used. The accelerating force is produced by a combination of the RF field and the plane undulator field. In UNDULAC-E the ribbon beam has small thickness and large width. A few aspects of the ribbon beam focusing in undulator linear accelerator are discussed below.

2 CHOOSING OF FIELDS AND TRANSVERSE BEAM FOCUSING ANALYSIS

The ion beam dynamics in UNDULAC with the plane electrostatic undulator, where the electrical fields were functions only from one transverse coordinate, was in detail studied in paper [2]. It was shown that in this case the focusing force is normal to the plane surface of the ribbon beam and conserves it's thickness. However it is important to ensure the beam focusing in another transverse direction - along the ribbon width. In this paper for 2D transverse focusing it was suggested to change the form of electrodes in order to create a nonuniform distribution of undulator field along the ribbon width.

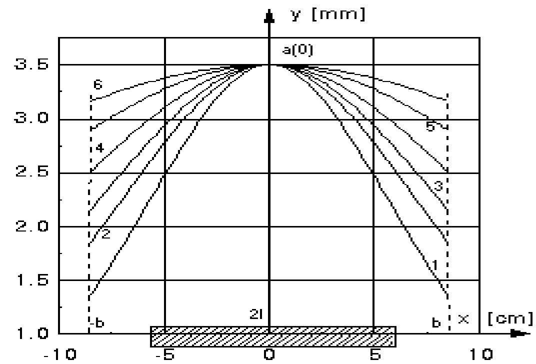

Figure 1.The shapes of the channel upper electrodes for different beam energies W: 1-50 keV, 2-100 keV, 3-150 keV, 4-250 keV, 5-500 keV, 6-1MeV (k_y/k_x=23, ω=1.256*10^9 1/s).

Let us choose the Cartesian coordinate system so that x axis is along width of a ribbon (Fig.1). The beam is accelerated along the longitudinal axis z. We consider the simplest case, when the form of electrodes is convex (transverse field Ey increases from a center). The required field distribution is created by system of the electrodes, mounted in a resonator and dc-isolated between each other. A periodic undulator field is generated by electrostatic potential differences, imprinted across the adjacent pairs of electrodes. Simultaneously RF-potentials $-\pm U_v \sin\omega t$ are applied to the electrodes of the upper and bottom row respectively. So the same electrodes are used to generate both the fields. The electrostatic field, created by the periodical system, can be represented as the sums of space harmonics

$$U_o = -\sum_{n=1}^{\infty}\Phi_{o,n}\cosh(nk_x x)\sinh(nk_y y)\cos\left(nk_z z\right) \quad (1)$$

where k_x,k_y are the transverse wave numbers, $k_z=\frac{2\pi}{D}$ is the longitudinal wave number, D is a period of the undulator, $k_x^2+k_y^2=k_z^2$. The RF field can be expressed by the series, similar to (1) except that now the summation is carried out on even harmonics, including n=0:

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$$U_v = -(\Phi_{v,0} + \sum_{n=1}^{\infty} \Phi_{v,2n}(x,y)\cos(2nk_z z))\sin\omega t \quad (2)$$

Calculating all three components of undulator and RF fields and substituting them in the motion equation of particle after averaging over rapid oscillations, as it had been done in [2], we can obtain the equation describing the slow evolution of radius-vector $\vec{r}$ in smooth approximation.

$$\frac{d^2\hat{\vec{R}}}{d\tau^2} = -\frac{1}{4}\nabla_{\hat{R}} U_{eff} \qquad (3)$$

Here $\hat{\vec{R}} = \frac{2\pi\vec{r}}{\lambda}$, τ=ωt, U_{eff} is the effective potential function depending on harmonics amplitudes of the undulator and the RF fields, as well as on slow phase $\psi = 2\pi\int\frac{dz}{D} - \omega t$ of a combinational wave field. The fundamental space harmonics amplitudes $E_{0,1}$, $E_{v,0}$ are responsible for the mechanism of ion acceleration and focusing.

