Control of Equilibrium Structure of a Toroidal Non-neutral Plasma in Proto-RT

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Abstract. The structure and its control method of toroidal non-neutral plasma equilibria have been studied in an internal conductor geometry. It was demonstrated that the potential profiles of toroidal electron plasmas can be altered by use of control electrodes. With a ring electrode negatively biased, the hollow potential of the plasma was eliminated, and consequently, the improvement in containment time was observed. Electrostatic fluctuations shows that the electrons were confined in dipole fields for up to 100 *msec*.

INTRODUCTION

Non-neutral plasmas have attracted a wide range of interests in its diverse applications as well as the fundamental physics. The self-electric field and the resultant strong flow induce various types of structure formations such as vortex dynamics. A high β equilibrium state with strong flow has been predicted by a two-fluid model [1]. Traps of charged particles including anti-matters [2] are also one of the main topics in atomic physics experiments.

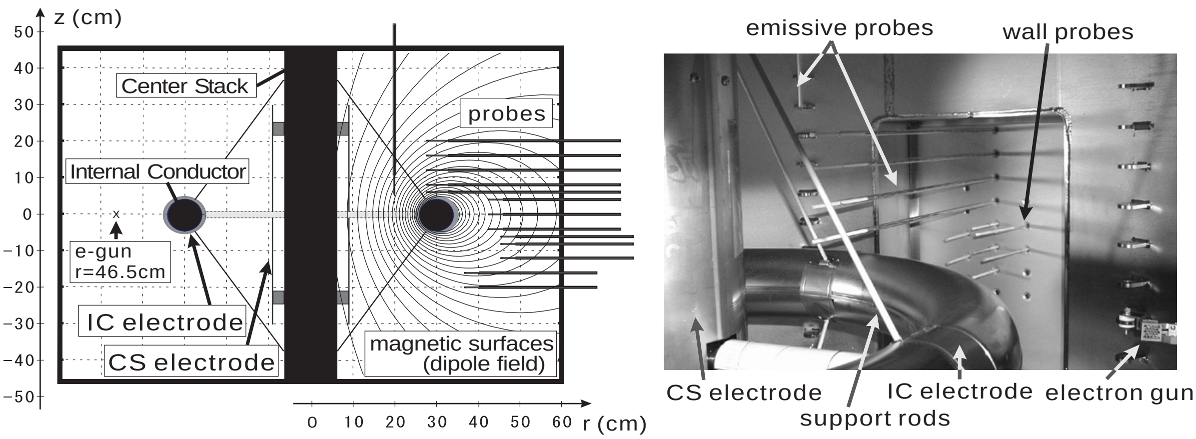
Toroidal trap systems have no open ends of magnetic field lines and consequently, no electrostatic potentials are required along the toroidal direction. This advantage allows toroidal systems to trap high energy or multiple species of different charges. For several decades, confinement of electron plasmas in toroidal magnetic fields have been studied [3, 4]. The toroidal field and the electric fields in a plasma produce an $\mathbf{E} \times \mathbf{B}$ drift, which overcome curvature drifts, and the motion of a single particle takes a closed orbit. However, the toroidal effects cause cross field transport of the particles [5], which prevent the long time containment of non-neutral plasmas in pure toroidal fields.

The Proto-RT (Prototype Ring Trap) device is a toroidal trap constructed for exploring various phenomena in non-neutral plasma physics [6]. Besides conventional toroidal field coils, Proto-RT has two kinds of poloidal field coils (a dipole field coil and vertical field coils) and can generate a variety of field configurations. Recently, the possibility of stable and long time confinement of non-neutral plasmas on magnetic surfaces has been predicted in a stellarator configuration [7]. In contrast to pure toroidal field devices, the poloidal coils of Proto-RT have made possible a containment of non-neutral plasmas on similar kinds of magnetic surfaces. However, Proto-RT has an internal conductor (IC) in the confinement region of the torus and the outer shell of IC is electrically grounded. Thus the confined non-neutral plasmas have hollow distribution, which might cause instability.

In this work, we have studied the structure of electron plasma equilibria and its control method in a toroidal device of the Proto-RT type (i.e., toroidal-internal conductor system). Externally applied electric fields can control potential and flow profiles in the plasma and thereby might contribute to the improvement in the containment properties. Experimentally, potential structures and the effects of biased electrodes upon the equilibria and containment time were evaluated. It was demonstrated that the potential profiles were successfully controlled by external electric fields. The negatively biased electrode cancelled the hollow potential profile in the plasma, and a long time containment of a torus electron plasma was observed.

