INSTITUTE OF PLASMA PHYSICS
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NUMERICAL SIMULATION OFF ION BEAM GENERATED IN THE DIODE WITH ANODE PLASMA COLUMN

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IPPCZ - 306

February 1991

RESEARCH REPORT

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ABSTRACT

The ion beam generation in the high current diode with anode plasma slab has been studied. The ions are exctracted from the anode plasma by the strong electric field of deep potential well (virtual cathode), arising after the propagation of relativistic electrons through the anode plasma slab. The movement of this potential well with the front part of ion beam leads to collective ion acceleration up to $\sim$ 10 MeV energy range.

1. INTRODUCTION

Light ion beams (LIB) generated by pulse power machines are promising candidates for energy drivers of inertial confinement fusion. Industrial application of the LIB in material processing seems to be also promising in future, since the LIB has better characteristics than previous steady-state, low-current, ion sources.

The LIB can be generated by various types of pulsed diodes . At the same time, new methods of collective ion beam acceleration have been developed. For example, the acceleration of ions can be achieved either by moving potential well (virtual cathode) or by slow waves excited in the plasma column laying behind the anode. The drawback of the former method is the short distance (~ 0.1 m) synchronous motion of ions and the virtual cathode. On the other hand, by this methods the light ions may be accelerated up to high energies (45 MeV for protons).

In this paper we analyse the mechanismus of collective ion acceleration in the high power diode of the accelerator START [1]. Our computer modelling is based on two-dimensional electromagnetic current tube numerical code 'POISSON2'. This code simulates the stationary behaviour of charged particle beams in selfconsistent electromagnetic field. Consequently, the rapid changes of virtual cathode potential and their influence on ion movement are not taken into account. The program package of 108 modules written in FORTRAN language [2] was adopted for the EC1045 computer of the Academy Computer Centre.

2. SIMULATION METHOD

Our simulation model describes the behaviour of electron and ion current tubes in external and selfconsistent electromagnetic fields. Each tube is characterized by particle trajectories and the corresponding electric current. Generally, the uneven discrete two-dimensional calculation grid is used. The space charge inside the tube is calculated from the continuity equation $\operatorname{div}\vec{j} = 0$. The boundary current density on the electrode surface S_o is $j|_{S_o} = j_o(\vec{r}_o, \vec{v}_o, \varphi)$, where j_o follows from the Child-Langmuir emission low [5]. Charged particle coordinates $\vec{r}$ and velocities $\vec{v}$ are determined by solving the equations of motion for ions or electrons in relativistic case :

$$(1) \qquad \frac{d\vec{p}}{dt} = Z\left\{-\operatorname{grad}\varphi + [\vec{v}\times\vec{B}]\right\}$$

$$(2) \qquad \vec{v} = \frac{\vec{p}}{m_o\sqrt{1 + \left(\frac{p}{m_o c}\right)^2}}$$

where $\vec{p}$ is the relativistic impuls of the charged particle with the rest mass m_o and charge Z; c is velocity of light, $\vec{E} = -\operatorname{grad}\varphi$ and $\vec{B}$ are selfconsistent electric and magnetic fields. The initial positions and velocities of emitted particles are $\vec{r}|_{S_o} = \vec{r}_o$, $\vec{v}|_{S_o} = \vec{v}_o$.

The potential field φ is related to the space charge density ρ by the Poisson's equation:

$$(3) \qquad \Delta\varphi = -\frac{\rho}{\varepsilon_o}$$

where ε_o is permitivity of free space.

One of the following boundary conditions is accepted :

$$\varphi|_{S_1} = a(S) \tag{4}$$

$$\frac{\partial \varphi}{\partial \vec{n}}\Big|_{S_2} = b(S) \tag{5}$$

$$\varepsilon_+ \frac{\partial \varphi}{\partial \vec{n}}\Big|_{S_+} = \varepsilon_- \frac{\partial \varphi}{\partial \vec{n}}\Big|_{S_-} \tag{6}$$

where $a(S)$, $b(S)$ are defined on the boundaries S_1 and S_2, ε_+, ε_- are permittivities of materials laying on left and right side of the boundary.

