Potential structure of a plasma in an internal conductor device under the influence of a biased electrode

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The present study examined the electric field structure in a magnetized plasma in a prototype ring trap (Proto-RT) device with an internal ring electrode. A radial electric field of up to 3 kV m^{-1} was produced in the broad region between the electrode and vessel wall when the ring electrode was negatively biased. The resultant $\mathbf{E}\times\mathbf{B}$ toroidal rotational speed is comparable to the ion sound speed. Positive biasing, however, created a gap between the plasma and the electrode, failing to produce an internal electric field. © *2004 American Institute of Physics.*
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The effects of electric fields and flow play an important role in the fundamental properties of plasmas. The formation of transport barrier at the edge region of the plasma and improvement of the confinement properties are intensively studied in tokamaks[1] and mirror machines.[2] Recently, the study of plasmas with flow in the entire region is developing, such as centrifugal confinement of rotating plasmas[3] or new relaxation states of plasmas[4,5] (represented by Double Beltrami fields[6]) that includes the effects of ion flow.

In experimental search for the relaxation states of the flowing plasmas, toroidal trap devices equipping a normal-conducting or superconducting internal coil[7] or a linear mirror device[8] have been constructed and fundamental research is currently being carried out. When a radial electric field is generated within the poloidal magnetic field configuration of the internal conductor device, the expected plasma flow is induced in the toroidal direction. In contrast to unmagnetized plasmas, in which electric potentials are Debye shielded, magnetized plasmas can accept various potential structures according to the distribution functions of charged particles. The study of the characteristics of the flowing plasmas requires the generation of a broad electric field inside the plasmas, and thus the potential control method is one of the essential issues for such studies. In the present study, we experimentally tested the effects of electrode biasing and demonstrated the formation of the radial electric field of a plasma in a toroidal internal conductor device.

Experiments were carried out on a prototype ring trap (Proto-RT),[7,9] whose cross-sectional view is shown in Fig. 1. The Proto-RT has an internal conducting ring that generates a dipole magnetic field. By combining vertical and toroidal magnetic fields, a variety of magnetic field configurations can be produced. The typical magnetic field strength is of the order of 10^{-2} T. A plasma is generated by a rf electric field with a frequency of 13.56 MHz and an input power of 200 W. The rf power is supplied to the plasma using capacitively coupled plates located inside the chamber. Hydrogen pressure was 5×10^{-4} Torr. Inside the chamber, a torus-shaped electrode is installed on the ring conductor.

The potential profiles of the plasma were measured by emissive Langmuir probes, terminating the circuits with high impedance (100 MΩ) voltage probes. The probe characteristics ($I-V$ curves) showed that the obtained potentials almost agree (though typically underestimating some volts) with the space potential of the plasma. Because the electron temperature was low ($T_e\sim5$ eV) and the variation of T_e was small throughout the experiments, the gradient of the measured "floating" potential gives a good approximation of the electric field in the plasma. Plane Langmuir probes (with a tip of 3×3 mm molybdenum plate) were also used to measure electron density and temperature.

In the 13.56 MHz rf experiments, the typical electron number density measured by the Langmuir probe was $n_e=1\times10^{15}$ m^{-3} and the typical electron temperature was $T_e=5$ eV. With an applied magnetic field strength of $B\sim0.01$ T, neutral gas density of $n_n=2\times10^{19}$ m^{-3}, and estimated hydrogen ion temperature of $T_i=0.5$ eV, the plasma parameters are estimated to be the following: Debye length, $\lambda_D=0.5$ mm; Larmor radii for electrons and ions, $r_{Le}=0.7$ mm and $r_{Li}=10$ mm, respectively; ion sound speed, $c_s=2\times10^4$ ms^{-1}; Alfvén velocity, $v_A=7\times10^6$ ms^{-1}; electron cyclotron angular frequency, $\omega_{ce}=2\times10^9$ s^{-1}; ion cyclotron angular frequency, $\omega_{ci}=1\times10^6$ s^{-1}; electron-neutral collision frequency, $\nu_{en}=3\times10^6$ s^{-1}; ion-neutral collision frequency, $\nu_{in}=6\times10^4$ s^{-1}; electron-ion collision frequency, $\nu_{ei}=5\times10^2$ s^{-1}; and neutral collisions exceeding ion-electron collisions ($\nu_{ei}\ll\nu_{kn}$).

