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Beam tracing in an accelerating system for plasma jet emitter

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Abstract

The plasma jet emitter has been developed as an intense and low divergence beam generator. The emitter can generate about 10 A and several keV energy proton beam, the current density is about 450 mA/cm^2 in the experiment at TRIUMF, CANADA[1]. This paper makes a comparison of the experimental data with the result of the simulation achieved by a newly developed program for the accelerating lens system of the plasma jet emitter. The program considers the space charge effect of the beam and the plasma. As the results, a good agreement can be got between the experiment and the simulation. One can optimize the lens system by this calculation.

1 Introduction

In an accelerator, ion sources play an important role to decide efficiency of generating beam. The plasma jet emitter is a new type of ion source developed by V. I. Davydenko et al., in Novosibirsk[2], to generate a high current neutral beam for plasma diagnostics in medium size tokamak. The same type of ion source has been developed in TRIUMF, CANADA for new pulsed optically pumped polarized H$^-$ ion source. For the diagnostics, the beam needs to have high brightness (about 3×10^8 A/cm^{2}rad^2[3]) and a low divergence (up to 2.0×10^{-2} rad). To realize them, a computer simulation is useful method in designing.

In this work, a simulation is applied to achieve the optimized designing the accelerating lens for the plasma jet emitter. A comparison using the experimental date at TRIUMF is done to investigate the precision of the calculation.

2 Plasma jet emitter

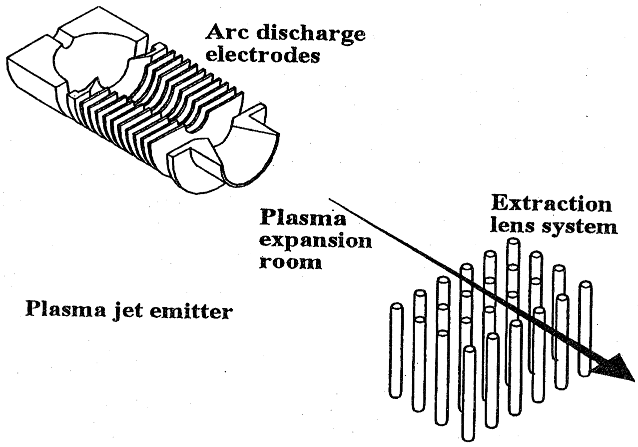

Fig. 1 The schematic drawing of electrodes for the plasma jet emitter.

Fig 1. shows the schematic drawing of electrodes for the plasma jet emitter. A pulse plasma is generated in a small vessel (called plasma emitter), which is sandwiched in arc electrodes, by using of a timing controller for a pulse valve to turn on hydrogen gas, and for pulse voltage to ignite an arc discharge in the vessel. The pulse plasma is lead to a vacuum expansion room through a nozzle on the plasma emitter. In the room, the plasma is expanded with no collision and no field unlike the duoplasmatron. The expansion makes cooling of the plasma as a distance from the anode electrode. The discharge produces a plasma emission at near the extracting system in having a density of about 10^{12} cm^{-3}[2] and an electrode temperature of about 5 eV. At the accelerating system, particles have almost parallel velocities to the beam axis because of the cooled plasma temperature. The plasma surface will be in less disorder than that of the other ion sources, which makes easer for the simulation model to treat the proton emittion. The plasma temperature around the surface will be about 5 eV that is enough small to get a low divergence beam.

Generally to extract the good quality beam from the plasma, a multi slits accel-decel lens system of three or four electrodes made of molybdenum wires is thought up. Especially the multi slit electrodes have a high transmission. In the work, four layers multi slits lens system is adopted for the plasma jet emitter to extract and accelerate protons from the expanded plasma. The grids are made of 0.2 mm molybdenum wires. The spacing between wires is 1.0 mm. The gap between the first (plasma electrode) and second grids is 0.75 mm, the second and third grids is 1.9 mm, the third and fourth (ground) is 2.9 mm. In the experiment, a high current and low divergence beam are found by changing the grid electrodes voltages each other manually.