According to Biot-Savart´s low the azimuthal component of selfconsistent magnetic field is determined by

$$B_\varphi = \frac{\mu_0}{r} \int_0^r j_z(r', z)\, r'\, dr' \tag{7}$$

where j_z is z-component of total current density.

The code 'POISSON2' solves the close set of nonlinear equations 1, 2, 3, 7 by the successive relaxation method. The method of relaxation of either the tube current or space charge can be chosen. Because of the negative charge cumulation effect (formation of virtual cathode near the anode plasma) we decided to let relax the space charge. The selection of relaxation process and the choice of the value of relaxation coefficients determine the stability and convergency of the procedure [3]. To a certain extent, the relaxation procedure with small value of relaxation coefficients replaces the time averaging of physical quantities. The relaxation process is stopped if the enumerated macroscopics quantities become almoust constant.

3. COMPUTER MODEL OF THE DIODE PERFORMANCE

The light ion beams can be generated by high current cylindrical diode with anode plasma slab (Fig. 1). Three different regions can be seen inside diode volume:

a) cathode-anode diode region, where the high current relativistic electron beam is generated,

b) plasma anode region through which the electron beam is propagated. The negative space charge of the beam is compensated by the positive charge of plasma ions,

c) accelerating drift tube, where the deep potential depression (virtual cathode) is formed due to negativ space charge of relativistic electrons penetrating the plasma slab.

Positive ions are extracted out of the boundary between b) and c) and accelerated by intense electric field appropriate to the virtual cathode. The diode parametrs are summarized in Table 1.

DIODE PARAMETERS Table I

cathode radius	r_c	=	0.5 cm
anode radius	r_a	=	3.0 cm
cathode-anode spacing	d_o	=	0.5 cm
plasma radius	r_{pl}	=	1.0 cm
thickness of plasma slab	l_{pl}	=	4.0 cm
drift tube radii	r_1, r_2	=	7.5 cm, 2.5 cm
length of drift tube	l_{dt}	=	31.0 cm
length of diode	l_d	=	60.0 cm
applied cathode voltage	V_{cat}	=	-0.5 MV

Two-dimensional radial and axial description in r.z plane is used to match the cylindrical symetry of this diode design. Proper choice of input parameters of computer model is the validity guarantee of numerical results. The shape of the diode boundary is approximated by a finite number of simple curves (parts of straight and circle lines). The number of curves representing the diode boundary in r-z plane was specified by KLIN = 16. Number of noted points (start and end points, centres of circles) is given by the parameter KPOINT = 18. Each region is divided into several zones. Every zone is characterized by its mesh. Typically, there are three zones in radial direction (KZONR = 3) and six zones in the longitudinal direction (KZONZ = 6). Mesh point interval dependes on the dimension of the zone and on the number of mesh points inside zone. Fine rectangular meshes $\Delta r \sim \Delta z$ are used between the cathode and plasma anode surface, and in the vicinity of plasma boundary from which the ions are extracted. The total number of defined mesh points is equal to 1736.

The generated electron (ion) beam is described by the set of current tubes. Each tube is specified by the particle trajectories, getting out of the base line laying on the emission surface. We choose the tube dimension comparable with the meshes in the closed neighbourhood of emittors. The electron (ion) emission current density was determined according to Child - Langmuir low (TIP = 1). At the very bigining of the diode performance the electrons are emitted by front part I and cylindrical part II of the cathode surface and no ions are present. We describe the electron beam by twenty four tubes; {19 initiated from the part I and 5 from cylindrical part II}. The numerical code POISSON2 doesn't allow to change the number of emitted current tubes during the calculation. Consequently, in stationary state, the ion beam is described by 11 ion's tubes (initiated from the plasma surface) and the number of electron's tubes had to be diminished to the number of thirteen. Naturally, it is expected that the steady state electron current would not be changed. To calculate the space form of each current tube the third order Runge-Kutta method was used. The initial distance d is elected to be greather than the distance Δz between the first two mesh points {in our case for electrons d_e = 0.0015 m, Δz = 0.0012 m and for ions d_i = 0.018m, Δz = 0.004 m}. The choice of the space step 0.2 for successive points on particle trajectory ensures that more than 5 points are situated within the mesh box $\Delta z \times \Delta r$.

