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PLASMA JET EMITTER: SIMULATION MODEL FOR THE PLASMA IN A SMALL ION SOURCE

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Abstract

A program that simulates a small ion source plasma in the cylindrical coordinate system is developed. In this computation, technique of Particle-in-Cell is used. The program includes the electromagnetic field of three dimensions, the process of the ionization by electron's collision, a discharge electric current and so on. Comparing the results of the calculation for ion source plasma using this program with experimental results for PIG ion source, we get good agreement for the electronic temperature, the electron and the ion density. As a result of this calculation, we will be able to analyze the plasma jet emitter that has cylindrical discharge tube with axial magnetic field by considering the collision mechanism and the examination of the initial condition.

1 Introduction

In an accelerator, an ion source plays an important role to decide efficiency of acceleration, brightness and/or intensity of the extracted ion beam. To optimize a quality and a utilization rate of the extracted beam, the characteristics of the source should be investigated by using simulation technique as well as experimental work.

In this work, we pay attention to small ion sources which have a cylindrical discharge tube with axial magnetic field. This type of ion source includes the plasma jet emitter and PIG type ion source. For the first step, we have calculated the PIG ion source plasma, because of its simplicity. Our purpose is to establish the method of simulation and suggest a model for explaining physical phenomena in the small plasma space.

2 Plasma in the cylindrical discharge tube with axial magnetic field

Figure 1 shows scheme of our ion source. Discharge processes in the cylindrical discharge tube with axial magnetic field are as follows. Electrons extracted from the cathode surface are accelerated by the electric field between anode and cathode. Then electrons interact with neutral particles and ionize them. The electrons have excessive energy, so electrons go forward after interacting with the neutral particles. Then electrons drift toward to another side of cathode, they are accelerated by the reverse electric field and return to the discharge space. In this way, ionization chain is continued.

This process is continued until the electron energy is less than ionization energy of neutral particle. These electrons drift to the anode. Ions produced by this ionization are attracted to cathode and knock the cathode. Then the cathode releases secondary electrons. They repeat above processes. As a result of this effect of amplification, the discharge reaches to the anode and discharge current becomes the value that is decided by the internal resistant of circuit. Characteristic of this ion source is that it has a small discharge space, because of spiral motion of electron by the axial electromagnetic field.

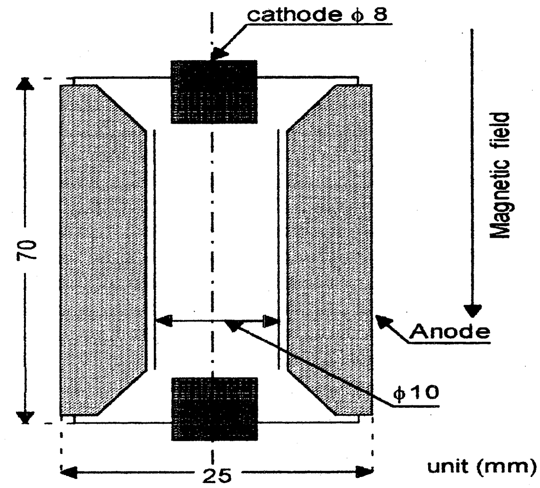

Fig.1 Scheme of the cylindrical discharge tube with axial magnetic field.

3 Modeling of the cylindrical discharge tube with axial magnetic field

This system has a symmetrical geometry about the $r-\theta$ plane and the z axis ($r=0$). From this geometrical feature, the following assumptions are made in this work.

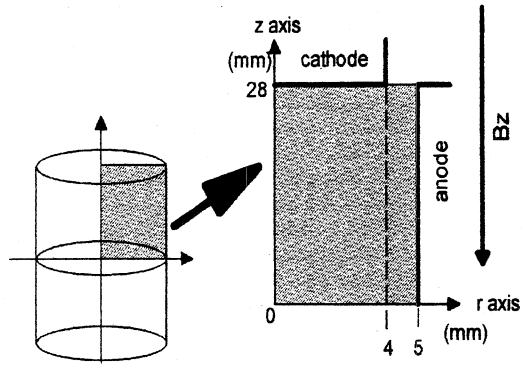

Fig.2 Coordinates of calculation area.

