ION BEAM FORMING DYNAMICS IN AN INJECTOR TAKING INTO ACCOUNT A PLASMA BOUNDARY

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The developed program code taking into account a shape and position of an emitting plasma boundary had been used to examine a deuterium beam forming in an injector. It has been shown that the beams formed by a three-electrode ion optical system have a complex density distribution in a beam phase space. For the narrow current range it is possible to have a beam crossover at the injector output with a radius of 1mm and divergence less then 20 mrad.
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1 INTRODUCTION

Now in the world some proton and deuteron linacs up to energy *1-1.5 GeV* and an average beam current of *5÷100 mA* are being developed [1]. These accelerators are intended for production of high neutron flows or for tritium production. For realization of these accelerators the high current injectors are needed with a high beam luminosity. In all designs it is supposed the injection of ion beams with the energy *50÷100 keV* in an initial part of the accelerator on the basis of a radio-frequency quadrupole focusing (*RFQ*). That imposes some requirements on a value and shape of the beam phase volume at an *RFQ* input.

The requirements to the ion optical performances of the injected beams have stimulated the mathematical modeling of ion beam forming from the plasma of gas discharge sources. One of the modeling problems is the definition of the shape and location of a self-consistent plasma boundary, from which ions are extracted, and initial conditions for starting particles. In the present work for examination of ion beam forming dynamics from plasma with the help of three-electrode ion optical system the code INJECTOR was used [2]. The code takes into account a location and shape of an emitting plasma boundary. The results of the numerical modeling are given for a deuterium beam with the output energy *100 keV*. The beam is intended for injection to a deuteron linac with the output energy *10÷12 MeV* for production of a medicine isotope-generator ^{99}Mo as a result of a nuclear reaction $^{98}Mo(d,p)^{99}Mo$ [3].

2 THE PROGRAM CODE FOR SIMULATION OF ION BEAM FORMING

The description of the INJECTOR code is given in [2]. The code is based on the solution of a motion problem for ions, emitted from a plasma boundary, in a self-consistent electric field produced by forming system electrodes with given potentials and a beam space charge. The emitting plasma boundary is supposed smooth and crossing an aperture in a plasma electrode 1, Fig. 1, which is contacting with plasma.

The shape of the boundary was supposed to be a surface of revolution of the second degree curve (spherical, elliptic or parabolic segment). In zero approach a plasma boundary position (a z_b point of crossing with a longitudinal *z*-axis) was defined from the balance of a kinetic plasma momentum and momentum of a vacuum electric field produced by injector electrodes: $nkT_e=\varepsilon_o E^2/2$, where *n* is the plasma density, T_e is the electron temperature, *E* is the electric field strength, *k* is the Boltzmann constant, ε_0 is the dielectric constant of vacuum.

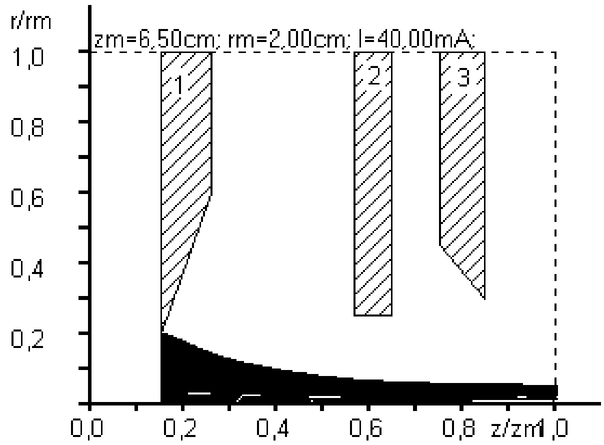

Fig. 1. Deuteron trajectories for the beam current I=40mA.

Since the initial parameters of the problem are supposed: a beam current *I*, electron T_e and ion T_i temperatures, the plasma density was determined from the expression for an ion saturation current: $I=0.4Zen\,(2kT_e/M)^{1/2}S$ [4], where *Ze* and *M* are the charge and the mass of an ion, respectively, *S* is the area of an emitting plasma surface.

The plasma boundary potential was guessed equal to the plasma electrode potential. The potential jump in a double layer was taken into account in the start ion velocity. I.e. it was supposed, that ions are starting along a normal line to the plasma surface with a velocity $v_o=(kTe/M)^{1/2}$, defined by the Bohm criterion [4].

The ion velocity component, tangential to plasma surface, was defined by the ion temperature T_i and was $(kT_i/M)^{1/2}$. Knowledge of the plasma boundary and the initial velocities of ions allows to calculate their trajectory in an injector ion optical system and respectively a space charge distribution $\rho(r,z)$. For the calculation of the space charge the method of macroparticles was used [5].

