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Formation of Toroidal Plasma Flow in an Internal Conductor Trap

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Abstract

The effects of electrode biasing and electron injection into a plasma were examined in an internal conductor device Proto-RT. By using a negatively biased ring electrode, radial electric field of up to ~2 kV·m^{-1} was generated in a broad region between the vessel wall and the electrode. The corresponding toroidal $\boldsymbol{E} \times \boldsymbol{B}$ drift speed ~10^5 m·s^{-1} is comparable to ion sound speed. In contrast, when electrons were injected into a plasma from an electron gun, potential gradient was not effectively generated, due to electron loss.

Keywords:

plasma flow, radial electric field, electrode biasing, electron injection, internal conductor device, dipole magnetic field, double Beltrami fields

1. Introduction

A relaxation theory of plasmas including the effects of ion flow has recently been proposed. The equilibrium state of two fluid plasmas is represented by double Beltrami fields [1] and it provides a condition for the flow velocity v and β value of the plasmas to satisfy $\beta + (v/v_A)^2/2$ = const., where v_A is Alfvén velocity. When the plasma has fast flow comparable to v_A, ultra-high β (possibly $\beta > 1$) state will be realized due to the effects of the dynamic pressure of the plasmas. In search for the new relaxation states of the flowing plasmas, toroidal trap devices equipping normal-conducting or superconducting internal coils have been constructed and fundamental researches are being carried out [2,3]. Formation of internal electric field and flow is one of the essential subjects in these studies. For the generation of radial electric fields in plasmas, several techniques might be used, such as non-neutralization of plasmas by the orbit loss of high-energy electrons or electron injection, or application of external electric fields. In this work, we studied the potential structures of RF plasmas under the influence of a ring electrode and electron injection from a gun using a LaB_6 cathode.

2. Potential formation in Proto-RT

Proto-RT [2,3] (cross-sectional view is shown in Fig. 1) is a prototype ring trap device with a normal-conducting internal conductor (IC). The combination of dipole, vertical, and toroidal magnetic fields provides a variety of static magnetic field configurations for the confinement. The typical

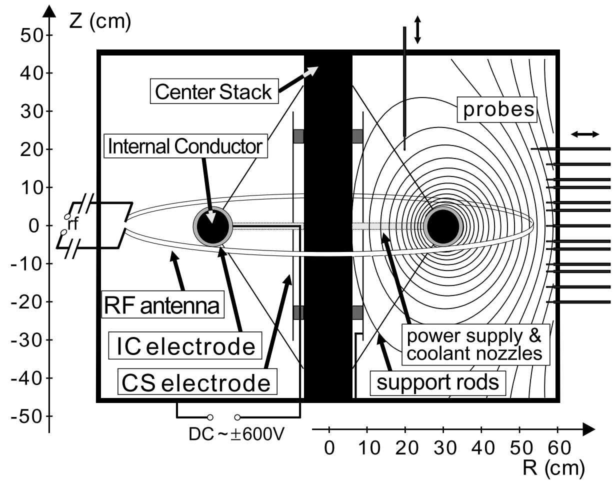

Fig. 1 Schematic view of the Proto-RT and magnetic surfaces generated by an internal ring coil and external vertical field coils (not seen).

magnetic field strength is of the order of 10^{-2} T. In the current experiments, plasmas are generated by RF electric field with a frequency of 13.56 MHz and an input power of ~200 W, supplied via an inductively coupled loop antenna located inside the chamber. Hydrogen pressure used was 4×10^{-4} Torr. Inside the chamber, a torus-shaped electrode on the ring conductor and a LaB_6 cathode electron gun are installed. The

