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

H. Saitoh, a) Z. Yoshida, H. Himura, J. Morikawa, and M. Fukao
Graduate School of Frontier Sciences, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

(Received 15 January 2004; accepted 4 March 2004; published online 17 May 2004)

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.

[DOI: 10.1063/1.1724833]

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 and mirror machines. Recently, the study of plasmas with flow in the entire region is developing, such as centrifugal confinement of rotating plasmas or new relaxation states of plasmas, which are represented by Double Beltrami fields 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 or a linear mirror device 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 plasma, 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), 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 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 \(\times\) 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 (\(T_e \sim 5\) 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 \(n_e = 1 \times 10^{15} \text{ m}^{-3}\) and the typical electron temperature was \(T_e = 5\) eV. With an applied magnetic field strength of \(B = 0.01\) T, neutral gas density of \(n_n = 2 \times 10^{19} \text{ m}^{-3}\), and estimated hydrogen ion temperature of \(T_i = 0.5\) eV, the plasma parameters are estimated to be the following: Debye length, \(\lambda_D = 0.05\) mm; Larmor radii for electrons and ions, \(\rho_{Le} = 0.7\) mm and \(\rho_{Li} = 10\) mm, respectively; ion sound speed, \(c_s = 2 \times 10^4\) ms\(^{-1}\); Alfvén velocity, \(v_A = 7 \times 10^6\) ms\(^{-1}\); electron cyclotron angular frequency, \(\omega_{ce} = 2 \times 10^9\) s\(^{-1}\); ion cyclotron angular frequency, \(\omega_{ci} = 1 \times 10^9\) s\(^{-1}\); electron-neutral collision frequency, \(\nu_{en} = 3 \times 10^6\) s\(^{-1}\); ion-neutral collision frequency, \(\nu_{in} = 6 \times 10^5\) s\(^{-1}\); electron-ion collision frequency, \(\nu_{ei} = 5 \times 10^2\) s\(^{-1}\); and neutral collisions exceeding ion-electron collisions (\(\nu_{ne} \ll \nu_{ke}\)).

In the above parameter region, electromagnetic forces and neutral collisional effects are dominant in determining the motion of charged particles. 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

\[
qn_k(\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) - m_k n_k v_k v_{ke} = 0. \tag{1}
\]
The pressure term can be neglected because of low density and temperature. Here $k = i, e$ indicates ion and electron, and $v_{nk}$ is the collision frequency between neutral particles and charged particles. By solving (1) for the velocity perpendicular to the magnetic field $v_{k_{\perp}}$, we obtain an approximate solution

$$v_{k_{\perp}} = \frac{q v_{nk}}{m_k \omega_{ci}^2} E + \frac{E \times B}{B^2}.$$  \hspace{1cm} (2)

Here, $\omega_{ci}^2 / v_{nk}^2 = 5 \times 10^5$ (for electron), and $3 \times 10^5$ (for ion) $\gg 1$ 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

$$j_r = q |n_i v_i + n_e v_e| = q^2 n_e \left( \frac{v_{in}}{m_i \omega_{ci}} + \frac{v_{en}}{m_e \omega_{ce}} \right) E_r.$$  \hspace{1cm} (3)

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

$$j_r = q^2 n_e v_{in} E_r = 1 \times 10^{-3} E_r.$$  \hspace{1cm} (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 $E \times B$ 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 $E \sim 10^3$ V m$^{-1}$ and with a typical magnetic field strength of $B \sim 0.01$ T, the toroidal rotational speed of charged particles by the $E \times B$ drift motion is $\sim 1 \times 10^2$ ms$^{-1}$. The mean free path of the ion between the collisions with neutral atoms is $\sim 1$ 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-
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 $\pm 600$ 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 ($\sim 2$ 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 $V_{IC} = 0$) 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 $V_{IC} = \pm 600$ 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 $V_{IC} > 0$, 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 $V_{IC} < 0$, 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 $E \times B$ 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 $S_{IC} = 0.59$ m$^2$ and by assuming the radial symmetry of plasmas around the IC electrode, the observed $E_r \sim 3$ kV m$^{-1}$ near the IC electrode and $I_{IC} \sim 1$ 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-
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 Béltrami equilibrium provides a condition for the ion flow velocity $v$ and the $\beta$ 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 $\beta$ (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 $v_A = 7 \times 10^6$ ms$^{-1}$ and the dynamic pressure of plasma flow does not affect the $\beta$ 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

This work was supported by a Grant-in-Aid for Scientific Research (14102033) from MEXT Japan. The work of H.S. was supported in part by a JSPS Research Fellowship for Young Scientists.