In the above parameter region, electromagnetic forces and neutral collisional effects are dominant in determining the motion of charged particles.[10] Because the experiments were carried out in a pure poloidal magnetic field configuration, a radial electric field yields toroidal rotation of the plasma. Neglecting the inertia term, the equation of motion for ions and electrons in a steady state is approximated as

$$qn_k(\mathbf{E}+\mathbf{v_k}\times\mathbf{B})-m_kn_k\nu_{nk}\mathbf{v_k}=0. \tag{1}$$

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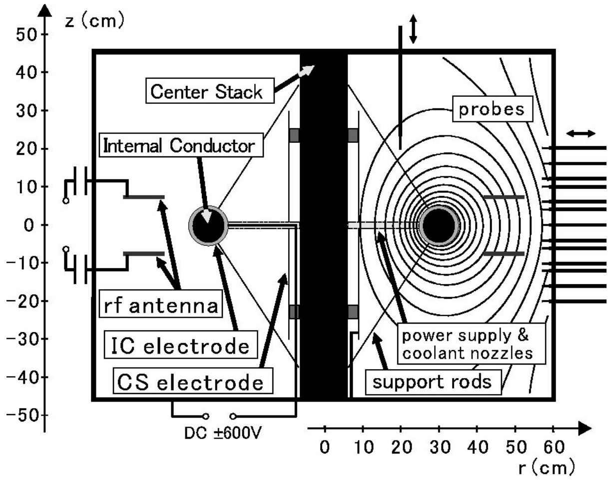

FIG. 1. Poloidal cross section of the Proto-RT chamber and magnetic surfaces of the poloidal field configuration. A pair of vertical field coils are located outside of the chamber (not seen). rf terminals are connected to a 13.56 MHz power source via dc cut capacitors and a matching circuit.

The pressure term can be neglected because of low density and temperature. Here $k=i,e$ indicates ion and electron, and ν_{nk} is the collision frequency between neutral particles and charged particles. By solving (1) for the velocity perpendicular to the magnetic field $\mathbf{v}_\perp$, we obtain an approximate solution

$$\mathbf{v}_{\mathbf{k}\perp}=\frac{q\nu_{nk}}{m_k\omega_{ck}^2}\mathbf{E}+\frac{\mathbf{E}\times\mathbf{B}}{B^2}. \tag{2}$$

Here, $\omega_{ck}^2/\nu_{nk}^2=5\times10^5$ (for electron), and 3×10^2 (for ion) $\gg1$ were used. In the geometry of the Proto-RT, the first term corresponds to the radial motion of charged particles across the magnetic surfaces and the second term is the toroidal drift speed. The relation between E_r and radial current density j_r is then given by

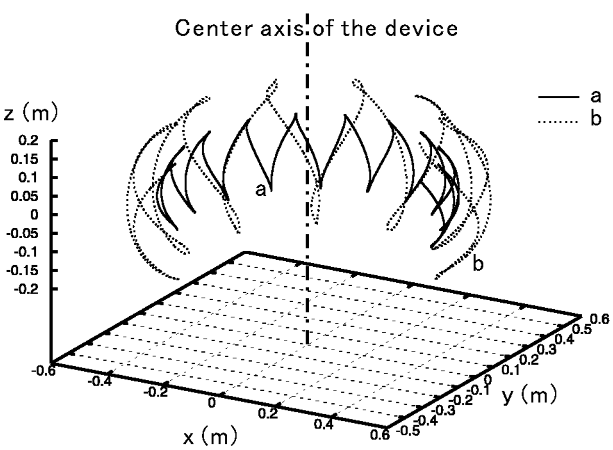

FIG. 2. Hydrogen ion orbits in the radial electric field and poloidal magnetic field of the Proto-RT. The initial position of the ion is (a) $r=0.4$ m, $z=0.1$ m and (a) $r=0.4$ m, $z=0.2$ m, respectively. Charged particles undergo toroidal $\mathbf{E}\times\mathbf{B}$ motion and reflection motion due to magnetic mirror effects.

