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Steady State Formation of an Electron Plasma in a Toroidal Geometry

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Abstract

A novel system of trapping of energetic particles and/or multi-species nonneutral plasmas with different charges has been developed. The system can trap energetic electrons emitted from an electron gun, and produce a nonneutral plasma in a closed magnetic field (inside a separatrix). In contrast to neutral plasmas, a nonneutral plasma has a deep potential well due to the charge nonneutrality, which result in a formation of a strong self-electric field in the plasma. The self-electric field and an external magnetic field produce a strong $\boldsymbol{E} \times \boldsymbol{B}$ drift flow. The peak value of negative potential formed by the electron plasma is several hundred volts, thus the density of the electron plasmas is calculated to be ~10^{13} m^{-3}. Using a directional probe, both toroidal and poloidal flow measurements have been tried. This initial data shows that the flow velocity is in the range between 10^6 and 10^7 m/s, being same order of $\boldsymbol{E} \times \boldsymbol{B}$ drift flow velocity.

Keywords:

nonneutral plasma, toroidal magnetic trap, electrostatic potential, radial self-electric field, $\boldsymbol{E} \times \boldsymbol{B}$ drift flow, shear flow, toroidal equilibrium, chaos in motion

1. Introduction

There is an increasing interest in developing toroidal trap of nonneutral plasmas. In contrast to the linear traps the plasma is endless in toroidal direction, therefore, no external electrostatic potentials are required for confinement. This property allows us to confine energetic charged particles, such as antiparticles, and/or multi-species nonneutral plasmas with different charges simultaneously. Also, the toroidal nonneutral plasma has been proposed as a high-β plasma source [1].

Some experimental researches on confinement of toroidal electron plasmas using pure toroidal magnetic fields with/without the help of external electric fields have been demonstrated [2]. In a single particle picture, an electron in a toroidal magnetic field should simply be lost from the trap due to gradient and curvature drifts. However, unlike neutral plasmas, nonneutral plasmas can be confined in a toroidal geometry without the help of an externally imposed rotational transform. This is due to an $\boldsymbol{E} \times \boldsymbol{B}$ drift rotation of the particle generated by the external toroidal magnetic field, the self-electric field induced by the space charge and/or the external applied electric field, which overcomes such drifts responsible for particle loss. Although in the presence of first order guiding center drifts the $\boldsymbol{E} \times \boldsymbol{B}$ drift surfaces no longer coincide with the potential surfaces, but are still closed (in the zero inertia limit), and thus the electrons can be confined. In this case, the self-consistently generated electric field with appropriate charge density is necessary for the confinement.

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Therefore, the external electric field which can induce the $\boldsymbol{E} \times \boldsymbol{B}$ drift of the particles before the formation of nonneutral plasma should be applied in advance, and/or other methods which can inject electrons toward the trapping region, for example, 'inductive charging process' are needed to trap the electrons [2].

In our new method, in addition to a toroidal magnetic field (B_t), we can apply a poloidal magnetic field (B_p), which can also produce magnetic shear. The combination of B_p and B_t makes the orbits of electrons closed, which enables the electrons to overcome the toroidal drifts (gradient $\boldsymbol{B}$ drift and curvature drift). In a toroidal magnetic trap, particles are required to be generated outside the trapping region and propagate across the magnetic fields to be trapped. In order to cause such a cross-field diffusion, an innovative method based on chaotic collision-less scattering near magnetic null ($\boldsymbol{B} = 0$) has also been proposed in our system. In the neighborhood of the magnetic null point, the conservation of adiabatic invariants is broken. The resultant increase in the degree of freedom causes chaos of the particle motion. Therefore, it would induce a transport of particles across magnetic fields. In fact, numerical simulation shows that chaotic particles have long orbit lengths [3,4].

2. Formation of a Electron Cloud in a Toroidal Geometry

We have conducted the experiments on the Proto-RT device shown in Fig. 1. The typical base pressure is about 3×10^{-7} Torr. Particles are trapped by a static (DC) poloidal magnetic field with a separatrix (shown in Fig. 2), which is produced by the combination of an internal ring conductor and vertical field coils. We also apply a toroidal magnetic field to produce magnetic shear. The magnetic field is of order 10^{-3} T and the corresponding gyro-radius is of order 10^{-2} m. The combination of these coils provides a great flexibility to produce various magnetic field configurations such as Dipole-like configuration with/without magnetic shear and closed-field configurations with magnetic null (X point). We use an X-point magnetic field configuration (shown in Fig. 2) in this experiment. The electrons can be accelerated up to 2 keV and launched from the electron gun installed on the mid-plane ($Z = 0$) 4.5 cm inside the magnetic null point. The electrons are injected 45 degree against the mid-plane (and tangentially to the R-Z plane). The electron beam current is about 4 mA. We can produce the electron plasma steadily as long as the electron gun is turned on in DC magnetic fields.

