CALCULATION OF EXTRACTION OPTICS FOR ION SYSTEM WITH PLAZMA EMITTER

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Abstract

The 2-D code for simulating of ion optics system of positive ion extraction from a plasma source is described. Example calculation of 100 kV optics for the extraction ion IHEP gun is presented**.** The trajectories of particles and emittance plots are resulted. The aberrations influence strongly on ion optics for considered geometry.

INTRODUCTION

Many programs for the simulating of positive and negative ion beam extraction systems are known now [1]. AXCEL, SLAC, WOLF, SNOW, KOBRA are widely applicable. The results of calculations on these and other programs are in agreement with experimental data; especially it is good for the case of positive ions. The most complex three- dimensional computing program has been developed in the Oak Ridge National Laboratory by Whealton et al. [2]. This program describes plasma in a source and takes into account the contribution of electrons in formation of plasma sheath. Pamela has made a faster and simpler original two-dimensional computer program of extraction optics calculation for positive and negative ions on the basis of a code SLAC [3]. The author used the procedure of space charge neutralization in the area of plasma-extraction region where potential determined from the solving of the Poisson's equation exceeded the given potential of plasma. Such procedure of plasma sheath determination has appeared to be successful as good agreement between the results of calculations and experimental data was found.

In this present work the 2-D code for design of extracting electrode system of positive ion beam is presented. It is written in FORTRAN and is run on IBM PC or any other compatible computer using DOS and WINDOWS extenders. Plots of trajectories, equipotentials and plots of the emittance can be obtained. With the aim of testing it the ion optics calculations were carried out with the help of the given here program and the KOBRA code (the KOBRA calculations are executed in ITEP). The comparison of the received results has shown coincidence of beam envelopes and emittance plots on the output of extraction system.

THEORY

The problem of positive ion beam extraction from plasma and it subsequent acceleration by the electric field is considered. We shall solve the problem in the cylindrical coordinates (r, θ, z) using the method of macro particles. In axially-symmetrical case these are infinitely thin evenly charged rings. The selection of ions is carried out with advanced surface of plasma penetrating into vacuum. At selection of ions from plasma there is no limiting flow restricted by a space charge due to the presence of electrons. The current of saturation limited by emission exists in this case always. The trajectories of ions begin at thermal velocities inside plasma on some distance from plasma electrode. The self-consistent problem is described by a system of the Poisson equation

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon_0}, \tag{1}$$

$$\rho = \rho_i + \rho_{e0} \cdot \exp\left(-\frac{e(\varphi_P - \varphi)}{kT_e} \right) \tag{2}$$

and the equations of the motions of ions

$$\frac{d\vec{p}}{dt} = -q \cdot \nabla \varphi \tag{3}$$

The equations (1) - (3) are solved in the region limited by simple closed curves with no fixed form and place of a plasma sheath. Here φ is the electrical potential, ρ_i the densiity of a space charge of ions, ρ_{e0} the density of a space charge of plasma electrons, φ_p the potential of plasma, e the charge of an electron, T_e the electron temperature, k the Boltzmann constant, ε_0 the dielectric permittivity of vacuum, p=Mv and q are momentum and ion charge. On separate segments of boundary curves the potentials are known or the Neumann boundary condition is satisfied The beam inside plasma is neutral. The electron charge with Boltzmann distribution in a transition layer near to plasma sheath besides ions is taken into account. Outside plasma $\rho_e = 0$.

The electrostatics problem, taking into account the potentials and the fields induced by a beam, is solved using the method of boundary integral equations with respect to the density of surface charge σ on electrodes [4,5]. The numerical solution of these equations is obtained by using the collocation principle with interpolation of density σ by the cubic spline. As a result the initial integrated equations are reduced to the system of algebraic equations with respect to the density σ in collocation points. The coefficients of matrixes of the received system are expressed by the integrals over electrodes contours of the product of weight spline functions and integral equation kernel. These are calculated numerically.

Space charge distribution and particles trajectories are determined from the simultaneous solving of the Poisson

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equation and equations of large particles motion by iteration. The numerical integration of the motion equations is performed by using the fourth order Runge-Kutt procedure. The continious set of rectangular grids with different sizes and the different number of cells is introduced to describe the space charge distribution. This set is needed to describe the nonuniformity of charge density near to a plasma sheath. The charge introduced by the k-th particle with the current I_k in the j-th cell is equal $Q_{kj} = I_k \cdot t_{kj}$, where t_{kj} is the time during which the k- particle passes the j-cell. Total charge in a cell is $Q_j = \sum I_k \cdot t_{kj}$. The space charge density within a cell is considered constant, then the charge density in the j - th cell with the volume V_j on the n - th iteration is