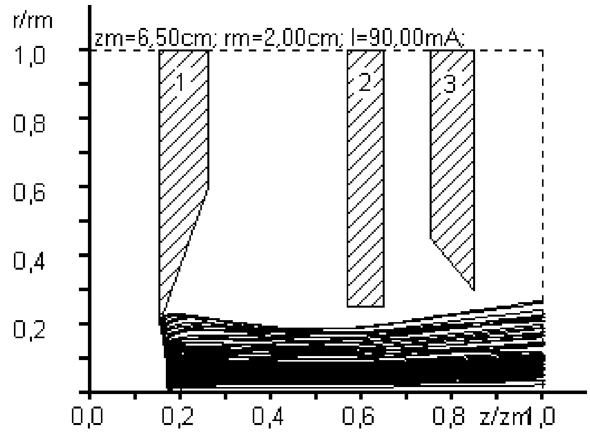

Fig. 2. Deuteron trajectories for the beam current I=90 mA.

For successive iterations of the electric field determination the Poisson equation was solved using a new space charge distribution. Every time the position of the plasma boundary was defined more exactly using the requirement that the electric field strength would be approximately zero in a point z_b where the boundary was crossed by z-axis. During the simulation the minimum boundary field strength was taken kT_e/eh_z, where h_z is a step along z-direction of a computing grid, e is elementary charge.

This process had been repeated until the converging solution had been succeeded.

3 RESULTS OF DEUTERON BEAM FORMING SIMULATION

The INJECTOR program code was used to simulate the forming process for a deuterium beam with the energy 1*00 keV*. The ion optical system with an accel-deccel potential difference between electrodes was considered. The respective ion injector is supposed to use for beam injection in *RFQ* of a deuteron linac of energy *10÷ 12MeV* for production of a medicine isotope-generator ^{99}Mo. This radionuclide may be produced due to a nuclear reaction $^{98}Mo(d,p)^{99}Mo$ under bombardment by deuterons of a target from a natural molybdenum or one enriched by a natural isotope ^{98}Mo [3].

The electron T_e and ion T_i plasma temperatures were chosen $T_e=5eV$ and $T_i=1eV$, respectively, as the most probable for many gas discharge plasma sources [6]. The geometry of the injector forming system is shown in Fig. 1.

The plasma electrode 1, Fig. 1, directly contacting with the gas discharge plasma, had potential $U_1=100\ kV$ relative to a grounded electrode 3. Radius of the input aperture in the plasma electrode 1 was $r_o=0.4\ cm$. A potential of an extraction electrode 2, Fig. 1, was $U_2= -10\ kV$. A length of an extraction gap between electrodes 1 and 2, Fig. 1, was $d=2\ cm$. i. e. the length d was above the minimum value causing a vacuum break down: $d\geq 1.4\cdot 10^{-3}U^{3/2}$, where d is in cm, $U=U_1-U_2$ is in kV [6].

In Fig. 1 and Fig. 2, the trajectories of deuterons are shown for two values of a total beam current I or accordingly for different plasma densities n. In Fig. 3 and Fig. 4 the respective distributions of particle density in a transverse phase plane of the formed beams are given.

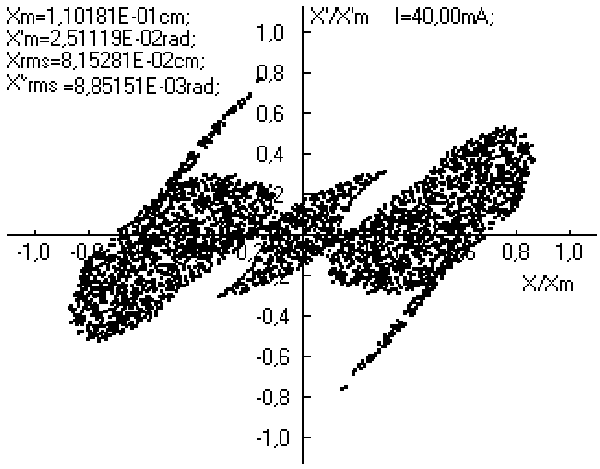

Fig. 3. Density distribution in a transverse plane of the beam phase space for I=40 mA.

Here in Fig. 3 and Fig. 4 the root mean square values (*rms)* of a beam width *Xrms* and its divergence *X'rms* at an injector output are indicated and also scales *Xm* and *X'm* of the respective coordinate axes.

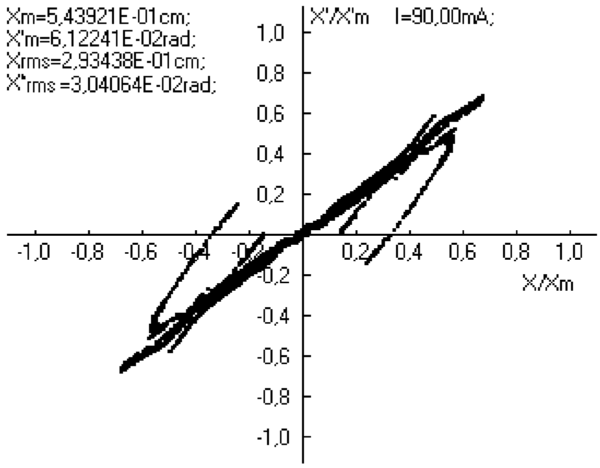

Fig. 4. Density distribution in a transverse plane of the beam phase space for I=90 mA.