We have measured the dependence of the floating potential (Φ_f) of a trapped plasma on the injected electron beam current (I_{beam}) (Fig. 3), and radial floating potential profiles $\Phi_f(R, Z = 0)$ using high-impedance (500 MΩ) potential probes (Fig. 4). The value of Φ_f increases monotonically until when the value of beam current reaches at ~1 mA. In this region, using $Q_{\text{total}} = I_{\text{beam}} \times \tau_{\text{trap}}$, ($Q_{\text{total}} = 8\pi^2 R \varepsilon_0 \Phi_f$; Q_{total} is the total

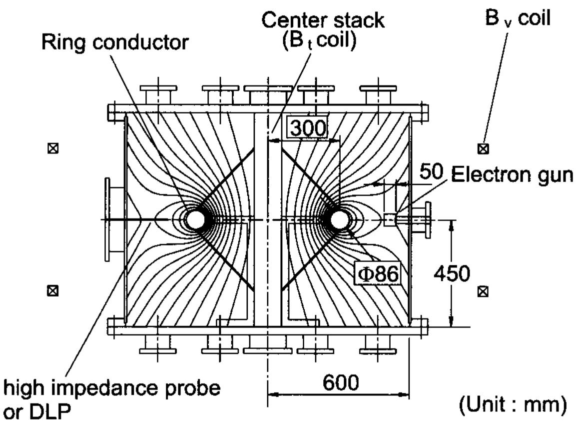

Fig. 1 Schematic diagram of experimental apparatus Proto-RT; the typical magnetic surfaces (X-point configuration) are shown in the chamber.

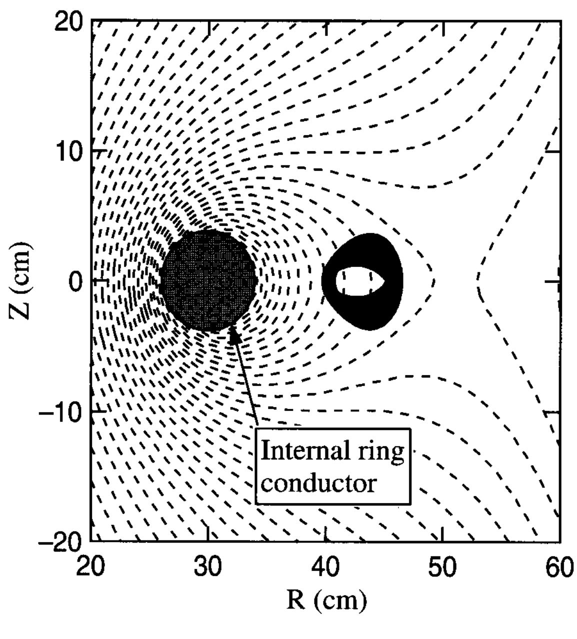

Fig. 2 Numerically calculated orbit of electron; the parameters are the same as those of the experiment.

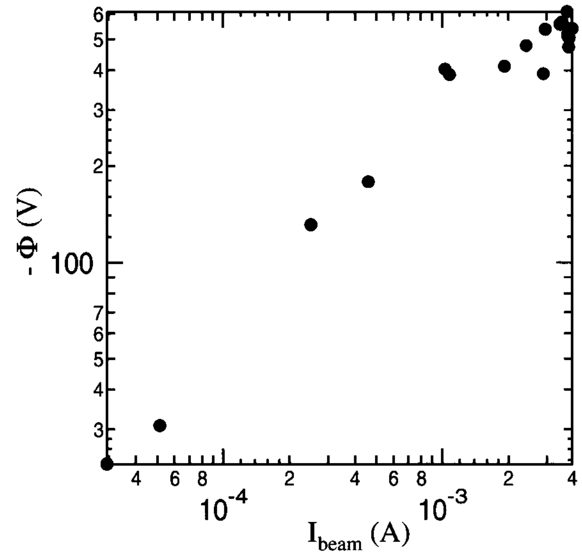

Fig. 3 Floating potential V.S. Injected beam current.

