First experimental result of toroidal confinement of non-neutral plasma on Proto-RT

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Abstract

Recently, an internal-ring device named Proto-RT (Prototype Ring Trap) was constructed at University of Tokyo, and experiments on the device have been just initiated. The goal of Proto-RT is to explore an innovative way which has a possibility to attain a plasma equilibrium with extremely high-β ($\beta > 1$) in a toroidal geometry using non-neutral condition. At the first series of the experiments, pure electron plasma ($n_e \sim 10^{12}$ m^{-3}) is successfully confined inside a separatrix. No disruption is so far observed. The confinement time of the electron plasma is the order of 1 sec. A shear effect of magnetic fields seems to result in longer confinement. The non-neutrality of $\Delta n_e \sim 10^{12}$ m^{-3} is already beyond the value required to produce an enough self-electric field **E** in plasma, causing a strong **E**×**B** flow thoroughly all over the plasma where the hydrodynamic pressure of the flow is predicted to balance with the thermal pressure of the plasma.

I. INTRODUCTION

A possibility of high-β equilibrium with strong flow has been theoretically pointed out [1], which is based on double-curl Beltrami field. In fact, several high-β solutions have been numerically found out in a cylindrical geometry. The requirement to this high-β equilibrium is to maintain two-fluid effects with the large velocity field whose magnitude is comparable to that of the magnetic field in plasma. Another significant feature of this equilibrium is that the thermal pressure of plasma is sustained by the hydrodynamic pressure of the strong flow, alleviating the strength of magnetic fields to confine plasma which offers attractive benefits including the lowest construction costs among toroidal fusion systems.

To obtain such a flow in plasma, a non-neutral condition is proposed [2] which can produce a self-electric field **E** in plasma, causing strong **E**×**B** shear flow if we apply an appropriate magnetic field **B** there. Then the question is asked on how the non-neutral plasma can be produced in laboratory experiments. Although several methods can be considered, we have proposed to add quasi-neutral plasma to pure electrons. To explore this way, the toroidal confinement of pure electron plasma has been conducted on Proto-RT. A description of the Proto-RT device and the diagnostics employed are explained in Sec. II. The first experimental data of pure electron plasma and a summary are given in Sec. III and IV, respectively.

II. APPARATUS OF PROTO-RT DEVICE

An internal-ring device named Proto-RT (Prototype Ring Trap) has been constructed to investigate the fundamental physics of (1) non-neutral plasma, (2) magnetic null, and (3) traps for positrons or antiprotons in a static magnetic field **B**. The primary objective of Proto-

RT is the study of toroidal confinement of pure electron plasma inside a closed **B** region as portrayed in Fig. 1, and chaos-induced anomalous resistivity in field null [3].

Figure 2 shows a schematic view of the Proto-RT device. A 1.18 m inner diameter and 0.90 m long vacuum vessel, which is made of 1.0 cm thick stainless steel (SUS304), contains an internal-ring (30.0 cm major radius and 4.3 cm minor radius) and a center stack with 11.4 cm outside diameter. The internal-ring, 6 mm thick stainless steel, has one toroidal and four poloidal cuts which present to help smooth flux surfaces around the ring. Inside the ring, there is a 175 turn copper wire with 3.2 mm diameter to produce a dipole-field (DF), and each of which is stiffen together with an epoxy. Two copper veneers are inserted into the coil as fins. Also, Freon is applied to cool the coil down. The Freon circulates in toroidal direction of the coil through a quarter-inch stainless tube that is attached to the fins. Furthermore, He_2 gas is filled up inside the ring to promote the heat conduction there. Both the tube and the gas are introduced in the internal-ring through the same bus-bar; In fact, there are two bus-bars on the internal-ring. The another one is used to energize the coil. To hold the ring with the bus-bars, a set of eight stainless steel rods having 3 mm diameter is used to connect the ring with the center stack. A ceramic tube covers each rod.

The inner diameter of the center stack, 4.0 mm thick stainless steel, is 10.6 cm through which a set of six toroidal-field (TF) coils passes in order to carry poloidal currents, being linked with the vacuum vessel. Each TF coil has ten-turn which is made of copper boards (1 mm thick each), and is cooled down by water. A vertical-field (VF) is added to produce a magnetic separatrix.