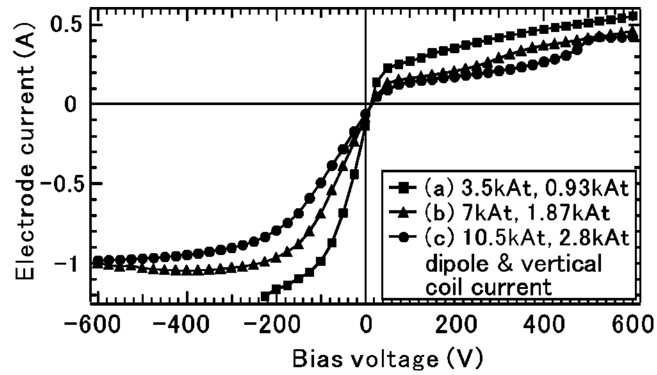

FIG. 3. Applied voltage on the IC electrode vs current between the electrode and chamber wall.

$$j_r=|q|(n_iv_i+n_ev_e)=q^2n_e\left(\frac{\nu_{in}}{m_i\omega_{ci}^2}+\frac{\nu_{en}}{m_e\omega_{ce}^2}\right)E_r. \tag{3}$$

Under the present experimental conditions, the ion term is dominant, and thus the radial current is transported primarily by ions:

$$j_r\simeq\frac{q^2n_e\nu_{in}}{m_i\omega_{ci}^2}E_r=1\times10^{-3}E_r. \tag{4}$$

Figure 2 shows the single ion orbit under the influence of dc electric and magnetic fields in the geometry of Proto-RT including the finite inertia term. The ions undergo an $\mathbf{E}\times\mathbf{B}$ drift motion in the toroidal direction, and also the orbit takes a banana-like trajectory due to magnetic mirror reflection. In the experimentally obtained electric field of $E\sim10^3$ V m^{-1} and with a typical magnetic field strength of $B\sim0.01$ T, the toroidal rotational speed of charged particles by the $\mathbf{E}\times\mathbf{B}$ drift motion is $\sim1\times10^5$ ms^{-1}. The mean free path of the ion between the collisions with neutral atoms is ~1 m, which is comparable to the machine scale length, and thus the individual motion induces an effective toroidal flow in the plasma.

For the formation of the radial electric field, a dc bias voltage V_{IC} was applied on the IC electrode against the ves-

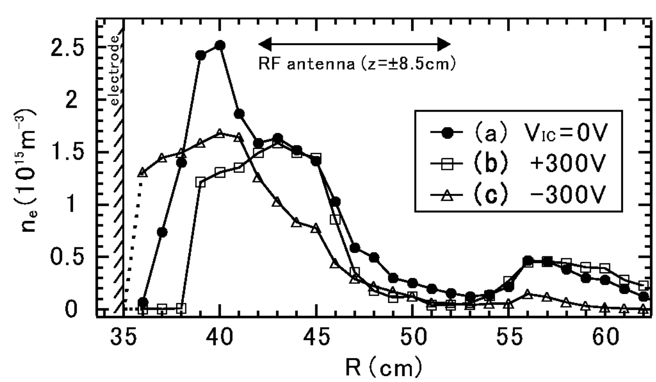

FIG. 4. Radial profiles of electron number density at $z=0$, (a) when $V_{\mathrm{IC}}=0$, the electrode is grounded, (b) positively biased $V_{\mathrm{IC}}=+300$ V, and (c) negatively biased $V_{\mathrm{IC}}=-300$ V.