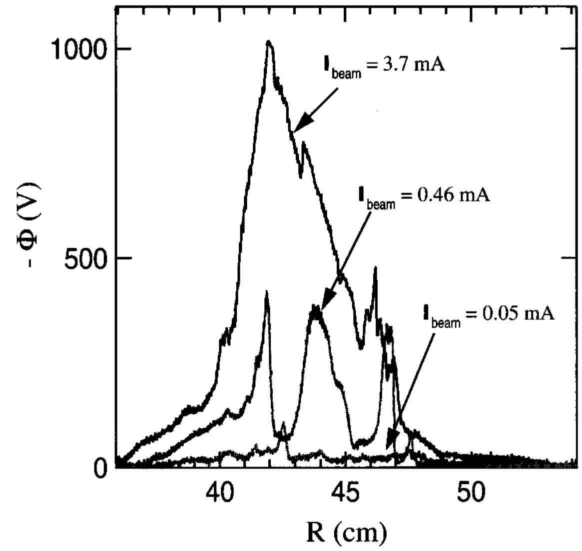

Fig. 4 Typical radial distribution of floating potential Φ_f (R, Z = 0) with respect to the injected beam current.

charge of an electron plasma, R: is major radius of a plasma), the trapping time (τ_{trap}) of a beam electron is estimated as about 100 µsec. Fig. 4 shows that the profile Φ_f become broad as the beam current increases. In Fig. 4, profiles have approximately parabolic shapes and some peaks, which imply that the plasma is consist of a bulk component with a spatially uniform density and a beam component with a high density. The maximum value of Φ_f is up to about –1000 V at R = 42 cm when I_{beam} = 3.7 mA. The relation between the floating potential Φ_f and space potential Φ_p in this electron plasma is not clear, but recent experiments indicate that the value of space potential Φ_p is of order 10^2 V [5]. Thus the inferred electron density is of order 10^{13} m^{-3}, which is approximately close to the Brillouin density limit, while the electron beam density is ~5 × 10^{13} m^{-3}.

Figure. 2 shows the numerically calculated electron beam orbit and magnetic surfaces using the present experimental parameters. In Fig. 4, the electron emitted at 4.5 cm inside the magnetic null is magnetized and has a closed orbit of 'trapped particle' inside the separatrix. Finally, the orbit is terminated at the position of the gun where the electron hits the source. In this case, we can estimate the trapping time of beam electrons (τ_{cal}) from the numerical results. The value of τ_{cal} is several microseconds, which indicate that the trapping of the electron plasma is achieved because τ_{trap} (~100 µsec) ≫ τ_{cal} (~1 µsec).

3. Flow in a Toroidal Electron Plasma

To measure the primary direction of flow in toroidal electron plasmas, a directional Langmuir probe (DLP) was applied in Proto-RT. Regarding the way to determine the flow from the probe currents, many theories and experiments of electrostatic probes have been performed on neutral plasmas for ion flow. Both parallel and perpendicular velocities of the ion flow have been estimated by a DLP or a Mach probe [6]. On the other hand, for electron flow, no sufficiently precise model has been available because of the faster thermal velocity of electrons. However, in a nonneutral plasma, a self-electric field exists which drives strong perpendicular $\boldsymbol{E} \times \boldsymbol{B}$ flow. And the faster perpendicular flow could be attained in the case where $\boldsymbol{E}$ is strong enough and the strength of $\boldsymbol{B}$ is relatively weak. In fact, recent experiments on Proto-RT showed distinct difference of the probe currents between the upstream perpendicular- and the downstream perpendicular direction [7].

The directional probe employed here consists of four cylindrical electrostatic probes. Each probe has the diameter of 0.4 mm. All tips of the DLP are approximately biased to plasma potential. In this experiment, the probe was inserted in the mid-plane (Z = 0) of Proto-RT. And, from the obtained probe current, flow velocities were calculated by the following procedure.

As the probe is almost at plasma potential the currents collected to the probe are mainly carried by free electrons. Thus, as first approximation, we estimate the flow velocity from the difference of the values between the upstream- and the downstream currents. Assuming $\delta V \sim \delta I / e\, n_e\, S$, where δI is the difference of DLP currents, n_e is the electron density and S is the area of the DLP tip, then the radial distributions of vertical (v_z) and toroidal (v_t) flow are obtained as shown in Fig. 5. On the mid-plane (Z = 0) radial $\boldsymbol{E} \times \boldsymbol{B}$ flow should be negligible due to the vertical symmetry of a toroidal plasma, then vertical flow (v_z) assumed to correspond to poloidal (azimuthal) $\boldsymbol{E} \times \boldsymbol{B}$ flow. Both toroidal and poloidal flow velocities are calculated to be of order $10^{6\text{-}7}$ m/s. It should be note that in this calculation the electron density is assumed to be $\sim 10^{13}$ m^{-3} which seems to be adequate in the Proto-RT experiments [7].