Same phenomena occur in both sides of $r-\theta$ plane. The electromagnetic field in the discharge space is uniform to the direction of θ. Therefore we use the $r-z$ coordinate in order to minimize the simulation space (see Fig.2). Actual geometry between the cathode and anode is more complex, but in this calculation we simplify this geometry as shown Fig.2.

We make assumptions about the interactions between charged particles and the walls as follows. Electrons are absorbed at the anode. When ions collide with the anode, they are elastically scattered. Ions are absorbed at the cathode. There is no interaction between the cathode and electrons.

4 Method of simulation

Basic equations and some conditions used for simulation are as follows.

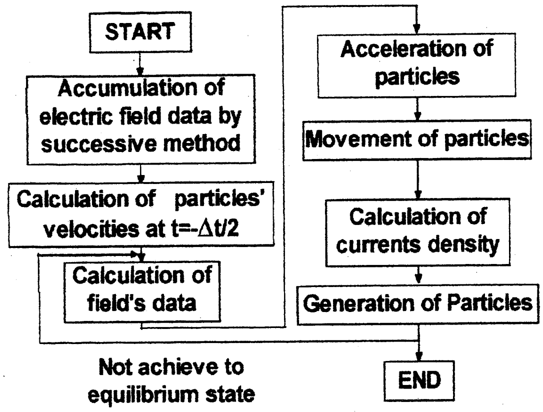

Fig.3 Flow-chart of the simulation.

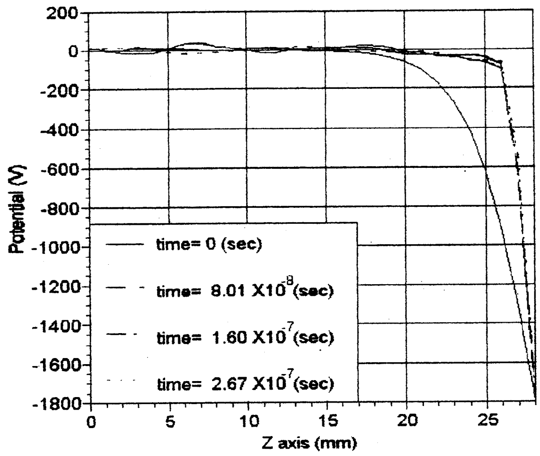

Fig.4 The change of time of the potential distribution on the central axis.

$$m\frac{\partial \boldsymbol{v}}{\partial t} = q\left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right), \qquad (1)$$

$$\nabla^2 \Phi = -\frac{\rho}{\epsilon}, \qquad (2)$$

$$\left.\begin{array}{rcl} \nabla \times \boldsymbol{E} & = & -\dfrac{\partial \boldsymbol{B}}{\partial t}, \\ c^2 \nabla \times \boldsymbol{B} & = & \dfrac{\partial \boldsymbol{E}}{\partial t} + \dfrac{1}{\epsilon}\boldsymbol{J}, \\ \nabla \cdot \boldsymbol{B} & = & 0, \end{array}\right\} \qquad (3)$$

where m is the mass, $\boldsymbol{v}$ the velocity, q the electric charge, $\boldsymbol{E}$ the electric field, $\boldsymbol{B}$ the magnetic field, c the light velocity, $\boldsymbol{J}$ the current density, ϵ the dielectric coefficient, t the time, ρ the charge density, Φ electric potential. These equations are translated to the finite-difference equations and numerically solved.

To develop the simulation code, we use a PIC (Particle-in Cell) method. This code uses Leap-Flog method [2] to calculate Eq.(1). Though this simulation is done in $r-z$ plane, $(r, z, v_r, v_\theta, v_z)$ are used as the parameters of particles. Because this calculation is carried out in the three-dimensional electromagnetic field.

The potential distribution is divided into two cases.
(a) The potential distribution by impressing voltage on the cathode without electric charge density.
(b) The potential distribution with electric charge density (not impressing voltage on the cathode).