Taking into account only the main space harmonics of the undulator and RF fields, the expression for U_{eff} can be written in the form

$$U_{eff} = \frac{1}{4}\{a_{0x}{}^2\cosh(2k_x x)\sinh^2(k_y y) + a_{0y}{}^2\cosh^2(k_x x) *$$
$$*\cosh(2k_y y) - 2a_{v,0}a_{0,y}\cosh(k_x x)\cosh(k_y y)\sin\varphi\} \quad (4)$$

Here $\vec{a}_0 = \frac{e\vec{E}_{0,1}\lambda}{2\pi mc^2}$, $a_{v,0} = \frac{eE_{v,0}\lambda}{2\pi mc^2}$ are the dimensionless amplitudes of the first undulator field harmonic $E_{0,1}$ and the zero Rf field harmonic $E_{v,0}$

Substituting (4) in equation (3) we obtain the system of three equations for x, y and z. The analysis of this system for paraxial particles ($k_x x$<<1, $k_y y$<<1) shows, that simultaneous focusing along x and y directions is possible if

$$a_{0y} > a_{v,0}\sin\varphi \qquad (5)$$

Oscillation frequency Ω_x will always smaller than oscillation frequency Ω_y:

$$\Omega_y{}^2 = c^2 k_y{}^2 \left(\frac{a_{0x}{}^2 + a_{0y}{}^2}{2}\right) + \frac{k_y{}^2}{k_x{}^2}\Omega_x{}^2 \qquad (6)$$

The main factor limiting the beam intensity in the ion accelerator is space-charge forces. In order to take into account Coulomb defocusing of particles, it is necessary to add the space-charge field of the beam in the right part of the equation (3).

3 COMPUTER SIMULATION OF SPACE CHARGE FIELDS AND BEAM DYNAMICS

To simplify estimation of the space charge fields we assumed that the cross-section of focusing channel is a rectangle, having ideally conducting walls, with a width 2b and a thickness 2a. The symmetrically disposed in this channel ribbon beam has a width of 2l and a thickness of 2t (fig.2). The computer simulation show that the installing of side walls at x=±b slightly influences simulation results if the ratio l/t>>1 and the ribbon width l< b.

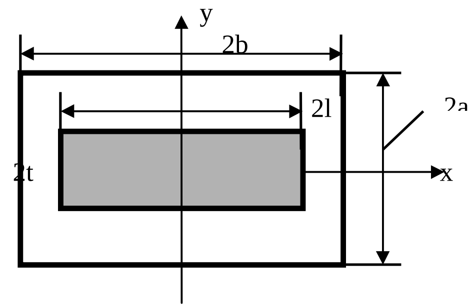

Figure 2.The cross-section of the focusing channel.

Let us designate E_l , E_t the maximum values of x- and y- components of the space charge field E_q accordingly. The frequencies of transverse oscillations Ω_x, Ω_y are chosen to take values of El, E_t and the ratio k_y/k_x into consideration. In our case E_l and E_t can be written as

$$E_{l,t} = \frac{\Lambda}{\varepsilon_0\pi(l+t)}\Gamma_{l,t} \qquad (7)$$

Where Λ is a linear space charge density, $\Gamma_{l,t}$ is the beam form factor which depends from the electrostatic shielding. If space charge shielding is neglected then $\Gamma_{l,t}$= 1 for any beams having circular (l=t) or elliptic (l > t) cross sections. But if the beam cross section is a rectangular $\Gamma_l \neq \Gamma_t$ (E_l/E_t=1 for l=t and then E_l/E_t increase from 1 to 2 for l>>t).

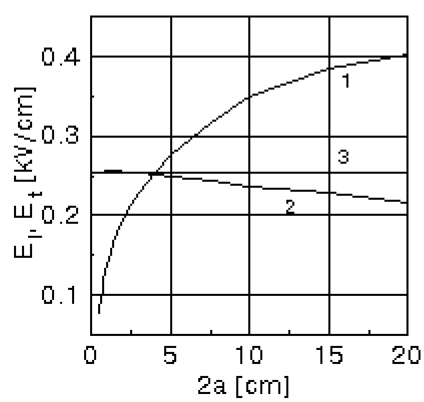

Figure 3. The dependencies of E_l and E_t on the channel thickness 2a.

