A SIMULATION CODE TO MODEL AN ION BEAM FORMING IN AN INJECTOR

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Abstract

A simulation code for modeling of an ion beam forming in a linear accelerator injector has been developed in BORLAND PASCAL environment. The code enables to calculate the main beam parameters at the injector output: a total ion beam current and its radial density distribution, a beam divergence, a phase portrait and upper limits of the injector. An algorithm is based on solution of self-consistent ion moving problem in the total electrostatic field, caused by the ion-optic system electrodes and the beam space charge. The solution is a result of successive approximations. At first a vacuum electric field is calculated, as a result of the finite-difference Laplace equation solution. Then an ion beam dynamics is calculated, solving the ion motion equations by the Runge-Kutta method of the fourth order. The ion beam dynamics enables to find a beam space charge distribution using “ a particle-in-cell” method. If an ion space charge is known, then it is possible to calculate more accurately the electric field, solving now the Poisson equation. That process is repeated some times (5-6 cycles) to get a converging solution. The result of the program processing is ion beam output parameters for given plasma density, an electron temperature, the geometry of ion-optic system and the potentials of its electrodes.

1 INTRODUCTION

Some designs of high-current linacs as for the applied purposes, and fundamental researches with intensive neutron fluxes, now are considered. [1]. These designs are based on usage high-current proton (deuteron) injectors, working either in a high duty factor mode or in a continuous (CW) one. For injection in an initial part of the accelerator, which as a rule has RFQ structure, the beams with a current $I \geq 100$ mA and particle energy about 100 keV are necessary. The choice of injection energy is substantially defined by the reliability requirement of an ion beam forming system. With the decrease of a potential difference on the forming system electrodes the electrical breakdown probability of high-voltage gaps between the electrodes decreases, the level of a parasitic X-radiation reduces, the beam current decreases. However at a low injection energy it is necessary to increase a wave length of RFQ accelerating field, that results in increasing of the RFQ cavity cross sizes, or in contrary case the sizes of initial accelerating cells and the channel apertures become very small. That complicates as manufacture as tuning of the accelerating structure elements, and reduces the channel acceptance. The aperture decreasing results in increasing of the beam phase density, when the accelerated current value is defined.

The important problem is matching of the injected beam phase volume to the RFQ acceptance. In some advanced projects, a special Low Energy Beam Transport line (LEBT) with focusing solenoids has been used for the matching [2, 3]. The length of such LEBT is about 2-3 m, and its main purpose is to form a convergent beam or its crossover at an RFQ inlet, which has a radius $r_{in} \leq 1$ mm. That is necessary for effective beam transmission through RFQ. In the LEBT, the ion-beam plasma is generated, as a result of the residual gas ionization by the beam particles. This plasma compensates a beam space charge and accordingly reduces beam expansion. However the electromagnetic oscillations can be excited in the plasma and they, as a rule, cause the phase volume growth of the beam, transported along the LEBT [4]. Therefore it is desirable to design such beam forming system of an injector to produce ion beams with ion-optical performances, needed for matching to RFQ without using the LEBT. This problem may be studied by a numerical modeling.

For a numerical modeling of an ion beam forming, the computer code INJECTOR has been developed. An ion emitting surface is the plasma boundary, which is limited by a round aperture in a plasma electrode, contacting with an ion source plasma.

2 BEAM FORMING SIMULATION CODE

The beam forming process in an injector is a self-consistent problem. It includes the definition of electric fields between injector electrodes with given potentials and at presence of a beam space charge. In turn, the beam particles dynamics in the total electric field determines the space charge distribution. The electric field in the area of the plasma electrode aperture determines a position of the emitting plasma boundary and consequently the ion start surface. Therefore the problem is solved by a successive approximation method in a cylindrical frame *(z,r)* (*z*-axial, *r*-radial coordinates). The initial parameters are: a beam current *I*, charge *Ze* and mass *M* of ions, an electron plasma temperature T_e, a radius r_o of the plasma electrode aperture, an ion injection energy *W*, shape of electrodes, their potentials and distances between them.