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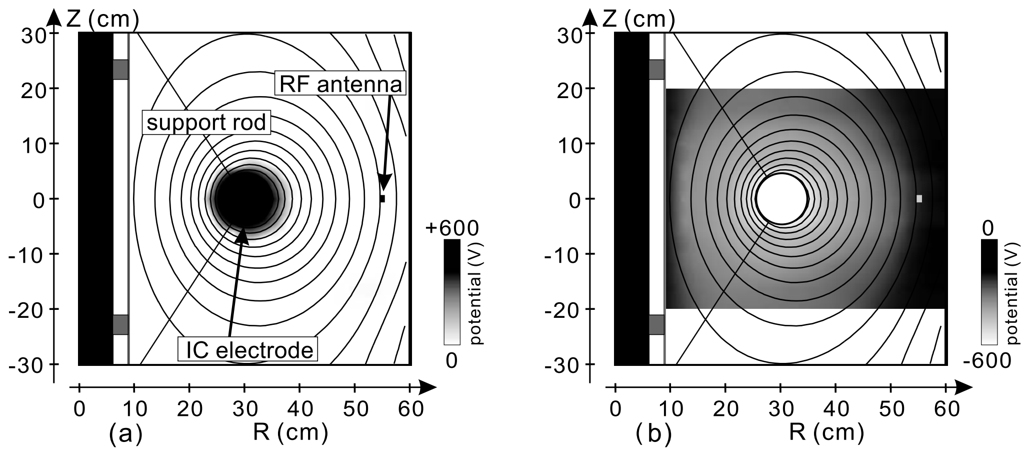

Fig. 2 2-d potential profiles of plasmas (floating potentials of emissive Langmuir probes) when the IC electrode was (a) positively biased: V_{IC} = +600 V and (b) negatively biased: V_{IC} = –600 V. Thin lines show the magnetic surfaces.

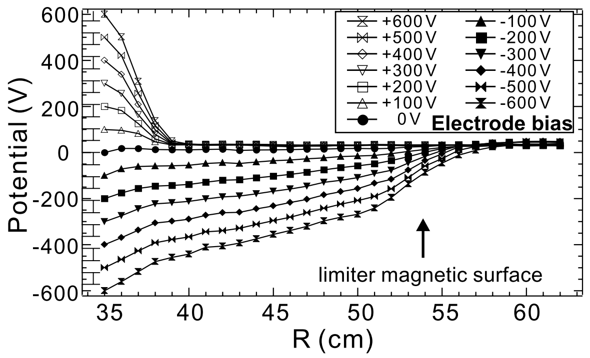

Fig. 3 Radial potential profiles of plasmas at Z = 0, in the variation of IC electrode bias voltage V_{IC} from –600 to +600 V.

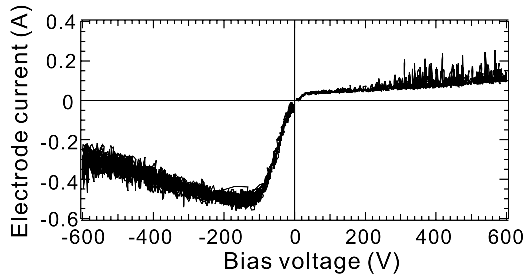

Fig. 4 IC electrode current vs bias voltage. Decrease of the current when V_{IC} < –200 V is due to the difficulty of RF matching.

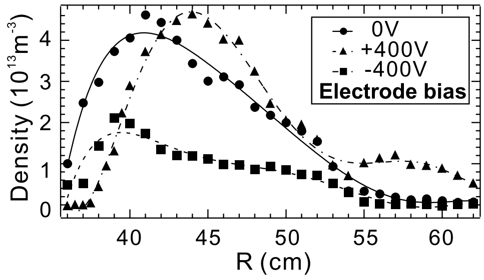

Fig. 5 Radial electron density profiles.

potential profiles of plasmas were measured by emissive Langmuir probes. Because the electron temperature is low (T_e ~ 5 eV) and also the variation of T_e is small throughout the experiments, the gradient of the measured floating potential will give a good approximation of the electric field in plasmas. Double probes for the electron density and electron temperature measurements were also employed.

2.1 Electrode biasing

The potential structures of plasmas under the influence of a positively or negatively biased ring electrode are shown in Figs. 2 and 3. Potential contours almost coincide with the flux surfaces of poloidal magnetic fields and the electric field is generated in the radial direction of the toroidal plasmas. When the electrode was negatively biased, internal electric field of up to 2 kV·m^{-1} was produced in a broad region between the electrode and the vessel wall. The corresponding toroidal $\boldsymbol{E} \times \boldsymbol{B}$ rotational speed is ~10^5 m·s^{-1}. In contrast, when $V_{IC} > 0$, potential gradient was observed in a very limited region near the electrode, and internal electric field was not generated. A current between the IC electrode and vessel wall, I_{IC}, in Fig. 4 also shows the strong asymmetry of the response of plasmas against the polarity of the electrode voltage. In the radial distributions of electron density in Fig. 5, a density gap is formed around the IC electrode when the IC electrode is positively biased. It leads to limit the current I_{IC} and also results in the observed flat potential profiles when $V_{IC} > 0$.