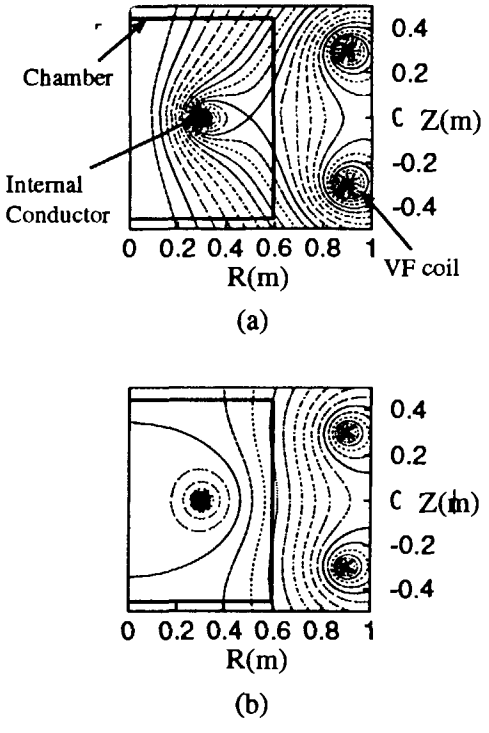

FIG. 1. Two types of magnetic surfaces; (a) The separatrix generates an X-point on the outside of the internal conductor. (b) The magnetic null points are located on the center axis.

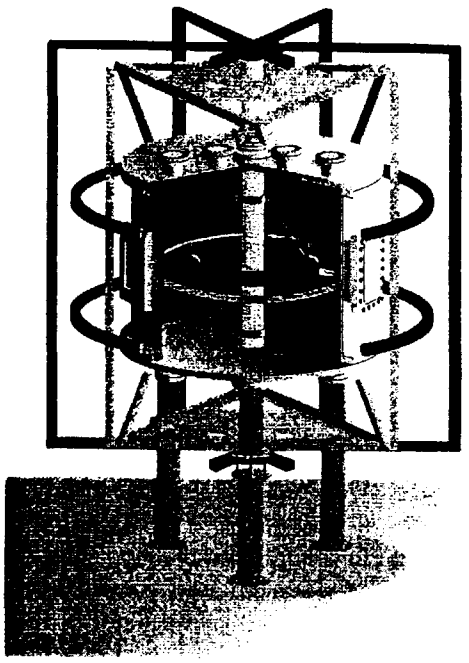

FIG. 2. Schematic view of Proto-RT; a toroidal non-neutral plasma confinement device. Dipole magnetic field is produced by an internal ring conductor. Toroidal magnetic field yields sheared magnetic field.

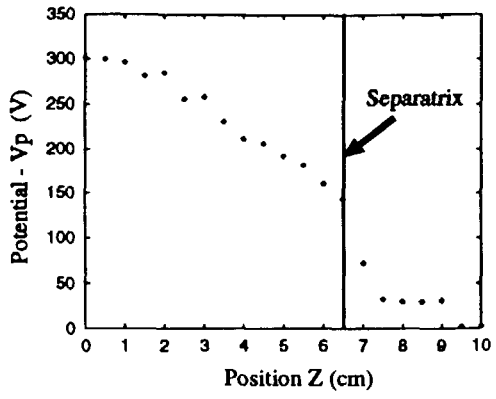

FIG. 3. Radial distribution of the electrostatic potential in a pure electron plasma.

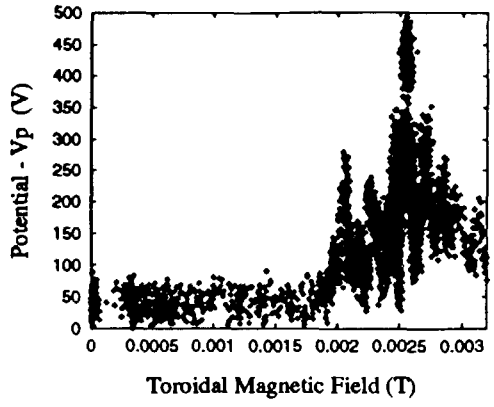

FIG. 4. Dependence of the confined plasma potential to the toroidal magnetic field.