3 Method of Simulation of the trajectories

The performance of the lens system is investigated by using of a computer simulation. The calculation program is developed originally for this work on the base of the IGUN program[4] with FORTRAN77. It is very difficult for computers to analyze plasma behavior numerically. Then the simulation adopts a simple mathematical model of the IGUN at the plasma sheath. It is assumed ions entered to the sheath with a directed energy of eU_i, where U_i is an ion's potential. And electrons are forming an electrostatic shield with an energy distribution obeyed by Boltzmann's law. The Poisson equation is given by

$$\nabla^2 U = -\frac{\rho_i - \rho_e}{\varepsilon_0}, \tag{1}$$

where

$$\begin{aligned} \rho_e &= e n_e \exp\left(\frac{U - U_p}{U_e}\right), \\ \rho_i &= e n_i \sqrt{\frac{U_i}{U_{p_i} - U}}. \end{aligned} \tag{2}$$

The plasma potential U_p is calculated by

$$U_p = U_w + \frac{U_e}{2} \ln\left(\frac{U_e M}{\pi U_i m}\right). \tag{3}$$

The electron and ion currents to the wall with potential U_w become balanced. The ion potential U_i and electron potential U_e are estimated each about $U_i \approx U_e \approx 5$ eV, then the plasma potential U_p is higher than the wall potential U_w by about 16 eV. U_w is the potential of the plasma electrode. Assuming quasi neutrality ($n_i \approx n_e$) at the plasma potential $U = U_p$, the right side of an expression in Eq. (1) can be rewritten by

$$\begin{aligned} -\frac{\rho_i}{\varepsilon_0}\left(1 - \frac{\rho_e}{\rho_i}\right) &= -\frac{e n_i}{\varepsilon_0}\sqrt{\frac{U_i}{U_p + U_i - U}} \\ &\times \left(1 - \frac{\exp\left(\frac{U - U_p}{U_e}\right)}{\sqrt{\frac{U_i}{U_p + U_i - U}}}\right). \end{aligned} \tag{4}$$

The electrical field around the plasma surface and the lens can be solved by using of the relaxation method with small meshes (10 μm). For one relaxation's step, in the case that a potential at a lattice is greater than the plasma electrode potential, the potential is calculated from the Poisson Equation with the right-hand side expression of Eq. (4). In other cases, a charge of the lattice point is estimated by the total charge in the lattice square. The electron compensation effect is assumed that the beam current density decreases to a half roughly. The calculation to solve the renewal Poisson equation is repeated until the solution has enough small convergence.

4 Results and discussion

The simulation is performed on the condition of the experimental data. In one case of the condition, the lens geometry is set to the same as the experiment. The beam current density j is set to 450 mA/cm^2. The plasma electrode voltage is 6.0 kV, second is 5.3 kV, third is -0.8 kV, and fourth is ground. This condition makes one of the largest current beams in the experiment. The plasma density is an adjustable parameter in this calculation. The results for two cases of the plasma density are given, the case (a) for plasma density $n = 2.5 \times 10^{12}$ cm^{-3}, (b) for $n = 5.0 \times 10^{12}$ cm^{-3}. These order of the density about 10^{12} cm^{-3} is proper because of the experiment[2]. The electric fields, the proton beam trajectories, the beam emittance, and the plasma surface position are the outputs of the program.

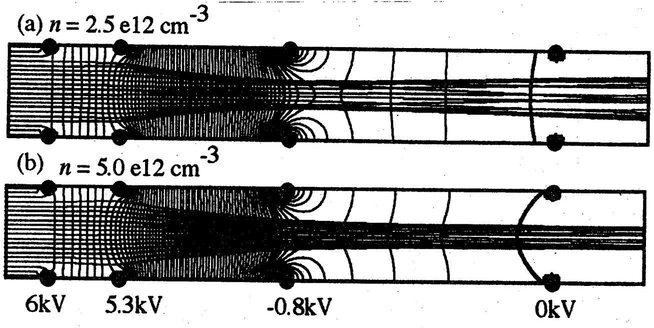

Fig. 2 The protons beam trajectories and the electric fields at the lens for a slit in the simulation. The geometry, given voltages, and the beam current density $j = 450$ mA/cm^2 are put in to the calculation in two cases of plasma density. (a) The plasma density $n = 2.5 \times 10^{12}$ cm^{-3}, (b) is $n = 5.0 \times 10^{12}$ cm^{-3}.