As well as in case of a proton beam in ref. [2], for a deuteron beam there are three modes of its forming, depending on a total beam current I or according to plasma density n. At small currents I with regard to the Child-Langmuir value $I_{ch}=(4/9)\ (Ze/M)^{1/2}\varepsilon_o U^{3/2}S/d^2$, the divergent beams are formed with a crossover in the extraction gap and a concave emitting boundary of plasma, Fig. 5, *I=10 mA*.

With increase of the beam current the crossover displaces to the injector output. At some current value $I=I_{opt}$, in this case $I_{opt}\approx 40\div 50\ mA$, at the injector output, Fig. 1, the minimum beam width, is produced, Fig. 3. The beam radius does not exceed *1mm*. Thus the normalized emittance is $\varepsilon_n=2\cdot 10^{-2}\ \pi\cdot cm\cdot mrad$. Simultaneously the emitting plasma boundary approaches to flat in limits of the plasma electrode aperture, Fig. 5, *I=40 mA*.

At $I>I_{opt}$ the plasma boundary becomes convex to the extraction gap, Fig. 5, *I=90 mA*, and the formed beams are strongly divergent and have no crossover, Fig. 2 and Fig. 4.

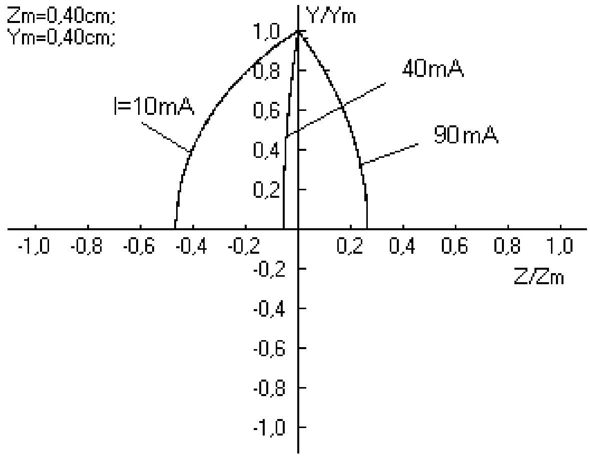

Fig. 5. Shape of the plasma boundary versus a beam current.

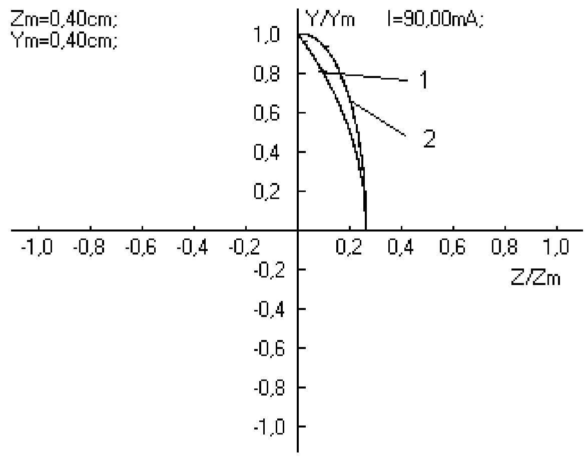

Fig. 6. Spherical (1) and elliptical (2) shapes of the plasma boundary for the beam current I=90 mA.

It is necessary to note that with the help of the smooth second-order curves it is impossible to obtain the solution with the constant electric field strength along the plasma boundary.

The results of modeling have given an oscillating character of the field strength. At currents of a formed beam of about $I \approx I_{ch}$ the minimum field oscillations and also the higher convergence rate of the solution are observed when the plasma boundary has an ellipsoid form with the relation of a vertical semi-axis to the longitudinal one of order 4, curve 2, Fig. 6.

4 CONCLUSION

The results of the mathematical simulation indicate that the chosen ion optical system allows to produce a deuterium beam with a radius no more than *1 mm* and divergence less then *20 mrad* at an injector output, but in a very narrow interval of a beam current of *40÷50 mA* at a deuteron energy *100 keV*. It is obviously possible to calculate a *RFQ* section, which will transport such a beam without a matching unit. At other currents of a beam or its ion optical performances, a matching unit, for example similar *LEBT* (Low Energy Beam Transport) used in [7], is needed. The nonlinear effects caused by a vacuum electric field, and a space charge field of a high current beam, are resulting in a complex particle density distribution in a beam phase space and are increasing a beam effective emittance.

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