EFFECTS OF A CONDUCTING MESH ON THE SPEED OF J×B DRIVEN ROTATING PLASMAS

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1. Introduction

The plasma centrifuge is one of plasma isotope separation methods which uses a strong centrifugal force acting on a $J \times B$ driven rotating plasma in a magnetic field [1, 2]. Since the separation factor increases exponentially with the ratio of the rotational energy to thermal energy of isotopic ions, it is important to maintain the low ion temperature or to decrease the ion temperature of the plasma as well as to increase the rotational velocity. The centrifuge device with a coaxial-gun geometry under development in our laboratory successfully generated a plasma rotating at a frequency as high as 1×10^6 rad/s and being ejected at a supersonic speed [2]. The problem is that a fraction of the discharge current flows within the downstream plasma over a long distance. Such a current (we refer to it as a permeating current) has a possibility of making the plasma unstable and increasing the ion temperature. So we tried to suppress the permeating current by installing a conducting mesh in front of the gun muzzle. In the present paper, we report the effect of floating mesh on the magnitude and axial distribution of the permeating current and on plasma properties such as the rotation frequency, the ion temperature and the number of ions transmitted through the mesh.

2. Rotating plasma device

Figure 1(a) shows the whole view of the experimental setup. A coaxial plasma gun of 2.5 cm in diameter is attached to one end of a Pyrex drift tube (15 cm diameter × 70 cm length) evacuated down to 3×10^{-6} Torr. The plasma gun and the drift tube are immersed in a uniform axial magnetic field B_z of up to 3.6 kG. After an operating gas (CH4 or Ar) is puffed into the anode-cathode gap, the plasma gun is energized by firing a 4-stage PFN ($C = 10$ μF and $L = 2$ μH) nominally charged to 9 kV. The current pulse lasts for 28 μs FWHM and its peak reaches 10 kA. The rotational velocity v_θ and the ion temperature T_i are evaluated from the

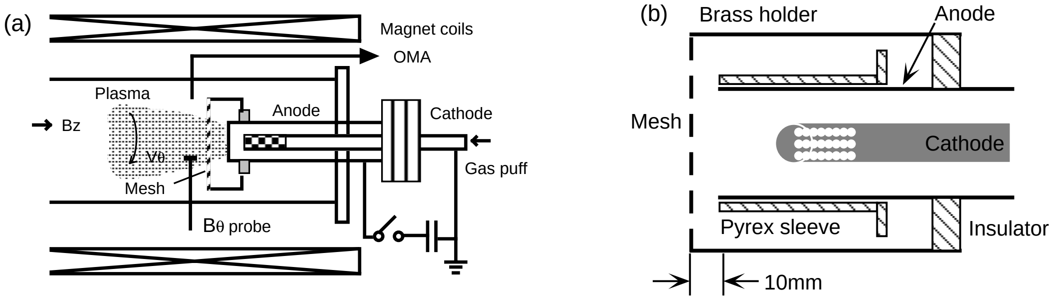

Figure 1. (a) Whole view of the experimental setup and (b) view of the plasma gun.

Doppler shift and the Doppler broadening of ion emission lines, respectively. The axial velocity v_z is derived from the time-of-flight (TOF) analysis for ion current pulses detected at $z=$5, 15 and 25 cm with a negatively-biased faraday cup. Since the faraday cup covers the whole plasma cross section, it is used also to measure the total number of plasma ions transmitted through the mesh.

3. Setup of conducting mesh

Figure 1(b) shows a close view of the plasma gun. A mesh of SUS304 or copper is attached to a brass holder of 60 mm in diameter and is placed at 10 mm in front of the anode. The mesh and holder are insulated from the anode. The wire diameter d_w and pitch p_w are changed over ranges 0.12–0.85 mm and 0.1–7.4 mm, respectively. Two mesh parameters are employed in order to arrange experimental data obtained: One is the thickness of equivalent sheet, T_g first proposed by Simpson [3] to model the plasma acceleration in vacuum-arc centrifuges and the other is the geometrical opacity O_w. They are expressed as

$$T_g = \frac{2(d_w/2)^2 \pi p_w}{{p_w}^2}, \qquad O_w = 1 - T_w = \frac{(p_w - d_w)^2}{{p_w}^2},$$

where T_w is the transparency. Since conductance ξ_g(S) of the anode mesh is expressed as $\xi_g = T_g/\rho$, T_g is proportional to conductance of the anode mesh for a given material, while O_w is a purely geometrical parameter.