4. RESULTS OF BIPOLAR ELECTRON AND ION FLOW

a) The simulation of the steady state relativistic electron flow

According to experimental results [4] the steady state of relativistic electron flow is achieved sooner than the initiation of ion flow. This delay enable us to calculate the electron and ion steady state flow separately. Our approached is based on the relaxation of space charge, the steady state of relativistic electron flow is achieved after 18 relaxation steps. The best choice of relaxation coefficient for the formation of steady state electron beam is $\omega = -0.05$. The dependence of the total electron current on the number of relaxation steps is shown on Fig. 2. The value of the steady electron current is $I = 10$ kA.

The spatial distribution of emission current density J_e on the cathode surface is shown on Fig. 3. The maximum current density $J_e^{max} \sim 7,5$ kA/cm^2 is got on the circumferencial cathode edge. The electron current emitted from the front part of the cathode $I_{fr} \sim 4$ kA causes the formation of the deep potential well behind the plasma column (see Fig. 4). The arising potential well is two dimensional with strong radial and longitudinal electric field components.

Beam selffocusing effect is manifested by electron particle trajectories depicted inside the plasma column (see Fig. 5).

The electron trajectories are bent by selfconsistent azimuthal magnetic field B_φ mainly in the vicinity of the anode aperture, where the electric charges are fully compensated. The spatial dependence of magnetic field $B_\varphi^{max}(z)$ along the z- axis is induced mainly by the outer current tube with highest electric current (see Fig. 5).

The processes of formation of potential depression and reversal influence on electron beam shape are stable. The electron trajectories are decline by the strong radial electric field of virtual cathode. This declination is greather for the higher value of tube electron current.

b) The simulation of ion flow

The formation of ion flow is delayed after the application of high voltage pulse to the diode [4], so we supposed that the ions are emitted from the outer part of plasma column into the steady state potential well. According to the Child - Langmuir law the ion emission density J_i equals to

$$(8) \qquad J_i = \frac{4\,\varepsilon_0}{9}\left(\frac{2.e}{M_i}\right)^{\frac{1}{2}}\frac{V^{\frac{3}{2}}}{d^2}$$

where M_i is mass of ions, V is extraction potential of the well, d is the distance between the bottom of potential well and the plasma surface. In our case, when the carbon ions are extracted from the plasma by the potential $V \sim -500$ kV and accelerated on the distance $d \sim 1\ 8$ cm, the ion current $I_i \sim 5.4$ A. Approximately, the same value ~ 5.6 A is obtained after 6 relaxation steps in our numerical model. The outer plasma surface was divided into equal sections (KTRA = 10, ten ionic tubes). In the section centre the perpendicular was drawn to establish the starting point. The initial velocity of each ion corresponds to the potential difference between the starting and central points. The best injection conditions were achieved, when the difference between the starting point z_o and central point z_{pl} grew up to $d_i = z_o - z_{pl} \sim 4.5\,\Delta z$, where Δz is mesh in longitudinal direction.

The electron and ion trajectories inside the drift tube at the very begining are depicted on Fig. 6. The strong electric field of potential well exerts the ions to oscillate in transversal and longitudinal direction. Owing to the stationary state of potential well some part of ion is returned to the plasma column or terminates on the tube wall. Regardless the oscillations the ions can be extracted along the axis of the drift tube. The energy of the carbon ions is $E_i \doteq 0.4$ MeV at the distance $d \doteq 4$ cm from the plasma surface (deaccelerating part of potential well).

The electron current $I_{fr} = 4$ kA remains unchanged during the iteration process, but the ion current decreases with the increasing number of iteration steps (from $I_i = 50$ A at the begining to $I_i = 6$ A after the six relaxation steps).

The compensation of the negative space charge by incoming ions leads to the depth diminishing of the potential well and backward shift of the point where the ions are reflected (see Fig. 7). This way, the declination of electron trajectories is smaller than in the case of steady state electron current (a) . The process stops when the electric field intensity on the plasma surface equals zero and no ions are emitted from the plasma surface.

The numerical results demonstrate that the diode with plasma anode can not be performed in the regime of stationary ion flow. Unstationary model is out of frame of numerical code 'POISSON2'. But some physical feature of bipolar flow may be eludicated, when the relaxatin coefficients are small(ω=-0.05).