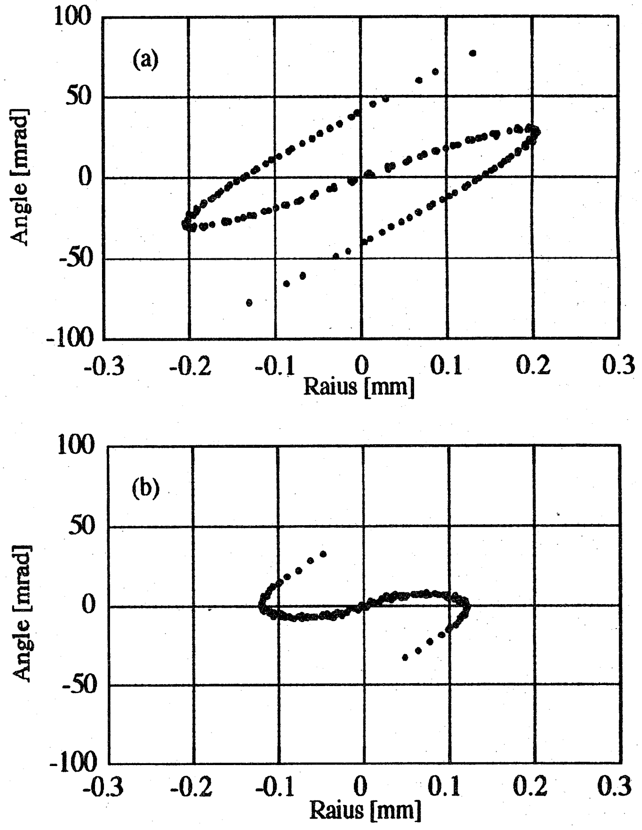

Fig. 3 The emittance diagram on the exit (fourth) electrode. The condition is the same as Fig. 2.

Fig. 2 shows the calculation results of proton trajectories. The beam is bundled up almost in this electrical field. The beam trajectory depends hardly on the plasma density. The high plasma density has a tendency to generate a thin beam for a slit. Fig. 3 shows the emittance diagram on the fourth electrode (ground) for a slit in the condition of Fig. 2. The divergence is enough small, under 50 mrad each other.

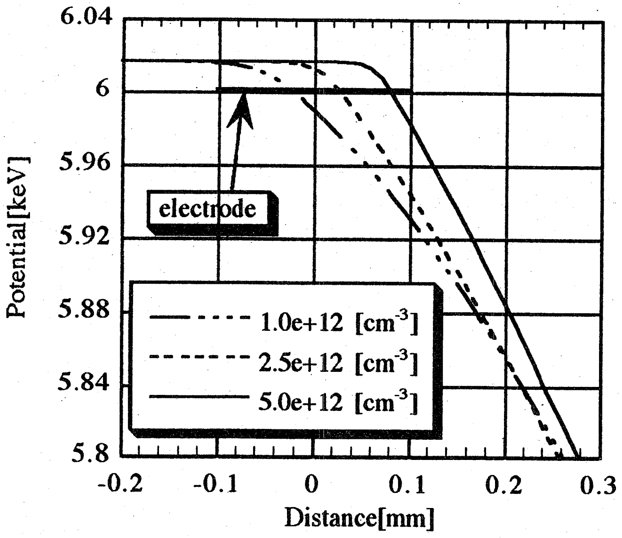

Fig. 4 The potentials along the center of the beam axis for one slit around plasma electrode (first) in three cases of plasma density. The "electrode" in this figure is a projection of the plasma electrode potential. The distance 0. mm is defined as a center of the plasma electrode in the horizontal axis.

Fig. 4 shows the potentials along the center of the beam axis for one slit around plasma electrode in cases of the plasma density 1.0×10^{12}, 2.5×10^{12}, and 5.0×10^{12} cm^{-3}. The plasma potential U_p is 6.015 keV from Eq. (3). The position of plasma sheath moves to downstream over the plasma electrode as the plasma density increases. As the simulation result, the position of plasma sheath depends on the plasma density. But the beam divergence has a little dependence on the position. In the expansion of the pulsed plasma, changing of the density will not much influence the beam divergence. Therefore, this simulation program for static plasma can estimate the performance of the extracted beam.

5 Conclusion

The simulation can make almost the same results of focusing as the experiment. The beam emittance can be estimated by the simulation. It is suggested that each conditions can be optimized by using the calculation on the assumption of the fixed parameters for other conditions.

Acknowledgements

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