EXPERIMENTAL SETUP

Experiments were carried out on the Proto-RT device (Fig. 1). The torus has a rectangular poloidal cross section of $0.9\ m \times 0.472\ m$ and is pumped to $3 \times 10^{-7}\ Torr$. In the chamber, toroidal fild (TF) coils are penetrating through its



(a) Schematic view of Proto-RT (b) Phtographic view inside Proto-RT

FIGURE 1. (a) The poloidal cross section and (b) the inside view of the Proto-RT device. Support rods, electric feeders, and a coolant nozzle are connected to the internal conductor, covered by ceramic insulators. To minimize the disturbance to the plasma, each probe was independently inserted into the chamber. Vertical field coils are located at outside of the chamber, $r = 90$ cm.

hollow center stack (CS) of 0.114 m diameter. Proto-RT also has two kinds of poloidal field coils; an internal conductor (IC) coil for dipole fields and a pair of vertical field (VF) coils. Electrons are injected into the torus of Proto-RT from an electron gun of LaB_6 cathode located at the equatorial ($z = 0$) plane. In this study, the gun is fixed at $r = 0.465$ m and fired at an acceleration voltage of 300 V. In the typical magnetic field strength of Proto-RT, ~ 0.01 T near the electron gun, the beam current obtained was 2 mA. The details of the device is given in literatures [6].

Equilibria of a torus non-neutral plasma are formed by a help of external electric fields from outside of the space charges. As far as an equilibrium is found in a device, the required external fields have automatically been generated by the induced image charges on the chamber. However, more actively, the equilibrium structure of the plasma can be externally controlled by applied electric fields. Proto-RT has a pair of plasma control electrodes on IC coil and CS in the vessel. These electrodes are electrically insulated from the chamber or each other, and can produce external fields around 1 kVm^{-1} in a vacuum chamber.

Two kinds of probes have been used in the experiments. One was a Langmuir probe for the measurements of potential profiles. The probe configuration in the device is shown in Fig. 1. To measure space potentials in non-neutral plasmas, where the strong flow is induced, we have employed emissive Langmuir probes [8]. The probe consists of a tip of 0.1 mm diameter thoria-tungsten spiral filament and molybdenum wire of 1.0 mm diameter covered with an insulating ceramic tube. It was terminated across a resistance of 100 $M\Omega$ and used as a floating probe, where the disturbance to the plasma is relatively small. In comparison with probe characteristics (I-V curves), the potential ϕ_H measured by these high-impedance emissive probes showed a good agreement with the space potential ϕ_p in a electron plasma. The probes were configured to form an array and each probe is movable along the radial direction (or z direction, for a z probe), so that the spatial distributions of the plasma and the effects of external fields are obtained.

The other probe was a wall probe for the measurements of image charges of the electron clouds. As a wall foil, a copper sheet was enclosed in an insulating glass tube and located inside the chamber. The foil is connected to the chamber through a resistance of 470 Ω or a current amplifier. Electrostatic fluctuation of the plasma and, in the current integrating mode, the variation of trapped charge are measured. The wall probe is also used for the evaluation of the confinement time of the plasma.

RESULTS AND DISCUSSION

Potential structures of electron plasmas in Proto-RT were measured in a variation of applied voltage on the IC electrode (Fig. 2). In dipole field configurations, the confinement region of the plasma agrees with the outer shell of the closed magnetic surfaces, but the distribution of the plasma is inwardly shifted, surrounding the IC electrode [9]. This is supposed to be due to the diffusion of electrons from the original beam orbit and the formation of the magnetized bulk component of the plasma. When the potential is not externally controlled (i.e., the IC electrode is grounded) or the