Electrostatic shielding of the space charge field in the channel varies significantly. The ratio Γ_l/Γ_t found above for free space and the amplitude E_l can be decreased for narrow channel. The fig.3 shows the dependencies of E_l (curve 1) and E_t (curve 2) versus the channel thickness 2a. The other parameters are constant: 2l= 11.5 cm, 2t= 0.5 cm, 2b=17 cm, I=0.2 A. The most interesting here is the curve 1, which demonstrates that the narrowing of the channel from 20 cm to 0.51 cm causes strong electrostatic shielding and the space charge field E_l decreases in some times. The E_t component varies under these conditions slightly (curve 2). The theoretical value of Et for an infinitely wide beam having the same values t and beam current density j is shown in fig.3 (straight line 3). Consequently it is possible to reduce significantly the space charge fields E_l using beams with large magnitude of l/t. However this approach is limited by the condition of focusing in the x-direction. Indeed as it follows from formula (4) the transverse focusing can be realized if the ratio $k_y/k_x \approx l/t$. In real systems (fig.1) the electrode shape is not a straight line but it is determined by the equation

$$\cosh(k_x x)\sinh(k_y y) = \sinh(k_y a(0)) \quad , \qquad (8)$$

where the wave numbers k_x and k_y and the synchronous particle velocity v_s are connected by the equation

$$k_x{}^2 + k_y{}^2 = \frac{\omega^2}{v_s{}^2(z)} \ . \qquad (9)$$

The channel thickness 2a(x) is described by the curve

$$2a(x) = \frac{2}{k_y}\sinh^{-1}\left(\frac{\sinh(k_y a(0))}{\cosh(k_x x)}\right) \qquad (10)$$

and decreases from 2a(0) to 2a(l). The minimum size a(l) must be more then the beam thickness t. This condition and also $E_{y\,max}$ are limited the ribbon width 2l.

The 2D particle simulation of self-consisting beam dynamics in the UNDULAC-E confirms the preliminary estimations obtained. The ion beam is represented by particles (‘superparticles‘). The dispersion of ion axial velocities were neglected, and all velocities were assumed to be equal to the one of the synchronous particle. The acceleration and focusing fields were calculated by the derivation of the effective potential U_{eff} . the equation of axial motion of synchronous particle was solved numerically using the Runge- Kutta method of 4th order. For the space-charge field calculations 2D regular mesh was put on the cross-section of the channel.

The space charge density in the mesh nodes is calculated by the ordinary area-weighting (PIC) method. It is accounted in this calculation that the ion concentration in a z-plane is proportional to the factor $v_s(z)/v_s(0)$, where $v_s(0)$ is the injection velocity of ions. The space charge potential U_q on the mesh was obtained from solution of the Poisson's equation using sequential over-relaxation (SOR). The space charge field E_q was obtained by numerical derivation of the calculated potential. To solve the ordinary differential equations of ions transverse motion we used well-known "leap-frog" numerical method.

Consider D^- ions dynamics in UNDULAC having L=2.5 m, wave length of the RF field λ=1.5 m, maximum amplitudes of RF-field $E_{v\,max}$=150 kV/cm; wave numbers k_x=14.2 1/m, k_y=332 1/m; the transverse sizes of the channel a=3.5 mm, b=8.5 cm; input sizes of the beam t=2.5 mm, l=5.75 cm; input energy of ions W_i=150 keV and input angular dispersion of ion transverse velocities 0.001. In this UNDULAC the ion current 0.6 A is accelerated without losses acquiring output energy 1.07 MeV. However, neglecting the shielding of the space charge fields in the same UNDULAC would result in channel 0.36 A and even 0.2 A current loss of about 6%. The beam current may be increased even more by using wider ribbons. So if in the same UNDULAC the channel has a=4 mm, b=11 cm and the beam has t=2 mm, l=10cm then the current of 1A is accelerated without loss.

More accurate estimations of UNDULAC's possibilities may be obtained in the future by 3D simulation.

4 CONCLUSION

The ribbon beam concept was used to increase the beam current in the undulator linear accelerator. The electrodes shape for 2D transverse focusing of the ribbon beam is found. It was shown that the electrostatic shielding of the space charge field reduces Coulomb defocusing of the particles in the narrow accelerating channel. The results of the numeral simulation of intense D^- beam dynamics confirm the possibility to receive the beam current of about 1 A in the UNDULAC-E.

REFERENCES

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