Long Time Confinement of Toroidal Electron Plasmas in Proto-RT

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1. Introduction

Toroidal traps for non-neutral plasmas [1-5] are attracting renewed interests in spite of its long history of the study. In a toroidal geometry, we can confine multiple species of charged particles at any degree of non-neutrality, because it uses no electrostatic potential along the magnetic field lines. Confinement of pure positron or electron-positron plasmas [1,6,7], and formation of fast flow and test for the resultant high β equilibrium of two fluid plasmas [8] (Double Beltrami state) are the expected applications of toroidal non-neutral traps.

Until very recently, the experiments of torus non-neutral plasmas were carried out only in a pure toroidal magnetic field configuration. The use of another configuration will open up a new scene in the study of toroidal non-neutral plasmas. Trap of non-neutral plasmas in a magnetic surface configuration [1-3] is currently conducted or designed using stellarator [1] or internal conductor devices.

In this study, we report the experimental investigation of the confinement properties of torus electron plasmas in Proto-RT (Prototype-Ring Trap) [2,9]. The use of magnetic surface (dipole) configuration and potential optimization [11] have made possible the stabilization of diocotron instability, and long time (i.e., comparable to the diffusion time due to the neutral collisions) confinement of toroidal electron plasmas was demonstrated for the first time.

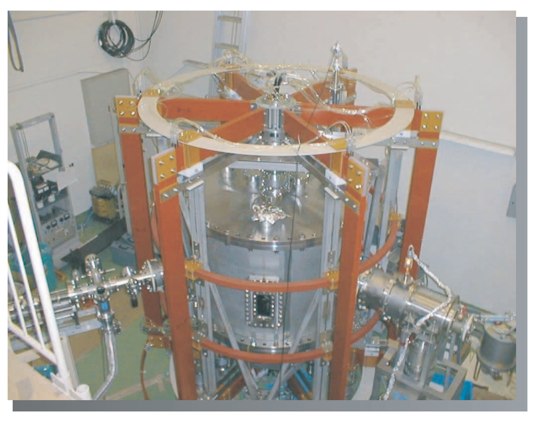

Fig.1 Outside view of Proto-RT

2. Setup and Diagnostics

Proto-RT (Prototype-Ring Trap)

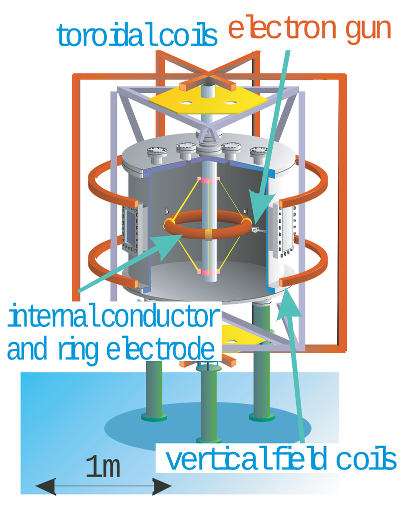

Table 1 Machine parameters of Proto-RT

Vacuum vessel	inner diameter	118cm
	height	90cm
base pressure	8 ~10^{-5}Pa (6 ~10^{-7}Torr)	
Internal conductor	major radius	30cm
	minor radius	4.3cm
(B~0.01T)	coil current	10.5kAt
Vertical field coils	major radius	90cm
	coil current	5.25kAt ~2
Toroidal field coils	center stack diameter	11.4cm
	coil current	30kAt
IC electrode	major radius	30cm
	minor radius	5cm
CS electrode	radius	9cm
	height	60cm

Proto-RT is a normal-conducting ring trap device constructed for investigating the injection and confinement of non-neutral plasmas on magnetic surfaces, relaxation states of two fluid flowing plasmas, and chaos-induced anomalous resistivity at magnetic null line. Besides toroidal field coils, Proto-RT also has an internal conductor for dipole magnetic field and a pair of vertical field coils, and the combination of these coils allows us to use a variety of magnetic field configurations. As an initial experiment, trap of electron plasmas on the magnetic surfaces of dipole magnetic field was carried out in this study.