4. Experimental results

Shielding of permeating current

A permeating current I_z was evaluated from the radial profile of an induced magnetic field B_θ measured with a movable magnetic probe. Provided that I_z flows uniformly within a radius of r_0, the B_θ profile becomes as shown in Fig. 2(a) from Ampere's law. Then, I_z is given by $2\pi r_0 B_\theta(r_0)/\mu_0$. Figure 2(b) shows the measured B_θ profile. A fairly well agreement between the prediction and the measurement supports the validity of the I_z model. Figure 3 shows Oscilloscope traces of discharge current (10 kA peak) and I_z without and with the SUS mesh. without the mesh, I_z amounts to 10$\%$ of the discharge current, while it reduces to 1–2$\%$ with the mesh of $T_g > 0.05$mm and $O_w > 0.1$. The axial profile of I_z without and with the SUS mesh is given in Fig. 4. Without the mesh, I_z of about 300 A reaches 10 cm downstream with gradually decreasing its intensity from 1 kA at the muzzle. By installing a SUS mesh of T_g=0.054mm and O_w=0.41, on the other hand, I_z decreases to 100 A, one tenth of that without the mesh, over the whole downstream distance although I_z in the rear of the mesh does not change. This demonstrates that a circuit of I_z is completely terminated at the mesh.

Effects on plasma properties

Figures 5 and 6 show the rotation frequency ω and the ion temperature T_i of carbon plasmas, respectively, as functions of mesh parameters. The frequency decreases with the increase in T_g and O_w and is halved from 2×10^6 rad/s for no mesh. The ion temperature also decreases with O_w to about one fourth of 40 eV for no mesh; however, it appears not to have clear dependence

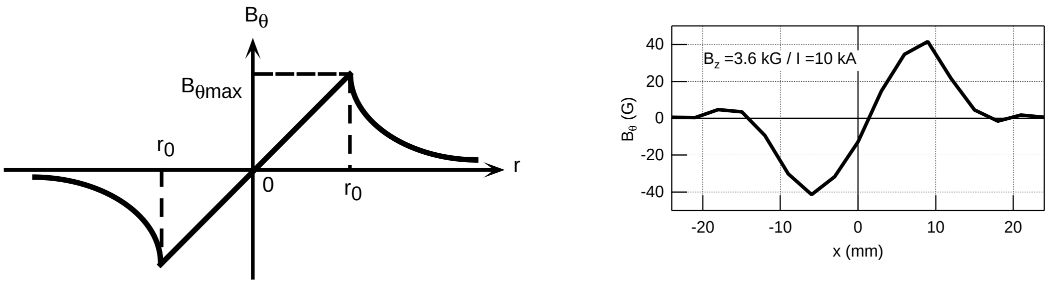

Figure 2. (a) Model B_θ profile and (b) measured B_θ profile.

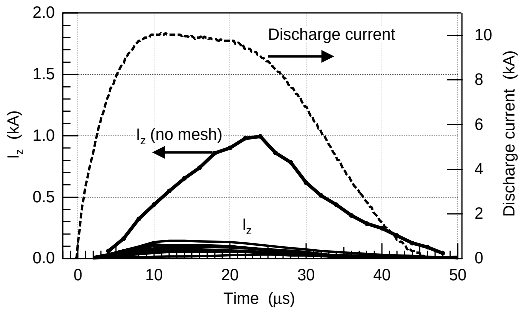

Figure 3. Waveforms of permetating current without and with the mesh.

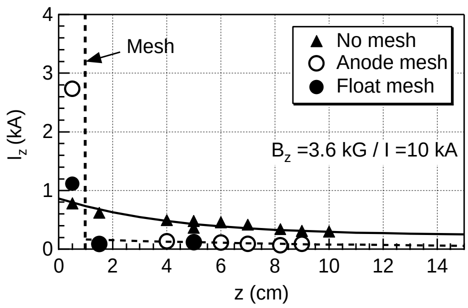

Figure 4. Axial profiles of permeating current without and with the mesh.

on T_g. The total ion number transmitted through the mesh was calculated from the ion current detected by the biased faraday cup under assumption of singly-charged ions. The ion number N_i decreased from $N_{i0} = 2.5 \times 10^{15}$ for no mesh according to the relation $N_i(O_w) = N_{i0}(1 - O_w)$ in case of the ballistic ion motion. The ion number appeared not to have correlation to T_w.