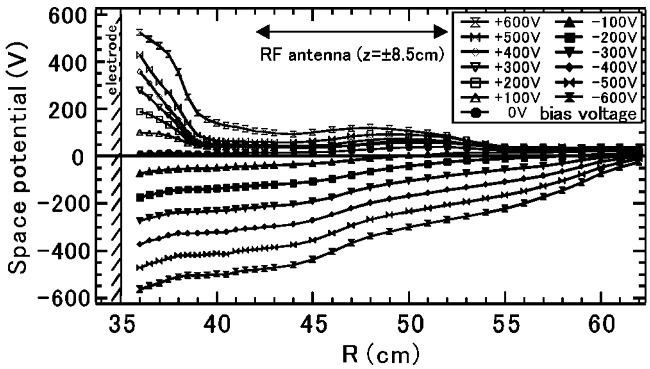

FIG. 5. Radial potential profiles (floating potentials of emissive Langmuir probes) of plasmas at $z=0$, with an IC electrode bias voltage of V_{IC} from -600 to $+600$ V.

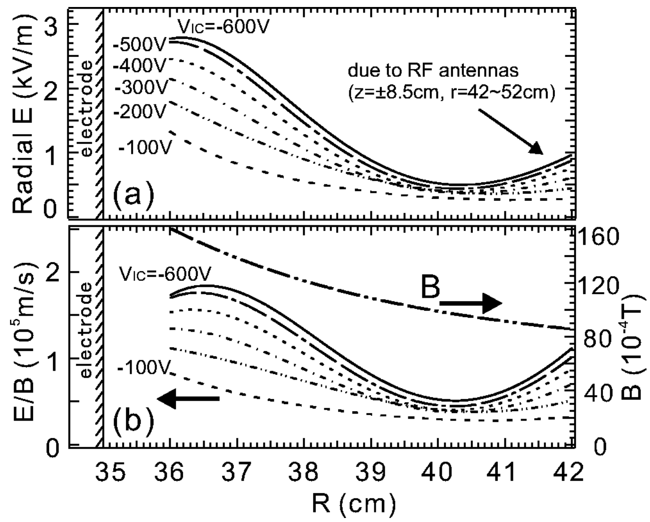

FIG. 7. The profiles of (a) radial electric field strength and (b) poloidal magnetic field strength B and $\mathbf{E}\times\mathbf{B}$ drift speed at $z=0$, when the electrode bias voltage was modified from $V_{\mathrm{IC}}=-600$ V to -100 V, calculated from the potential distribution in Fig. 5.

sel wall. Figure 3 shows a current I_{IC} between the IC electrode and the chamber as a function of V_{IC}. The applied magnetic field suppressed the radial current carried by the collisional transport of ions, and a bias voltage up to ± 600 V was successfully applied. As shown in Fig. 4, the density distribution of the plasma was modified by the applied bias voltage on the electrode. The displacement of the density profile (~ 2 cm) is much larger than the Debye length ($\lambda_D \sim 0.5$ mm). When the IC electrode, which is located in the confinement region of plasmas, is positively biased, a region of very low density (less than 1% of when $V_{\mathrm{IC}}=0$) is formed around the IC electrode.

The radial potential profiles of plasmas in the variation of V_{IC}, and the two-dimensional potential profiles when $V_{\mathrm{IC}}=\pm 600$ V are shown in Figs. 5 and 6. Potential contours coincide almost exactly with the flux surfaces of poloidal magnetic fields excepting the neighborhood of the rf antennas, and the electric fields are mainly generated in the radial direction. In the potential distribution of the condition $V_{\mathrm{IC}} > 0$, a voltage drop was observed in a very limited region near the electrode, which corresponds to the low density region in Fig. 4. In contrast, when $V_{\mathrm{IC}} < 0$, a smooth potential gradient was generated in the wide range of the confinement region of the plasma between the IC electrode and the vessel wall because the low density region was not formed in these cases.