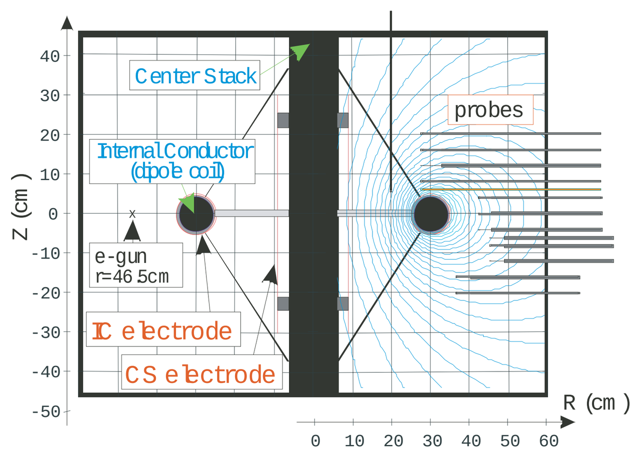

Fig.2 Bird-eye view and cross section of Proto-RT

For the optimization of the potential profiles of toroidal electron plasmas, two electrodes are installed in the confinement region of the Proto-RT vessel. In this experiment, we used a ring electrode on the dipole coil and the effects of potential biasing up to ±350V (DC, against the vessel wall) were examined, while the electrode on the center stack is shorted to the chamber.

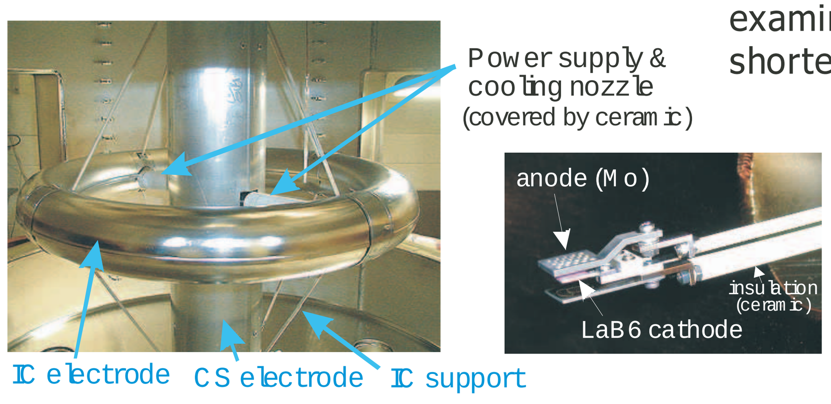

Fig.3 Inside Proto-RT: electrodes and electron gun

Electrons are injected by a LaB_6 cathode electron gun located at r=46.5cm and z=0. At an operating acceleration voltage of 300V, electron beam current obtained was in the order of 10mA. The circuit of electron gun is operated by an FET (Hitachi 2SK2393) high speed semiconductor switch (t_d ~300nsec).

Emissive Langmuir Probe - Measurement of Space Potential

Internal potential distribution is measured using an array of emissive Langmuir probes. The probe tip is a thoria-tungsten spiral filament and heated by a passage of a current. For the measurements of potential profiles, the tip is terminated across a high impedance (100MΩ) voltage probe, in order to avoid perturbations to the plasma. When compared with the I-V characteristics of emissive and cold (non-emitting) probes, measured potentials (Φ_H) are quite close to the "floating" potentials. The floating potential of the I-V curve of sufficiently heated emissive probe is close to the space potential, and thus Φ_H of emissive probe gives a good approximation of the space potential in electron plasmas.