For the radial profile of Φ_f in Fig. 4 the measured toroidal flow direction at $Z = 0$ corresponds to the $-\nabla\Phi_f \times B_p$ direction, which implies that the trapped electron plasma exists outside the ring conductor (like the electron orbit plotted in Fig. 2). On the other hand, the measured poloidal flow direction does not correspond to the $-\nabla\Phi_f \times B_t$ direction exactly. This discrepancy seems to be caused by the large parallel particle flux (the beam electron velocity is about 10^7 m/s and the density is $\sim 5 \times 10^{13}$ m^{-3}) from the electron gun in a strong poloidal field region (near the ring conductor). For the toroidal flow, the magnitude of B_p is about $\sim 3 \times 10^{-3}$ T at $R = 43$ cm and the strength of the radial electric field E_r is estimated to be $\sim 3 \times 10^3$ V/m from the value of the $\nabla\Phi_p$ ($\Phi_p \sim 10^2$ V). Thus, the $\boldsymbol{E} \times \boldsymbol{B}$ flow velocity in toroidal direction is expected to be 10^6 m/s, which is comparable to the value measured by the directional probe. Also, the $\boldsymbol{E} \times \boldsymbol{B}$ flow velocity in poloidal direction is of order 10^6 m/s because B_t is of order 10^{-3} T.

Using the relation of $\Omega \sim v_t(v_z)/R_{\rm rot}$, the radial distribution of angular velocity can roughly be obtained as shown in Fig. 6. ($R_{\rm rot}$ is a distance between a center of the rotation and the probe position.) As recognized from the profiles, the velocity fields seem to have strong shear in both toroidal and poloidal directions, although more accurate measurements and analyses are required to conclude it confidently.

4. Summary

We have successfully produced a toroidal electron plasma steadily by trapping electrons emitted from an electron gun. As a result, The negative potential Φ_f is deeply formed in the Proto-RT device. The value of Φ_f is approximately monotonous increase function of the injected beam current when the beam current is small (less than ~ 1 mA). In this region, the trapping time of beam electron is estimated to be ~100 μsec. The

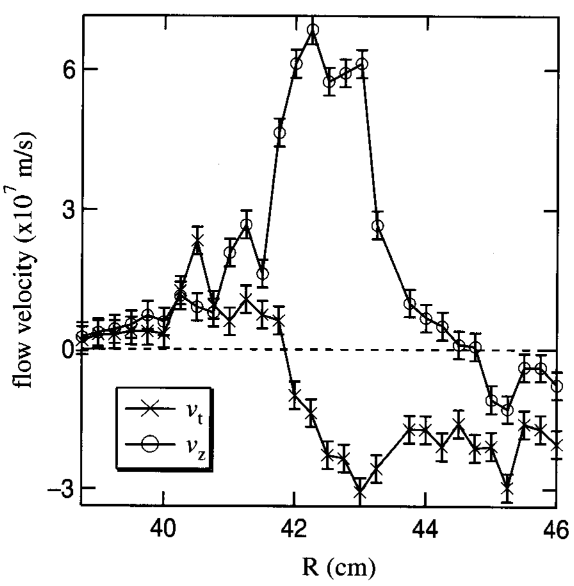

Fig. 5 Typical radial distribution of flow in a toroidal electron plasma (X-point configuration).

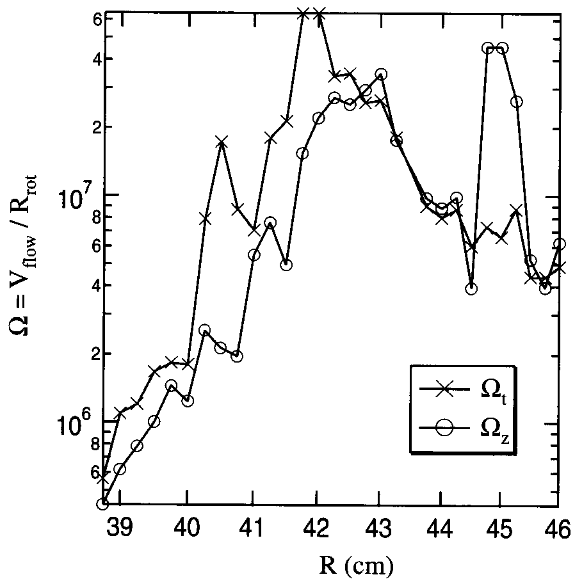

Fig. 6 Typical radial distribution of angular velocity $\Omega = V_{\rm flow}/R_{\rm rot}$ in a toroidal electron plasma (X-point configuration).

(plasma) potential reaches ~10^2 V and the correspond plasma density is ~10^{13} m^{-3} which is close to the Brillouin density limit.

To measure flow in toroidal electron plasmas, we have applied a directional Langmuir probe (DLP). In a nonneutral plasma, a self-electric field exists which drives strong perpendicular $\boldsymbol{E} \times \boldsymbol{B}$ flow. Using the DLP, toroidal and poloidal flow measurements have been tried. An initial data shows that the flow velocity is in the range between 10^6 and 10^7 m/s, which seems to be consistent with $\boldsymbol{E} \times \boldsymbol{B}$ drift flow velocity. From the roughly calculated radial distribution of angular velocity the velocity fields seem to have strong shear in both toroidal and poloidal directions. Although the data show the existence of equilibrium flow with shear, further studies are required to conclude those confidently.

Acknowledgments

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