The solution algorithm consists of a cyclic sequence of some steps. For zero approximation the vacuum field potential distribution *U(z,r)* is calculated between the forming system electrodes without an ion beam. For this purpose the Laplace equation $\Delta U(z,r) = 0$ is solved for a two-dimensional computing grid (z_i,r_i), using an upper relaxation method [5]. Then the axial $E_z(z_i,r_i)$ and the radial $E_r(z_i,r_i)$ electric field components are determined by numerical derivation of potential in the grid crosses. The field components E_z and E_r allow to calculate trajectories of ions, starting with the plasma emitter surface. For this purpose the Lorentz motion equations $M\cdot d^2z/dt^2 = ZeE_z(z,r)$, $M\cdot d^2r/dt^2 = ZeE_r(z,r)$ are being solved. The Runge-Kutta fourth order method is used for the solution [5]. The integration time step Δt is determined as $\Delta t\cdot v_{max} < h/2$, where v_{max} is an ion output velocity, h is a mesh width.

In zero approximation, the surface, from which ions are starting, is found from a momentum balance on plasma boundary: $nkT_e = \varepsilon_0 E^2/2$, where n is a plasma density, k is the Boltzmann constant, ε_0 is the dielectric constant, E – an electric field strength [6]. The plasma density n is determined, knowing a value of an input current $I = 0.4Zen(2kT_e/M)^{1/2}S$ (S is a plasma emitter area). The ion start velocity v_0 is defined from the Bohm criterion $v_0 \approx (kT_e/M)^{1/2}$ [6].

When the ion dynamics is known, then the space charge density $\rho(z_i,r_i)$, produced by the beam, can be computed in the grid crosses, using the macroparticles method ("cloud-in-cell") [5]. For this purpose the emitting plasma surface was divided into thin concentric rings, that were identified with macroparticles, which dynamics is described by the Lorentz motion equations.

The obtained zero approximation for the space charge density $\rho(z_i,r_i)$ is used to specify electric fields and the beam particles motion in the injector forming system. Now the Poisson equation $\Delta U(z_i,r_i) = -\rho(z_i,r_i)/\varepsilon_0$ must be already solved. After that the macroparticles dynamics and the plasma boundary are defined more exactly. However, the plasma boundary now is determined, using $E=0$ requirement on its surface.

This iteration process is repeated some times to get a convergent solution, when the beam performances at the injector exit do not change. The result of the solution is the beam density distribution in a phase space and a radial current distribution at the injector exit.

The described algorithm has been realized as the INJECTOR program code in an Integrated Development Environment (IDE) BORLAND PASCAL. Further it was adapted to IDE DELPHI32 for PC IBM. The program code INJECTOR has been used for a numerical modeling of proton beam forming in three-electrodes ion-optics system of a high current injector, for definition of extreme possible parameters of produced beams.

3 RESULTS OF THREE ELECTRODES SYSTEM SIMULATION

A three electrodes forming system with accel-deccel electrode potentials was selected for modeling, Fig.1. It is