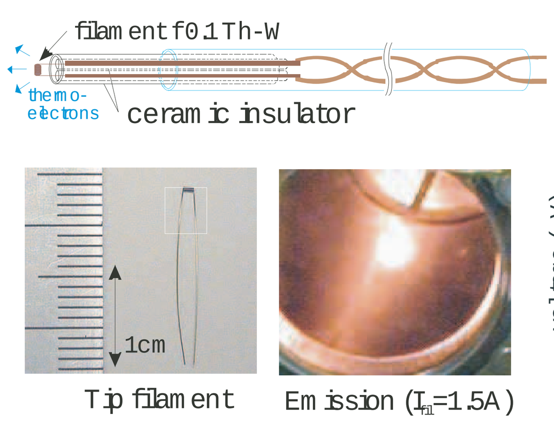

Fig.4 Emissive probe construction

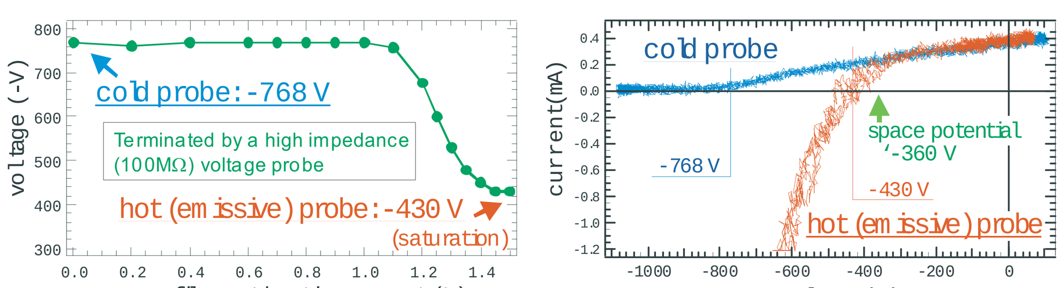

Fig.5 High impedance-emissive measurements (Φ_H) and probe characteristics

Wall Probes - Fluctuation and Confinement Time Measurements

For the measurements of electrostatic fluctuations and remaining charge of electron plasmas, we have employed a "wall probe". As a wall tip, sensor foil (copper sheet of 5×15 mm) is installed in a insulating quartz tube and located just outside the confinement region in the chamber. The foil is grounded to the chamber via a current amp, and detected image current indicates the oscillation in plasmas. By integrating the escaping image current when the plasma is externally destroyed, charge confinement time is also measured by wall probes.

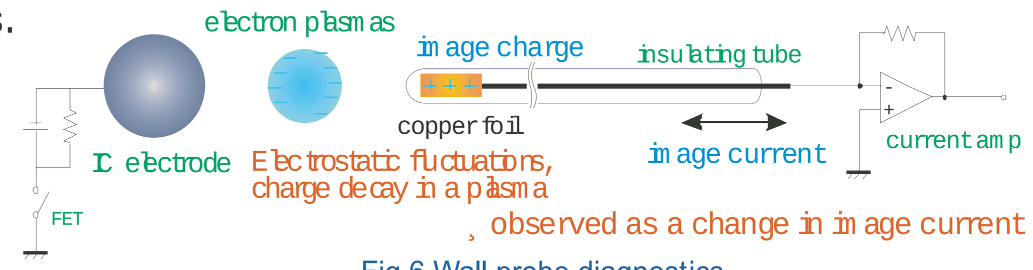

Fig.6 Wall probe diagnostics

3. Results and Discussion

Potential Control by a Biased Electrode

By applying a potential (V_{IC}) to the electrode, potential distribution was successfully modified in a toroidal electron plasmas.