The profiles of radial electric field strength and the corresponding $\mathbf{E}\times\mathbf{B}$ drift speed obtained from the potential profiles in Fig. 5 are shown in Fig. 7. Because the rf coupling and density distribution of the plasmas were modified according to the magnetic field strength or background neutral density, it was not a straightforward operation 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 $S_{\mathrm{IC}}=0.59\ \mathrm{m}^2$ and by assuming the radial symmetry of plasmas around the IC electrode, the observed $E_r \sim 3\ \mathrm{kV\,m}^{-1}$ near the IC electrode and $I_{\mathrm{IC}} \sim 1$ A generally agree with the relation between E_r and I_{IC} in (4), suggesting that the observed radial electric field and electrode current are under-

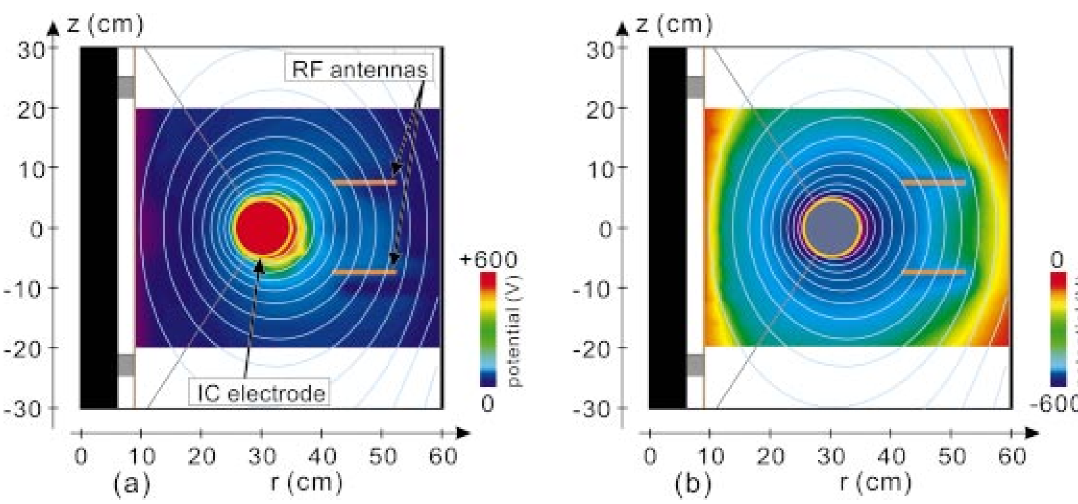

FIG. 6. (Color) Potential distribution of plasmas in the poloidal cross section of the Proto-RT, (a) when the IC electrode was positively biased ($V_{\mathrm{IC}}=+600$ V), and (b) negatively biased ($V_{\mathrm{IC}}=-600$ V). Thin lines show the poloidal magnetic surfaces.

stood as the transport due to the neutral collisions of ions.

Although electric field or flow was successfully generated in the plasma in the Proto-RT, the obtained plasma parameters are still in the electrostatic regime. The Double Beltrami equilibrium provides a condition for the ion flow velocity v and the β value of the plasma to satisfy $\beta + (v/v_A)^2/2 = \text{constant}$, where v_A is Alfvén velocity. It follows from this equation that an ultrahigh β (possibly $\beta > 1$) state will be realized due to the effects of plasma flow, when v is comparable to v_A. In the present experiments, the Alfvén velocity is as fast as $v_A = 7 \times 10^6\ \mathrm{ms}^{-1}$ and the dynamic pressure of plasma flow does not affect the β value, primarily due to the obtained relatively low electron density. An increase in the plasma density, possibly by means of another plasma generation method, would make it possible to test the effects of the plasma flow on the equilibria in future experiments.

ACKNOWLEDGMENTS

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