The experimental results on accelerator START 2 show, that the acceleration of carbon ions up to 20 MeV in a vacuum drift tube is achieved by the movement of potential well. We can simulate this movement by the successive positions of the potential well in stationary states, but it is imposible to diagnose these states experimentaly. In every respect, our simulation suitable complements the measured results.

5. SUMMARY

The steady state relativistic electron flow trough the anode plasma column into a vaccuum drift tube was analysed. The deep two dimensional potential well with strong radial and azimuthal electric field was created. The mutual influence of beam shape and selfconsistent electric and magnetic fields was demonstrated.

The process of ion beam formation was analysed under the assumption that the potential well remaines stable. The calculated values of ion emission current and the energy of ions at the centre of potential well agree with the mesured experimental data. It was shown that the ion beam acceleration strongly depends on the movement of potential well. In our numerical model this movement was not taken into account, the potential well is filled by the ions and after some iteration the potential well disappeared. This process is finished when the electric field on the plasma surface equals zero and the ion emission current is negligible.

The authors wish to thank ing. K. Jungwirth CSc. and ing. J. Ullschmied CSc. for their interest and support and many helpful discussions.

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Fig. 2. The relaxation of electron current to the steady state, n is number of relaxation steps. The relaxated current (full line 1), 3/2 law current (dashed line 2).

Fig. 3. The dependence of the electron emission current density on the current tube number (c.t.n.) I - flat part of the cathode, II - cylindrical part of the cathode.

Fig. 4. The distribution of the virtual cathode potential in the drift tube space (after the 18th iteration step).

Fig. 5. The steady state relativistic electron trajectories and the distribution of the tube current in drift tube space. The dependence of selfconsistent azimuthal magnetic field B_φ generated by the current of outer tube [No 10].

Fig. 6. The selected ion trajectory injected into the drift tube at the begining of ions injection (after the 18th iteration step) .

Fig. 7. The electron and ion trajectories injected into the drift tube at the end of ions injection (after the 21st iteration step), when the virtual cathode disappeared.

Fig. 1.

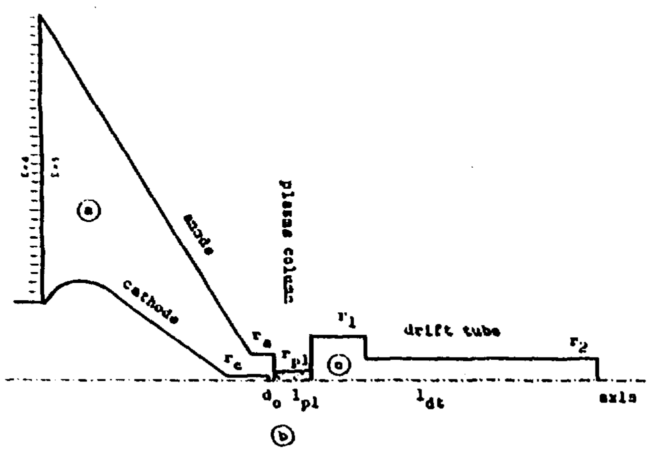

Fig. 2.

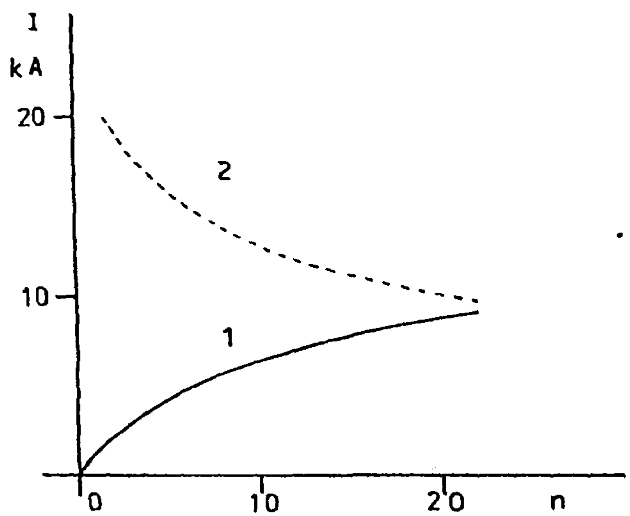

Fig. 3.