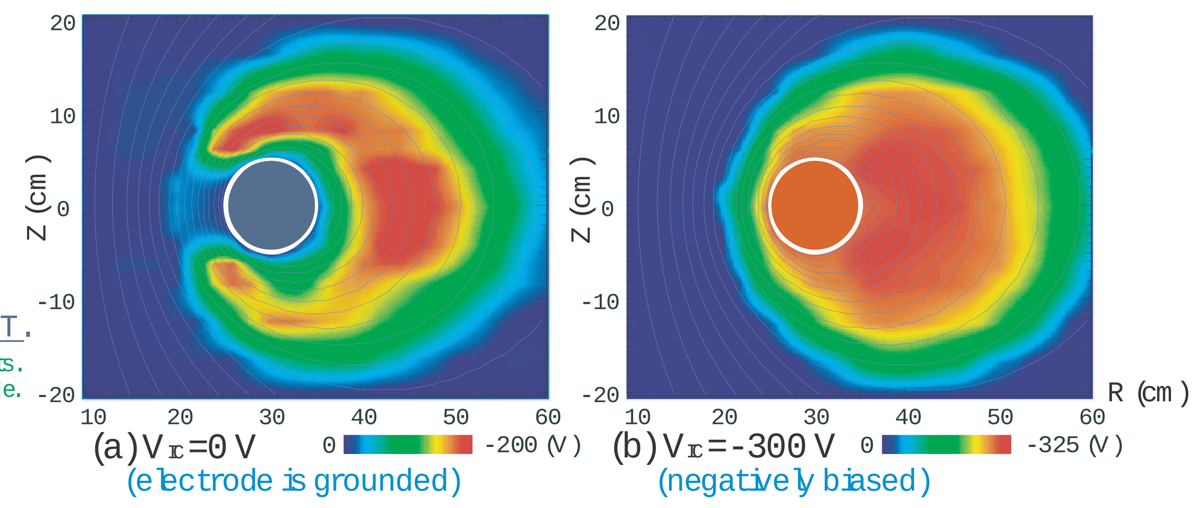

Fig.7 2-d potential contours and magnetic surfaces of dipole field in a poloidal cross section of Proto-RT.

Images are reconstructed from 284 data points. Blue and red circles show the biased electrode. Acceleration voltage of gun is V_{acc}=300V, at base pressure (6×10^{-7} Torr), typical magnetic field strength is 120G (dipole configuration).

Non-neutral plasmas in a ring trap have a hollow distribution around the internal conductor. When V_{IC} is not externally controlled (i.e., the electrode is shorted to the chamber), the potential profile is also hollow, as shown in Fig. 7 (a), resulting a strong **E×B** flow shear that may destabilize the Kelvin-Helmholtz (diocotron) instability. The potential hole is eliminated using the negatively biased electrode, and in Fig.7 (b), potential contours are surrounding the internal conductor. Fluctuations in the wall probe signal when V_{IC}=-300V reduces by a factor of 10, in comparison with when the electrode is grounded. After the stop of electron injection, long lasting oscillating signals indicating the confinement of electron plasmas were observed by controlling the bias voltage of the IC electrode.

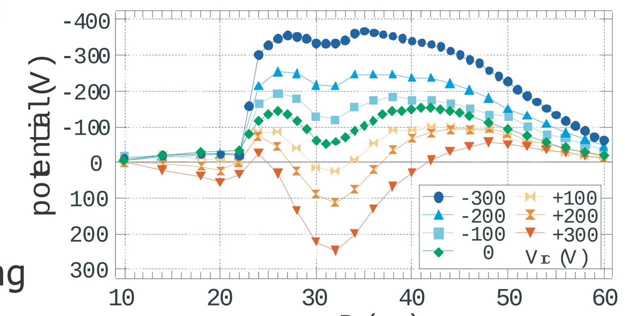

Fig.8 Radial potential profiles at z=+6cm.

V_{acc}=300V, base pressure, B_{typ} ~120G (dipole). Electrode bias (V_{IC}) was modified from -300 to +300V.