Proto-RT uses three DC power supplies, (1) TF: 50 V · 500 A, (2) DF: 60 V · 60 A, (3) VF: 60 V · 30 A×2, to form a well-controlled static **B**. By properly programming these currents, we can flexibly create various magnetic configurations as shown in Fig. 1. The vacuum vessel is pumped down to $3\text{-}4\times10^{-7}$ Torr for the present experimental research. In Proto-RT, radio frequency of 13.56 MHz (up to 1 kW) is available to launch an electromagnetic wave to plasma through a toroidal loop antenna having 1.0 m diameter. An electron gun is installed at $z = 0$ to inject electrons which can be accelerated up to 2.0 kV. The head of the gun is movable in not only the radial direction but also the tangent plane perpendicular to r-z plane.

Regarding to diagnostics of Proto-RT, two potential probes are now used to measure electrical potentials $-\Phi$ of pure electron plasma from which number of electron density n_e can be inferred. An array of probes having semiconductor tips and electrodes will be installed to determine static **B** and **E** simultaneously. A conventional Faraday cup is used to provide electron energy E_e. Also, a directional faraday cup is now being built to measure precise electron flow flux $n_e v_f$.

III. FIRST RESULT OF PURE ELECTRON PLASMA

Since the TF coils were completed in January of 1998, we have performed the first experiments to confine pure electrons in the separatrix shown in Fig. 1 (a). Electrons are injected from the electron gun which is placed near the X point. Plotted in Fig. 3 is a profile of $-\Phi$ along the z axis. Each data is taken in separate shots and the head of the electron gun is set just inside the separatrix for the profile in Fig. 3. The value of $-\Phi$ is about 300 eV at $z = 0$, and then monotonically decreases to ~ 150 eV at the separatrix (z = 6.5 cm). It should be noted that a steep gradient of $-\Phi$ appears at the separatrix, indicating that the electrons are well confined inside the separatrix. Assuming there is no positive charge there, the value of n_e can be calculated to be ~ 10^{12} m^{-3} from $\nabla^2\Phi = en_e / \varepsilon_0$.

The value of $-\Phi$ strongly depends on the strength of B_t. It is recognized from Fig. 4 that $-\Phi$ inside the separatrix is about 50 V without B_t. However, as B_t is applied, $-\Phi$ significantly increases up to ~ 500 V (B_t ~ 25 G), implying that a shear effect of **B** results in longer confinement of pure electrons inside the separatrix. This might be attributed to

suppression of microturbulence by a magnetic shear. In fact, a preliminary measurement of electrostatic fluctuations provides the frequency in range of 10^6 –10^7 Hz with the magnitude of 10^{-3} of the ambient potential, and the value of $\tilde{\Phi}/\Phi$ seems to decrease as B_t is applied up to 25 G.

Finally, from the decay signal of the potential probes, we can estimate the confinement time τ_N of pure electrons. The value of τ_N is the order of 1sec.

IV. SUMMARY

In summary, we have completed to construct an internal-ring device, Proto-RT. The magnetic field B of Proto-RT is static so that experiments on the device can be performed in well-controlled laboratory setting. Moreover, the device has a great flexibility to produce various **B** configurations such as a closed-field configuration with X point, Spherator type, and Dipole fields. Those properties allow us to investigate fundamental physics of (1) magnetically confined plasma, (2) trapping of antimatter, (3) anomalous resistivity in magnetic null and so on. Regarding to (1), the experiments to confine pure electron plasma have been just initiated, and the value of $n_e \sim 10^{12}$ m^{-3} seems to be attained inside a separatrix. No disruption of pure electron plasma is so far observed. The confinement time of the electron plasma is inferred to be the order of 1 sec. A shear effect of magnetic fields results in longer confinement of the plasma. According to a simple calculation based on the generalized Bernoulli's law [1, 2], such non-neutrality of $\Delta n_e \sim 10^{12}$ m^{-3} is already enough to attain $\beta_{\text{center}} \sim 3.5$. Thus, a plan to inject a high-pressure quasi-neutral plasma to the pure electrons is now going on to explore the expected high-β equilibrium with flow.

[1] S.M. Mahajan and Z. Yoshida, Phys. Rev. Lett. **81** (1998) 4863.
[2] Z. Yoshida *et al.*, in *Proceedings of 17th IAEA Fusion Energy Conference* (IAEA), IAEA-CN-69/ICP/10 (R) (1998).
[3] Z. Yoshida *et al.*, Phys. Rev. Lett. **81** (1998) 2458.