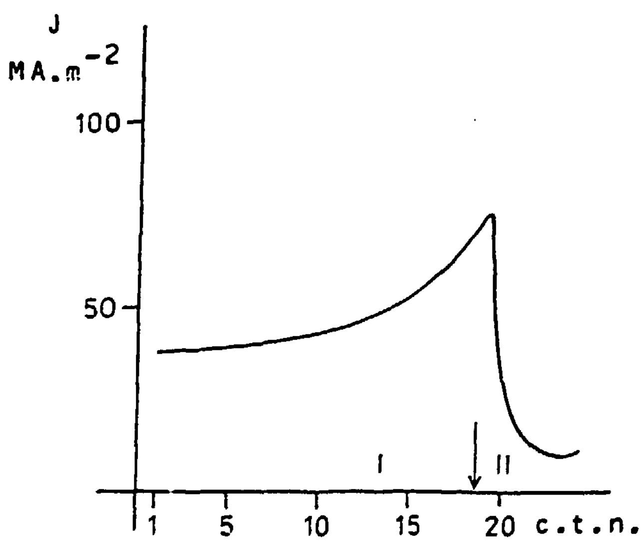

Fig. 4.

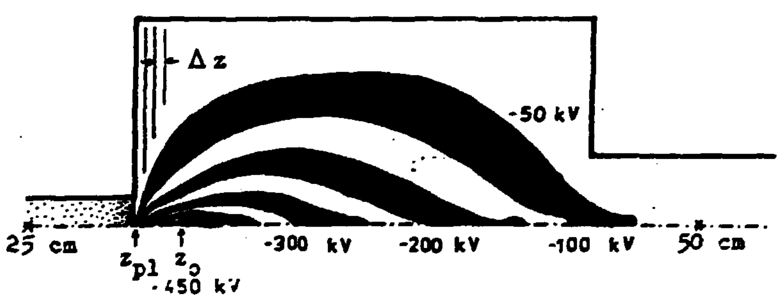

Fig. 5.

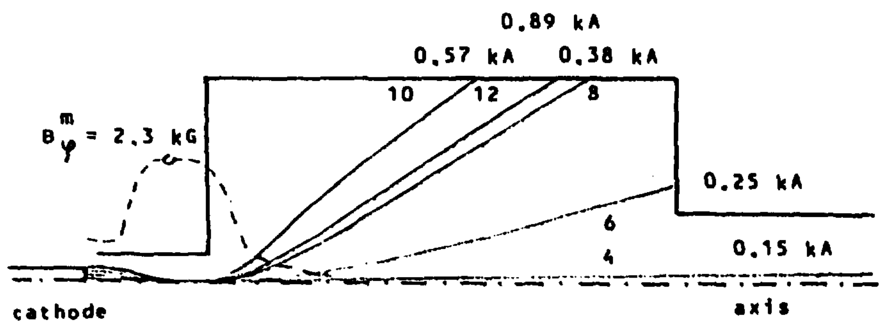
0.89 kA
0.57 kA
0.38 kA
10
12
8
B_φ^m = 2.3 kG
0.25 kA
6
4
0.15 kA
cathode
axis

Fig. 6.

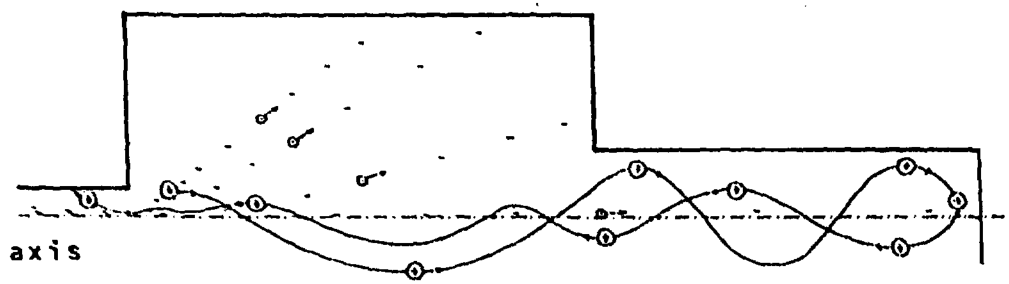

Fig. 7.