Numerical Simulation of Ion Beam Generated in Diode with Anode Plasma Column

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Ion beam generation in a high current diode with anode plasma slab has been studied. Ions are extracted from the anode plasma by a 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 the ion beam leads to a collective ion acceleration up to \( \approx 10 \text{ MeV} \) energy range.

1. Introduction

Light ion beams (LIBs) generated by pulse power machines are promising candidates for energy drivers of inertial confinement fusion. Industrial application of the LIBs 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 a collective ion beam acceleration have been developed. For example, the acceleration of ions can be achieved either by moving a potential well (virtual cathode) or by slow waves excited in the plasma column lying behind the anode. The drawback of the former method is the short distance (\( \approx 0.1 \text{ m} \)) synchronous motion of ions and the virtual cathode. On the other hand, by this method the light ions may be accelerated up to high energies (45 MeV for protons).

In this paper we analyse the mechanism 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 'POISSON 2'. This code simulates the stationary behaviour of charged particle beams in a 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 adapted for the EC1045 computer of the Academy Computer Centre.
2. Simulation method

Our simulation model describes the behavior 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 $\text{div} \boldsymbol{j} = 0$. The boundary current density on the electrode surface $S_0$ is $j|_{S_0} = j_0(r_0, \mathbf{v}_0, \varphi)$, where $j_0$ follows from the Child-Langmuir emission law [5]. Charged particle coordinates $\mathbf{r}$ and velocities $\mathbf{v}$ are determined by solving the equations of motion for ions or electrons in relativistic case:

$$
\frac{d\mathbf{p}}{dt} = Z[-\text{grad} \varphi + (\mathbf{v} \times \mathbf{B})], \tag{1}
$$

$$
\mathbf{v} = \frac{\mathbf{p}}{m_0 \left[1 + \left(\frac{p}{m_0 c}\right)^2\right]^{1/2}}, \tag{2}
$$

where $\mathbf{p}$ is the relativistic momentum of the charged particle with the rest mass $m_0$ and charge $Z$; $c$ is the speed of light, $\mathbf{E} = -\text{grad} \varphi$ and $\mathbf{B}$ are the selfconsistent electric and magnetic fields, respectively. The initial positions and velocities of emitted particles are $\mathbf{r}|_{S_0} = r_0, \mathbf{v}|_{S_0} = \mathbf{v}_0$.

The potential field $\varphi$ is related to the space charge density $\rho$ by Poisson's equation:

$$
\Delta \varphi = -\rho/\varepsilon_0, \tag{3}
$$

where $\varepsilon_0$ is the permittivity of free space.

One of the following boundary conditions is accepted:

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

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

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

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

According to Biot-Savart's law the azimuthal component of the 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 the $z$-component of total current density.