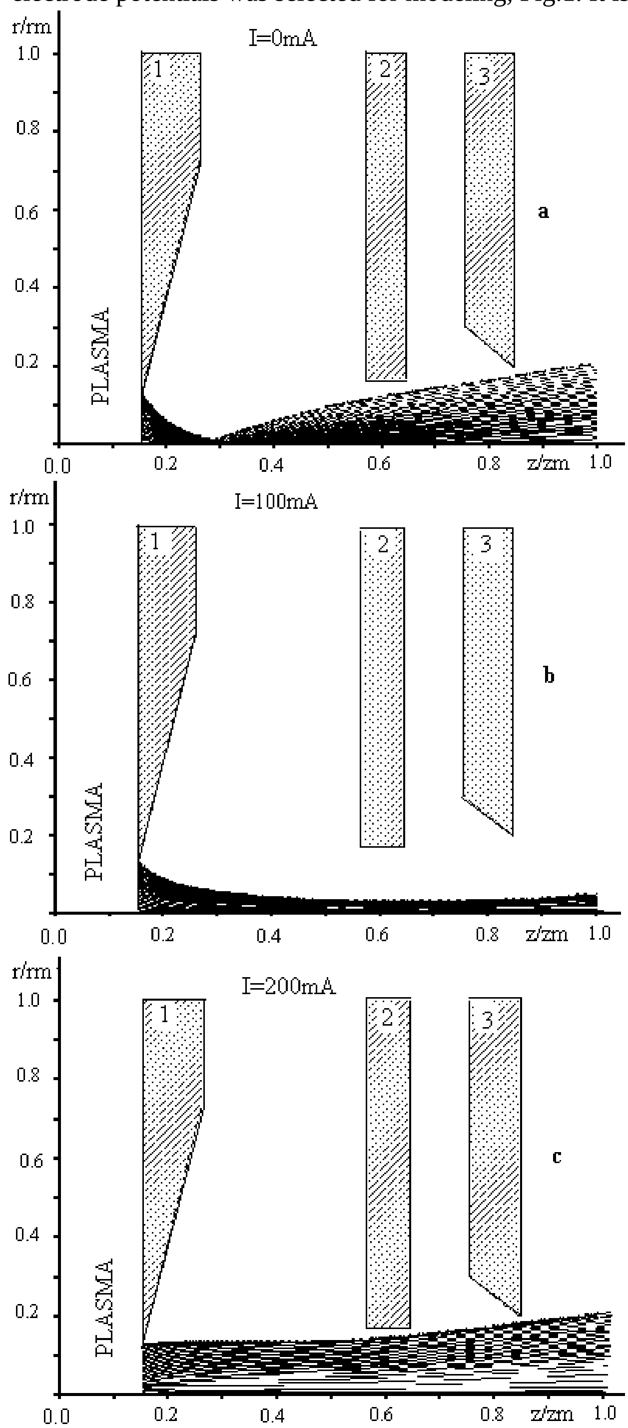

Figure 1: Three modes of a proton beam forming in an injector versus of a beam current (U_1=150kV, U_2=-10kV, r_m=3cm, z_m=6.5cm).

the simplest one and is often used in high current injectors [2]. The plasma density to the left of a plasma electrode 1 (Fig. 1) was varied $n=10^{11}$-$5\cdot10^{12}$ cm^{-3}, an electron temperature makes T_e=5 eV, i.e. the experimental values have been used.

An emitting aperture in an electrode 1 makes r_0=4 mm, and its potential is U_1=150 keV reference to a grounded electrode 3. It is supposed that the injector exit is situated from the exit electrode 3 at a distance of its aperture diameter. A potential of an extraction electrode 2 was U_2=-(0.05-0.2)U_1. The gap between electrodes 2 and 3 represents a potential hill for electrons, being generated in a beam drift space behind the electrode 3. The vacuum electric field strength in the extraction gap reached 70 kV/cm, i.e. was near to a limit, defined by $d\geq 1.4\cdot10^{-3}U^{3/2}$, where d is an extraction gap in cm, U is a gap voltage in kV [7].

Depending on the plasma density n on an emitting surface (or a beam current I), there are three modes for the ion beam forming, Fig. 1 (a,b,c). The mode is determined by a relation between the beam current I and the Child-Langmuir current $I_0=(4/9)(2Ze/M)^{1/2}\varepsilon_0 U^{3/2}S/d^2$ for an extraction gap.

At small currents $I<<I_0$ all ion trajectories are intersecting the system axis between the plasma and the extraction electrodes, Figure 1a. But particles, starting at larger radiuses in the emitter plane, are intersecting the axis closer to the plasma electrode.

These aberrations of the ion-optics system are caused by nonlinearity along r of a radial electric field component E_r, especially near to the input aperture edge (r_0). The strong focusing effect of the first gap results in forming of a divergent beam with radius of 6 mm at an injector exit.

With the current growth the beam space charge decreases a focusing effect of a vacuum field component E_r and that displaces a beam crossover to the injector exit. At some value $I=I_{opt}<I_0$ the beam crossover may be produced at the injector exit with minimal radius r_{opt} and divergence r'_{opt}, Figure 1b. For given forming system and electrode potentials it is watched at I_{opt}=120 mA, $r_{opt}\approx$0.7 mm, $r'_{opt}\approx$30 mrad. It is necessary to note, that the ion-optics system aberrations give a hallo around of a dense beam core. Its current is less than 20 % of a total beam current. At the beam currents $I>I_{opt}$, the divergent beams are forming beginning with the emitting surface, Fig. 1c.

A current value $I=I_m$, at which the particle trajectories are touching the electrodes, is maximum one for given beam forming system. For the system, shown in Fig. 1, it has taken place at I_m=250 mA. That was less than the Child-Langmuir current $I_0\approx$300 mA.

At the beam currents $I>I_0$ the plasma jet is streaming to an extraction gap, and its boundary may have a complicated form. It is necessary to use a hydrodynamics approximation for the calculation of a dense plasma flow through the input aperture. It is a natural limitation for the application of the INJECTOR program code.

When potentials of the forming system electrodes are varied, the dynamics of beam forming will be approximately similar, if the value $I/(U_1-U_2)^{3/2}$ is the same.

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