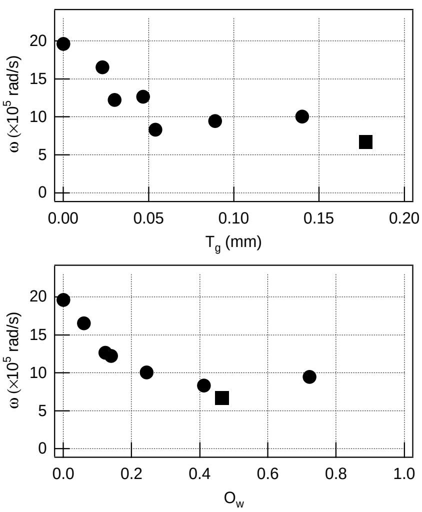

Figure 5. Rotation frequency of C^+ ions as functions of T_g and O_w.

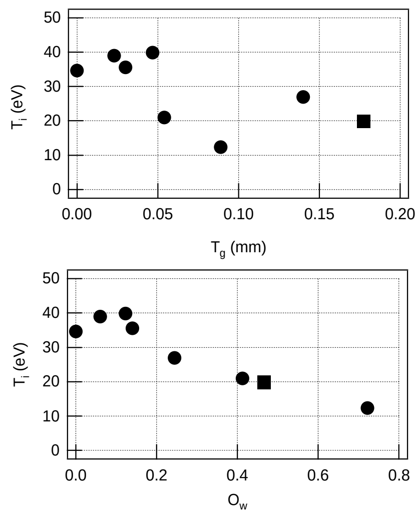

Figure 6. Ion temperature of C^+ ions as functions of T_g and O_w.

Here, we compare the results with Simpson's model [3]. Recently, Simpson developed a steady-state model to analyze plasma acceleration characteristics in vacuum-arc centrifuge. In a vacuum-arc centrifuge, the discharge current I flows from the mesh anode into the solid cathode. If E_r is the radial electric field in the plasma, E_{rg} is the radial electric field in the mesh and ϕ is the potential drop in the anode sheath, we have $E_r = \partial\phi/\partial r + E_{rg} \approx E_{rg}$. Ohm's law for the mesh becomes $\xi_g E_{rg} = I_{rg}$ where I_{rg}(A/m) is the radial current per unit length of the surface. Since $I_{rg} \propto I$, the rotation frequency is predicted to be $\omega = -E_r/rB_z \propto I/\xi_g B_z$. For fixed I and B_z, we have $\omega \propto \rho/T_g$. In comparison with Simpson's model, there is a difference in the assumption; the mesh is not the anode but the floating electrode in the present case. Only 10$\%$ (1 kA) of the discharge current passed through the floating mesh. This is because the sheath established on the surface limits this current to the ion saturation current as in a floating double probe. In this situation, E_r will not be line-tied by the mesh and Simpson's scaling $\omega \propto \rho/T_g$ can not be applied. In fact, if ω is replotted for only a narrow range of O_w from 0.33 to 0.47 (approximately a fixed O_w), it appears constant against ρ/T_g. On the other hand, ω, T_i and N_i are well correlated to the geometrical opacity O_w although the mechanism for deceleration and cooling of plasma ions and the reason for their correlation to O_w are not understood yet.

In plasma centrifuge, the equilibrium mass separation factor α for plasmas in rigid rotation given by

$$\alpha = \exp\left(\frac{\Delta M}{M}\cdot\frac{M{v_\theta}^2}{2T_i}\right), \qquad \frac{\Delta M}{M} = \frac{2\,(M_H - M_L)}{M_H + M_L},$$

where $\Delta M/M$ is the relative mass difference between heavier (M_H) and lighter (M_L) isotopes. It is important to note that for a given $\Delta M/M$, α is determined by the ratio of the rotational energy to the thermal energy of the ions. Since the conducting mesh is found to decrease both rotational and thermal energies by the same factor, it is difficult to expect improvement in α by the mesh.

5. Conclusion

In summary, the conducting mesh set in front of the gun muzzle at floating potential decreased the permeating current down to one tenth. The rotation frequency, the ion temperature and the ion number transmitted through the mesh also decreased with correlation to the geometrical opacity O_w of the mesh. The mechanism underlying is not clear yet. The surface conductance of the mesh proposed in Simpson's model appeared to have little effect on our results.

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