$$\rho_j^{(n)} = \frac{Q_j^{(n)}}{V_j} \qquad (4)$$

To speed up the rate convergence an under relaxation method is applied. The iterative procedure at the calculating of the potential in the greed nodes and density of a charge in cells is written as

$$\varphi^{(n+1)} = \omega \cdot \overline{\varphi^{(n+1)}} + (1-\omega) \cdot \varphi^{(n)}, \qquad (5)$$

$$\rho^{(n+1)} = \omega \cdot \overline{\rho^{(n+1)}} + (1-\omega) \cdot \rho^{(n)}, \qquad (6)$$

where $\overline{\varphi^{(n+1)}}, \overline{\rho^{(n+1)}}$ - the potential and the charge density calculated on n + 1 iteration, and $\varphi^{(n)}, \varphi^{(n+1)}$ and $\rho^{(n)}, \rho^{(n+1)}$ - accepted actually values of the potential and the charge density on n and n + 1 iterations, respectively; $0 < \omega < 1$ – the relaxation parameter.

The procedure of neutralization of a space charge is introduced in those cells of the region (r, z) where total potential of electrodes and beam exceeds given potential of plasma φ_p. Such procedure of space charge neutralization is performed at the end of each iteration after calculating of ion trajectories and determining of beam charge in cells and potential in nodes according to (5), (6). The electrical field is only calculated in the nodes of a grid. In the beam motion region the field is determined by the parabolic interpolation by its values in nine nearest units. For calculation the potentials and fields only one calculation of matrixes of their values in the grid nodes and in the collocation points for unit density of surface and space charges is needed. Then the potentials and fields on each space charge iteration are calculated by multiplication of these matrixes to a vector of the surface charge density in the collocation points and vector of space charge density in the grid cells. This approach allows to decrease essentially the time of the solution of the self-consistent problem.

RESULTS

Calculations have been carried out for a proton beam with the output energy 100 keV and the current 150-200 mA. At first the simulation of the three-electrode ion optics system (IOS) has been carried out. The geometry of electrodes of a gun maintained on one of installations in IHEP was used in calculations (fig.1). It was required to investigate influence of an extending voltage on the optical characteristics of a beam. Dependence of optical characteristics from of such parameters as electron temperature, initial axial and transverse velocities of ions also was investigated.

The density of a ion current inside plasma J, the electron temperature T_e, the potential of plasma φ_p and accelerating electrode φ_2 were considered known. The potential of a plasma electrode φ_1 was determined from a condition of equality ion and electron currents going on an isolated wall adjoining with plasma

$$0.344 q n_0 \sqrt{\frac{2kT_e}{M}} = e n_0 \sqrt{\frac{kT_e}{2\pi m_e}} \cdot \exp\left(-\frac{e(\varphi_P - \varphi_1)}{kT_e}\right)$$

and it was differed from φ_p on $3.55 \cdot kT_e/e$ eV [6]. For about 1000 large particles were used at modelling up. It was supposed that the density of an ion charge is uniform in a plane of start inside plasma also all particles have equal axial velocities. The moments of rotation and initial radial components of particles velocities were set on a way “chaotic start”. The electron temperature varied from 0.1 up to 5 eV, the initial axial energy of protons changed from 2 up to 100 eV, and initial transverse energy from 0.05 up to 0.2 eV.

Fig. 1 shows the trajectories of ions for the accelerating voltage $U = \varphi_2 - \varphi_1 = 125$ kB. The emittance plots in planes r, r′ and x, x′ are given in figs. 2a and 2b, respectively[*]. Fig. 1 shows that the overfocusing of beam is observed and the large part of it (about 16 %) is landed on the flange. The loss of beam decrease approximately twice if the density of plasma is increased by 10 % at constant U or the accelerating voltage is reduced up to 110 kV at constant density. The particles taking off with an emission surface close the edge of a plasma electrode form the S-figurative distortion in fig.2a. The change of the extending electrode form and value of an accelerating voltage from 110 kV up to 130 kV has little influence on the emittance plots and the value of root-mean-square emittance E_{4rms} for 90 % of intensity of a beam. The change of electron temperature both initial axial and transverse of ion temperature (within given limits) doesn’t influence much on a beam envelope and plot of emittance.

The essential improvement of the ion-optical characteristics of a beam is reached if four-electrode IOS with two-cascade acceleration of ions of the same accelerating voltage is used (see fig. 3 and figs. 4a, 4b). Solid line in fig. 4b corresponds to the effective ellipse for 90 % of intensity of a beam. The decreasing of aberrations and

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[*] The procedure of emittance construction in a plane x, x' for the large particles representing evenly charged rings with the moments of rotation is given in [5].