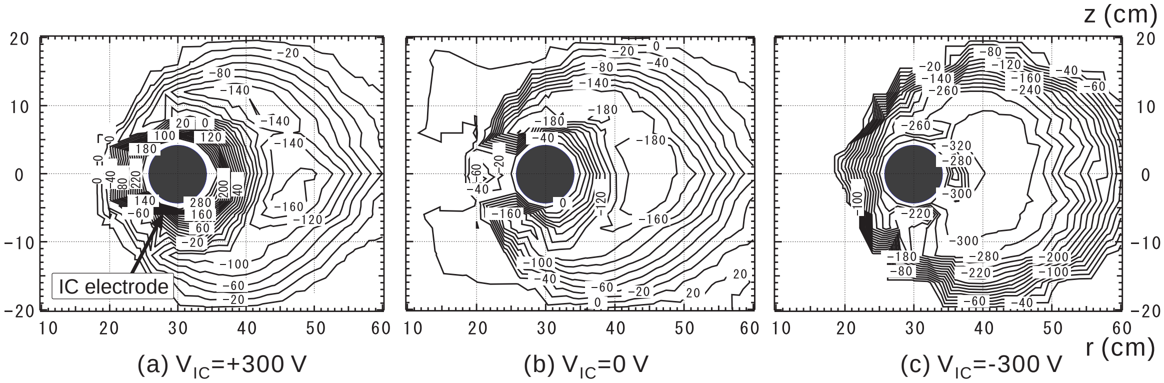


FIGURE 2. Potential profiles and its control in the poloidal cross section of Proto-RT measured by emissive probes. V_{IC} is an electrostatic potential on the internal conductor. Electrons were injected by an acceleration voltage of 300 V in a dipole magnetic field (coil current $I_{dipole} = 5.25$ kAt). The CS electrode is grounded. The potential is not equal to 0 at $r = 59$ cm, the inside diameter of the chamber, because the inside surface of the diagnostic flange is located at $r = 65$ cm. The corresponding number density of the electron $n \sim 2\times 10^{13}$ m^{-3}, and the total trapped charge $Q \sim 2\times 10^{-7}$ C.

electrode is positively biased, the potential profiles also take hollow distributions around the IC electrode (Fig. 2 (a) and (b)). In these cases, the ridge of the potential peak is surrounding the IC electrode, and the resultant $\mathbf{E}\times\mathbf{B}$ drift flow takes a sheer distribution, which may cause a diocotron instability. In contrast, negatively biased IC electrode eliminates the hollow potential profile (Fig. 2 (c)).

Figure 3 shows the electrostatic fluctuations from the plasma. When the potential structure is not externally controlled (i.e., the IC electrode is grounded), the electrostatic fluctuation from the plasma decays with a 40 μsec exponential curve after the stop of the electron supply at $t = 0$. However, when the IC electrode is negatively biased so that the hollow potential profile is eliminated, the fluctuation signals were observed for much longer period. In Fig. 3 (b), the amplitude of the oscillation rapidly grow again during the first damping oscillation ($t = 300$ μsec). This signal shows an unstable change in the amplitude until $t = 1.4$ $msec$ with decreasing its frequency. After $t = 1.4$ $msec$, the amplitude of the signal decreases with an approximately 3$msec$ exponential decay, keeping an almost constant frequency. The fundamental frequency of the oscillation of this period is proportional to $1/B$ and approximately proportional to V_{IC}, the externally applied electrostatic potential on the IC electrode. These properties agree with a diocotron oscillation in an electron plasma, and the corresponding density for the $l = 1$ mode is $n \sim 3\times 10^{11}$ m^{-3}.

When V_{IC} was more negatively biased than -250 V, the electrostatic fluctuation was detected with a longer delay from $t = 0$. Figure 4 (a) is the typical oscillation signal of the plasma in a strong external field. A large amplitude