Fluctuation and Confinement Time

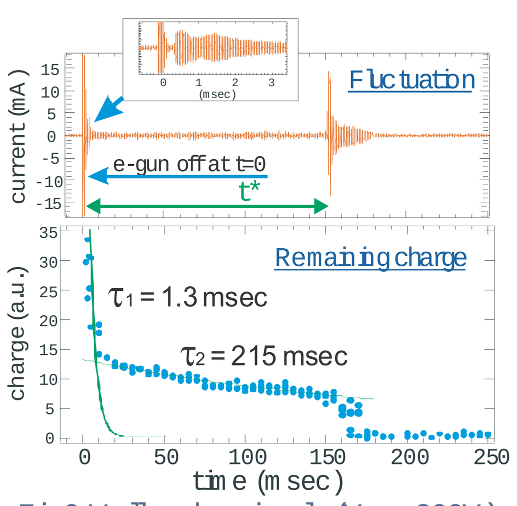

Fig.9 Wall probe signals (V_{IC}=-300V)

Electrons are injected from t=-100 to 0 μsec. V_{acc}=300V, base pressure, B_{typ}120G (dipole). Electrode bias voltage V_{IC}=-300V.

An example of fluctuation and trapped charge, when the electrode is negatively biased, is shown in Fig. 9. During the electron injection, observed dominant frequency was 510 kHz. After the stop of electron injection, both the amplitude and frequency of the oscillation damped and a quiescent state follows. The first stable phase lasts for ~0.3 msec until the fluctuation grows rapidly. The amplitude decays again, when the frequency dropped to 43 kHz. As shown in Fig. 10, the fundamental frequencies at this period (i.e., just before the second quiescent phase) are proportional to E/B. This scaling and the frequency drop during the charge decay suggest that the observed fluctuations are due to the diocotron oscillation. The second stable phase lasts relatively long (t*~100 msec) and ended by a fast growth of fluctuation (typical time constant is 100 μsec), possibly caused by the ion resonance instability.

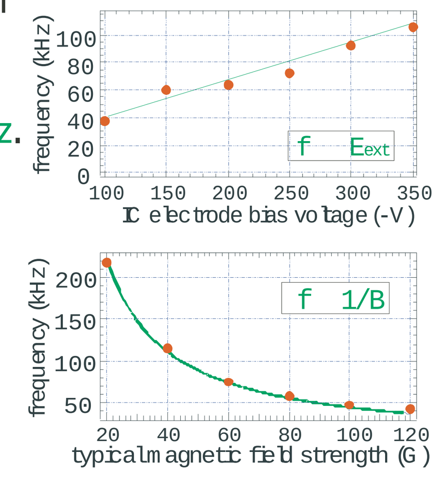

Fig.10 Fluctuation frequencies vs electric and magnetic fields.

V_{acc}=300V, base pressure, dipole field. (a) B_{typ}=60G, (b) V_{IC}=-250V.

The "life time" t* of electron cloud as a function of the background neutral gas pressure P and the magnetic field strength B is shown in Fig. 11.

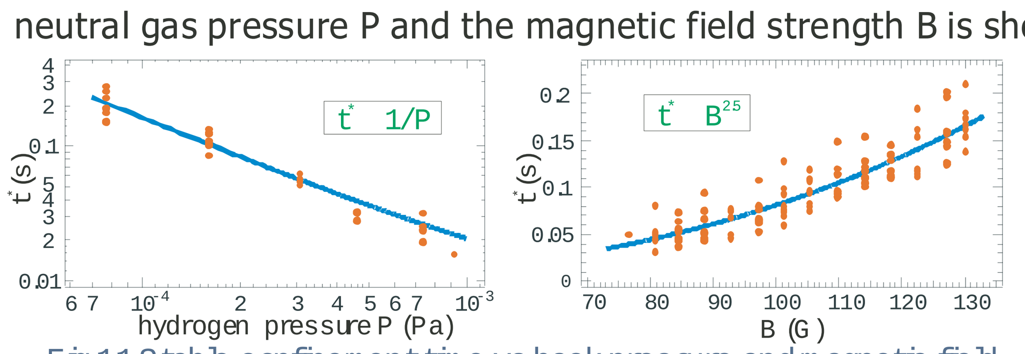

Fig.11 Stable confinement time vs back pressure and magnetic field

V_{acc}=300V, base pressure, B_{typ}=120G (dipole). Electrode bias voltage V_{IC}=-300V. Stable confinement time t* ~ $P^{-1}B^{2.5}$