In the computation, the case (a) data is used as the basic potential distribution data by electrode and the case (b) data is used as the potential distribution data for expressing the spatial electric charge effect. Finally, the whole potential distribution is computed by piling up these data.

The discharge current is estimated by only considering the number of ionization events; ionization phenomena play significant roles in the present simulation. The number of ions and electron which are generated per unit time is assumed so as to be equivalent to be experimentally obtained result[1].

In this work, to simplify this model we use only the hydrogen ions and elections. This calculation is carried out by using spur particles which represent huge number of these particles, because many particles exist in the discharge space. Cathode potential is -1.8 kV, axial magnetic field is 0.09 T. Figure 3 shows the flow chart of the simulation. This computation is continued until the number of particles reach to equilibrium value.

5 Results and discussion

The Figure 4 shows the potential distribution along the z axis (r = 0 mm). Fluctuations of the potential are seen all over the discharge space. The steep potential gradient which is located in the ion sheath is seen near the cathode (z = 26 $\sim$ 28mm). This is characteristic phenomenon in the plasma.

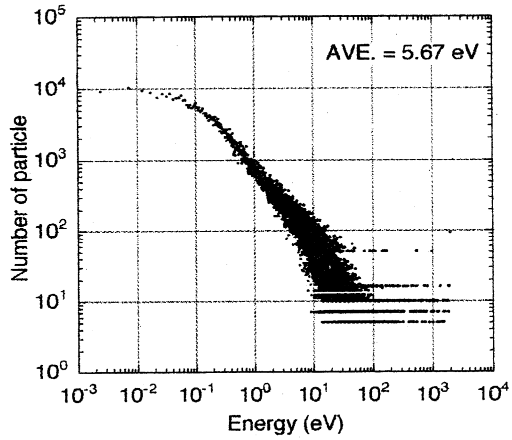

Fig.5 The distribution of the electron energy.

Figures 5 and 6 show energy distribution of electron and hydrogen ion, respectively. Both distributions have maximum value near 0 eV and exponentially decrease toward high energy. The average energy of the electrons is 5.67 eV. That of the hydrogen ions is 3.74 eV. These results are slightly higher than the values of experimental report[1] because the electrons are caught and accelerated by the fluctuation of the potential.

Both number densities of electron and hydrogen ion are around $10^{12}\mathrm{cm}^{-3}$ and these values are approximately equal to the experimental values[1].

6 Conclusion

In this work, a simple model for the simulation of the plasma in the cylindrical discharge tube with axial magnetic field was established. The results of this calculation agreed well with the experimental results[1]. From these results, this model could be useful for studying the plasma in the cylindrical discharge tube with axial magnetic field.

The simulation of the plasma could be done more accurately by examining the width of Δt, the number of the super particle and the boundary condition of the Maxwell equation. Furthermore, we will be able to analyze the plasma jet emitter by considering the collision mechanisms and the initial condition of particles.

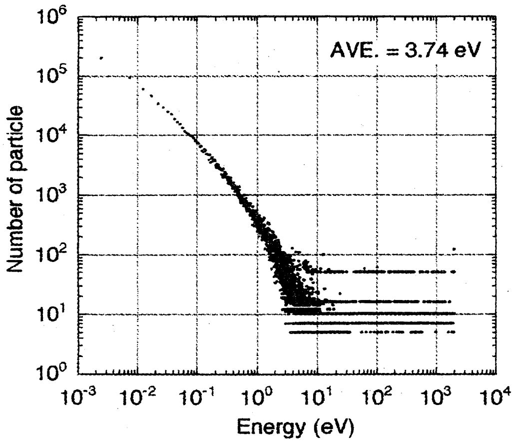

Fig.6 The distribution of the hydrogen ion energy.

References

[1] Fumiaki Noda, Kyushu University, The master theses : Study of small PIG ion source for super conductive cyclotron (1994)

[2] C.K. Birdsall : Plasma Physics via Computer Simulation, Mac Graw Hill (1985)