In the current 13.56 MHz RF experiments, typical electron number density is $n_e = 5 \times 10^{13}$ m^{-3} and typical electron temperature is T_e = 5 eV. With the applied magnetic field strength B ~ 0.01 T, neutral gas density $n_n = 1.4 \times 10^{19}$ m^{-3}, and estimated hydrogen ion temperature T_i = 0.5 eV, plasma parameters are calculated to be Debye length λ_D = 2 mm, Larmor radii for electrons and ions r_{Le} = 1 mm and r_{Li} = 10 mm, ion sound speed $c_s = 2 \times 10^4$ m·s^{-1}, Alfvén velocity $v_A = 3 \times 10^7$ m·s^{-1}.

In the above parameter region, electromagnetic forces and the effects of collisions with neutral atoms are dominant in the motion of charged particles [4] and because the experiments were carried out in a pure poloidal magnetic field, radial electric field is sustained only by the toroidal rotation of the plasma. In a steady state, the motions of ions and electrons are approximated as

$$\boldsymbol{v}_{k\perp} = \frac{q\nu_{nk}}{m_k\omega_{ck}^2}\boldsymbol{E} + \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2}, \qquad (1)$$

because cyclotron frequency ω_{ck} exceeds collision frequency ν_{nk}: $\omega_{ck}^2/\nu_{nk}^2 \gg 1$. In the magnetic and electric configuration of the Proto-RT device, the first term corresponds to the radial motion of charged particles across the magnetic surfaces due to the radial electric field and collisions with neutral atoms, and the second term is the $\boldsymbol{E}\times\boldsymbol{B}$ drift motion in the toroidal direction due to the poloidal magnetic field and the radial electric field E_r. Figure 6 shows a single ion orbits in DC electric and magnetic fields in Proto-RT without the effects of collisions with neutral atoms. The relation between E_r and radial current density j_r is given by

$$j_r = |q|\,(n_i v_i + n_e v_e) = q^2 n_e\left(\frac{\nu_{in}}{m_i\omega_{ci}^2} + \frac{\nu_{en}}{m_e\omega_{ce}^2}\right)E_r. \qquad (2)$$

Because the first term is dominant, the radial current across the magnetic surfaces is mainly transported by ions:

$$j_r \simeq \frac{q^2\nu_{in}n_e}{m_i\omega_{ci}^2}E_r \sim 3\times10^{-5}E_r. \qquad (3)$$

Because the RF coupling and density distribution of the plasmas are modified according to the magnetic field strength or background neutral density, it was not straightforward to obtain the parameter dependence of the radial electric field E_r and the radial current I_{IC} between the IC electrode and the vessel wall. However, with the surface area of the IC electrode S_{IC} = 0.59 m^2 and by assuming the radial symmetry of plasmas around the IC electrode, the observed E_r ~ 5 kV·m^{-1} near the IC electrode and I_{IC} ~ 0.3 A generally agree with the relation between E_r and I_{IC} in Eq. (3), indicating the observed radial electric fields and the electrode current are explained as the transport due to the collisions with neutral atoms.

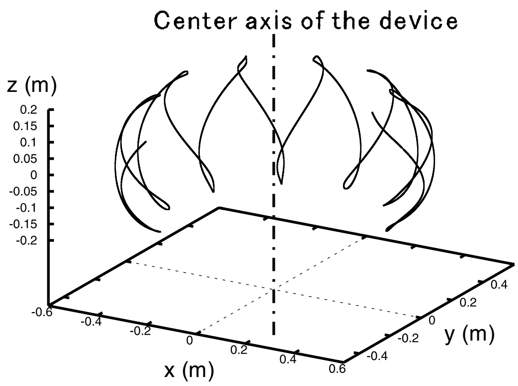

Fig. 6 The typical orbit of a hydrogen ion in the magnetic and electric field configuration in the Proto-RT.