Both t* and the decay time τ_2 of trapped charge are elongated by the enhancement of the strength of magnetic field and degree of the back pressure, and the life time t* is scaled as ~ $P^{-1}B^{2.5}$.

From the potential profiles in Fig. 7, number density and charge of trapped electron cloud during the injection phase are calculated to be $1\times10^{13}m^{-3}$ (at peak) and 3×10^{-7}C, by solving Poisson equation. Potential profiles after the stop of electron injection are not obtained because of the perturbation problem of Lagnmuir probes. However, judging from the frequency drop in the diocotron oscillation and also the change of image charge on the wall probe, the trapped charge in the quiet phase are estimated to be ~10^{-8}C.

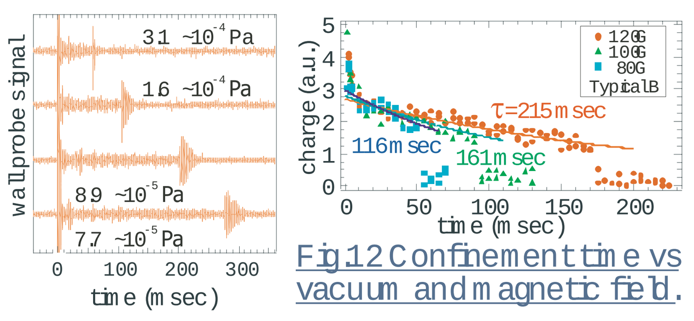

Fig.12 Confinement time vs vacuum and magnetic field.

V_{acc}=300V, electrode bias voltage is V_{IC}=-300V.

Upper Limit of the Confinement Time, Stablization by Magnetic Shear

In the relatively high base pressure (~10^{-4} Pa~10^{-6} Torr) of Proto-RT, neutral collisional effects are dominant in the diffusion process of electron plasmas. Using the experimental parameters of magnetic field strength B=0.01 T, electron number density n_e~$10^{12}m^{-3}$, and estimated electron temperature T_e~1eV (which is close to the **E×B** drift speed of electron plasmas), the classical diffusion time is τ_D~$\nu_{en}^{-1}\lambda_D^2 r_L^{-2}$~0.1sec, and both decay time τ_2 and life time t* are comparable to τ, suggesting the current confinement time is set by the diffusion due to the electron-neutral collisions. Some preliminary experiments also show that the electrostatic fluctuations during the trap phase are stabilized by the effects of magnetic shear [10].

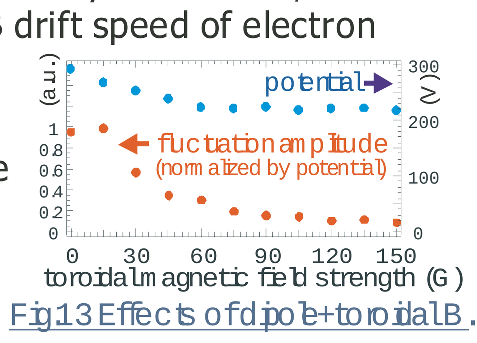

Fig.13 Effects of dipole+toroidal B.

4. Conclusion

Long-term confinement (comparable to the early liner traps) of toroidal electron plasmas was achieved in the dipole magnetic field configuration of an internal conductor device, by controlling the internal potential distribution. It is demonstrated that magnetic surface configurations have an excellent confinement property for non-neutral plasmas, and it might be useful as applications for novel traps of charged particles such as anti-matters or other multi-fluid non-neutral plasmas.

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