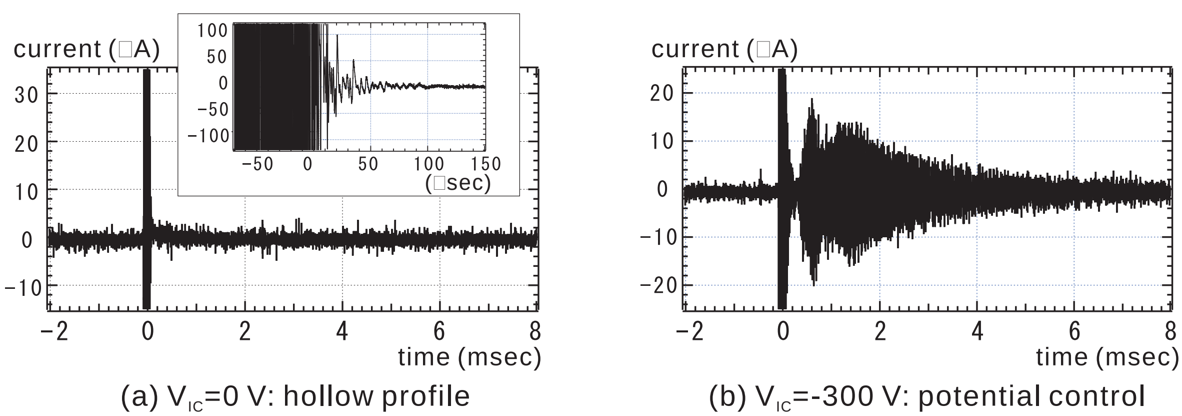


FIGURE 3. Electrostatic fluctuations measured by wall probes. The IC electrode is (a) grounded or (b) negatively (-300 V against the chamber) biased. Electrons were injected by a gun with an acceleration voltage of 300 V from $t = -75$ to 0 μsec. When the potential profile were adjusted to eliminate the hollow profile, the oscillating signal were continuously observed.

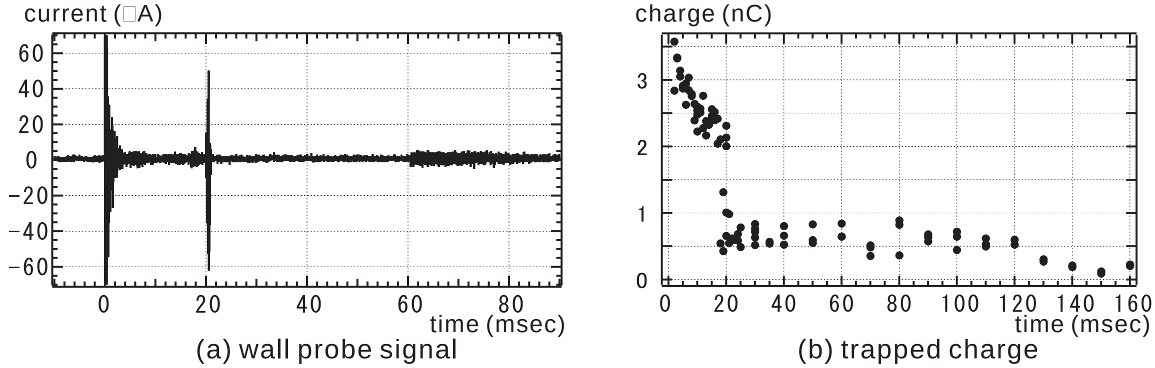


FIGURE 4. (a) The electrostatic fluctuation of the plasma and (b) the integrated current of image charges flow to the wall probe, when a strong external electric field and magnetic field ($V_{IC} = -350\ V$ and $I_{dipole} = 10.5\ kA$) is applied. The electron gun is stopped at $t = 0$.

oscillation and small long signal appear at $t = 20$ *msec* and after 60 *msec*. The fundamental frequency of each oscillation is 42.5 *kHz* and 4.4 *kHz*. We have estimated the confinement time of the plasma by using the image charge measurements. The potential on the IC electrode was changed from $V_{IC} = -350\ V$ to $0\ V$ at t, and the image charges flow to the wall probe was measured. The damp of V_{IC} causes a destabilization and the plasma decays at t (cf. 3 (a)). By the comparison of the image charges of trapped electrons with potential profiles obtained by the Langmuir probe array, the contained charge and its decay was determined. Before the large amplitude oscillation appears at $t = 20$ *msec*, about 2 % of the total electrons during the injection from the gun shows a good containment property and slowly decreases with an approximately 50 *msec* exponential decay. The confined charge rapidly drops at this point, but about 0.3 % of the electrons are still trapped for another 100 *msec*.

In summary, the optimization of the potential profiles has made possible a long time containment of toroidal electron plasmas in dipole field configrations. Plasmas with density $n \sim 3 \times 10^{11}\ m^{-3}$ were confined for 20 *msec* and those with $n \sim 4 \times 10^{10}\ m^{-3}$ for 120 *msec* after the stop of the electron supply, although the obserbed disruptions caused sudden decay of the trapped charges. These confinement time has a sensitive dependence on the back pressure of the device and the strength of the magnetic field. It is probable that the electron-neutral collision set this limit, and the improvement in these parameters might contribute to the longer confinement of torus electron plasmas.

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