2.2 Electron injection

Figure 7 shows a potential profile of a plasma when electrons are injected into the plasma with an acceleration voltage of 1 kV and beam current of 0.2 A. Although a small potential gradient was formed near the electron gun, the potential drop saturated around *zero* and the generated radial electric field remained less than 50 V·m^{-1}. The increase of the acceleration voltage of the electron gun or the heating current of the cathode (electron beam current of up to ~0.5 A and acceleration voltage of up tp 1.3 kV) does not contribute to form a large potential well inside the plasma.

Assuming that the observed potential drop of ~30 V is due to the injected electrons, the charge of the injected and trapped electrons is of the order of 10^{-7} C. From the injected beam current of ~1 A, the confinement time of electrons is estimated to be τ_e ~ 0.1 μs. In pure electron experiments in Proto-RT, obtained maximum electron confinement time is τ_{pe} ~ 100 ms and it is much larger than τ_e. Generated space potential of the plasma and the potential of the IC electrode, when electrons are injected into a vacuum (no RF plasmas)

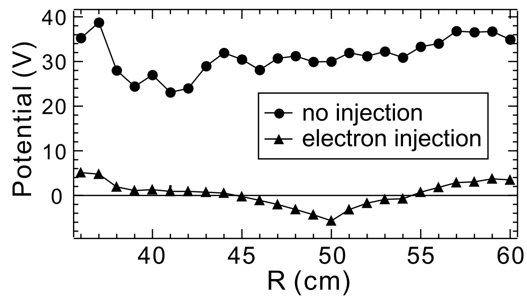

Fig. 7 Potential profiles in the Proto-RT, with and without the electron injection. The gun is located at R = 50 cm and Z = 0.

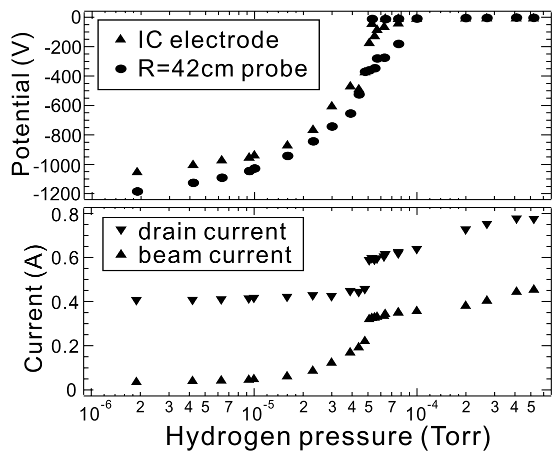

Fig. 8 (a) Electrostatic potentials generated by an electron gun as functions of background pressure and (b) the drain and beam current of the electron gun, without the generation of RF plasmas.

vessel, are shown in Fig. 8. In the pressure range of above $P_0 = 6 \times 10^{-5}$ Torr, electron cloud does not formed and also the increase of the gun current was observed due to the collisions of electrons with neutral atoms. However, when RF plasmas were generated in the hydrogen pressure of 4×10^{-5} Torr ($< P_0$), the generated potential reduced to around zero, suggesting the electrons loss is caused by a diffusion via RF plasmas.

3. Conclusion

The effects of electrode biasing and electron injection into a plasma were examined in an internal conductor device Proto-RT. When the ring electrode was biased, both the electrode current and internal electric fields of the plasmas showed a strong asymmetry according to the polarity of the electrode bias voltage. By using a negatively biased ring electrode, radial electric field of up to ~2 kV·m^{-1} was generated, and it is consistent with the radial current due to the transport of ions by the collisions with neutral atoms. The corresponding $\boldsymbol{E} \times \boldsymbol{B}$ toroidal drift speed is comparable to the ion sound speed. In the current experiments of electron injection, potential gradient was not effectively generated due to the electron loss via RF plasmas.

Although electric field or flow was successfully generated in the plasma in the Proto-RT, the obtained plasma parameters still remain in an electrostatic range in the present experiments. The Alfvén velocity is two order of magnitude larger than the obtained drift speed of the plasma, v, and thus the effect of the dynamic pressure of plasma flow on β value is negligibly small. An increase in the plasma density, possibly by means of another plasma generation method, will reduce the Alfvén velocity (e.g. plasma density $n_e = 10^{17}$ m^{-3} give a more realistic value of $v_A \sim 10^6$ m·s^{-1}) and would make it possible to test the effects of plasma flow on the equilibria in future experiments.

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