E_{4rms} can be connected with correcting of plasma border at the expense of introduction of an additional accelerating electrode. The halo of a beam for IOS-4 is less than for IOS-3. At same current four-electrode IOS provides formation of a beam with greater brightness and allows to operate parameters of a beam (a radius and a slope of envelope) on the output of ion gun by change of voltage on the first and second accelerating interval without loss of intensity of a beam.

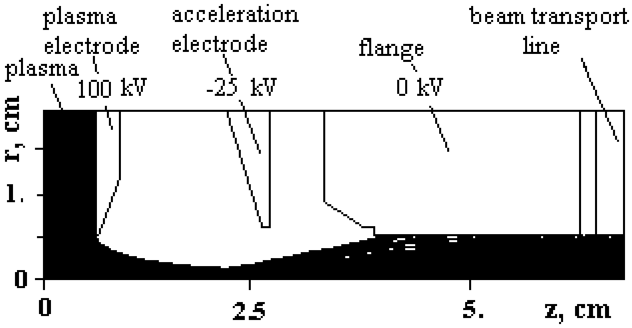

Fig.1: Geometry of the three-electrode IOS and trajectory of ions. T_e = 2 eV, density of ion current in a plane of extraction J=255 mA/cm^2, current on an output I=182mA

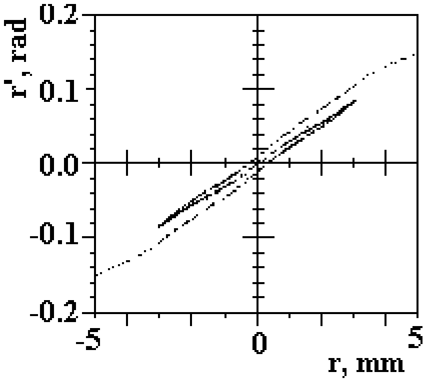

Fig. 2a: **r**, **r′** emittance plot for three-electrode IOS

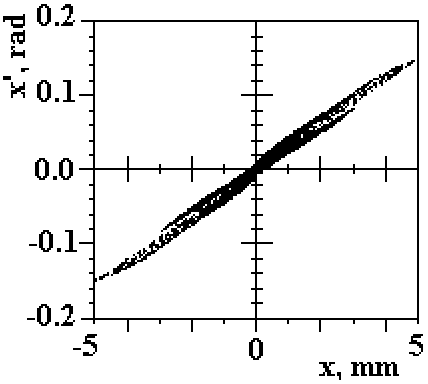

Fig. 2b: **x**, **x′** emittance plot for three-electrode IOS. $E_{4rms}=5.45 \cdot 10^{-5}$ cm·rad for 90% of intensity of a beam

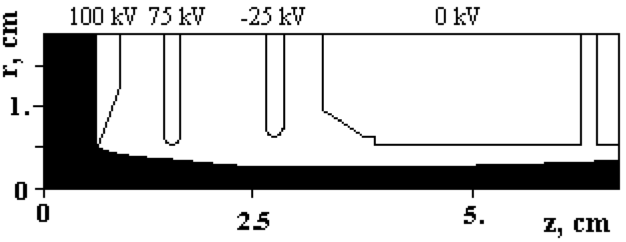

Fig. 3: Geometry of the four-electrode IOS and trajectory of ions. T_e = 2 eV, density of ion current in a plane of extraction J=238 mA/cm^2, current on an output I=186mA

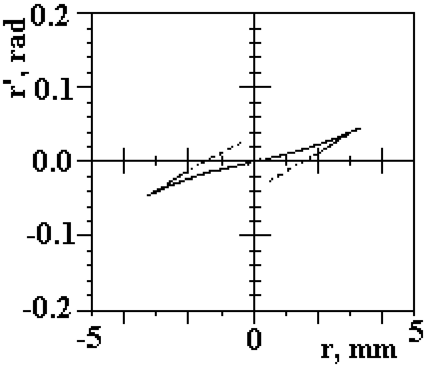

Fig. 4a: **r**, **r′** emittance plot for four-electrode IOS

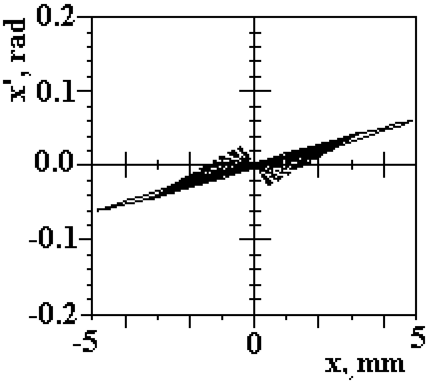

Fig. 4b: **x**, **x′** emittance plot for four-electrode IOS. $E_{4rms}=3.0 \cdot 10^{-5}$ cm·rad for 90% of intensity of a beam

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