Long-Lived Pure Electron Plasma in Ring Trap-1

Haruhiko SAITOH, Zensho YOSHIDA, Junji MORIKAWA[1)], Sho WATANABE, Yoshihisa YANO and Junko SUZUKI

Department of Advanced Energy, University of Tokyo, Kashiwa 277-8561, Japan
[1)] *High Temperature Plasma Center, University of Tokyo, Kashiwa 277-8568, Japan*

(Received 22 August 2007 / Accepted 7 September 2007)

The Ring Trap-1 (RT-1) experiment succeeded in producing a long-lived (of the order 10^2 s), stable, non-neutral (pure electron) plasma. Electrons are confined by a magnetospheric dipole field. To eliminate a loss channel of the plasmas caused by support structures, a superconducting coil was magnetically levitated. This coil levitation drastically improved the confinement properties of the electron plasma compared to previous Prototype-Ring Trap (Proto-RT) experiments.

Keywords: non-neutral plasma, pure electron plasma, superconducting magnetospheric device, dipole field

DOI: 10.1585/pfr.2.045

A new method has been needed for confining non-neutral plasmas with arbitrary compositions of particles having different charges, particularly for the development of antimatter physics [1–4]. Conventional methods, which use electric fields that are plugged into the system are not applicable for plasmas containing both positively and negatively charged particles. In the Prototype-Ring Trap (Proto-RT) experiment [3, 4], we demonstrated stable confinement of non-neutral plasmas in a toroidal magnetic surface configuration. The observed confinement time, τ_e, was close to the classical diffusion time set by collisions of electrons with neutral atoms, and a pure electron plasma of the total number of $\sim 10^{11}$ was trapped for approximately one second. In Proto-RT, a normal-conducting coil was mechanically supported in the confinement region by thin wires. The support structure could be a serious obstacle for plasma confinement [4]. The Ring Trap-1 (RT-1) [5] is a novel device with a levitated superconducting coil that generates a magnetospheric dipole field. By eliminating the effects of a loss channel caused by the coil support structures of the coil, the levitated magnetospheric configuration realized a long-lived toroidal non-neutral plasma.

Figure 1 shows a schematic of the superconducting magnetospheric device, RT-1, whose main subject is study on the diverse phenomena of flowing plasmas [6, 7]. Electrons were injected by an electron gun with a LaB_6 cathode placed at the edge of the confinement region. The cathode was negatively biased to acceleration voltage ($-V_{acc}$) against the vacuum chamber. Electrons were injected from $t = -0.3$ to 0 s with a V_{acc} of up to 500 V and a typical beam current of 0.1 mA. The electron gun was movable in the radial direction on the mid-plane at $Z = 0$. RT-1 uses a dipole field coil made of Bi-2223 high-temperature superconducting wire, which is magnetically levitated in the chamber by a proportional-integral-derivative (PID) feedback control system. The dipole field coil was operated with a permanent current of 250 kAT, which in combination with the field generated by the levitation coil generated a spherator-type magnetic configuration. The separatrix was located at $R = 92$ cm on the mid-plane of the device.

Figure 2 shows the visualized magnetic surfaces of RT-1. These surfaces show good agreement with the calculated surface shape illustrated in Fig. 1. Electrons were injected from $R = 80$ cm and ionized hydrogen gas in the

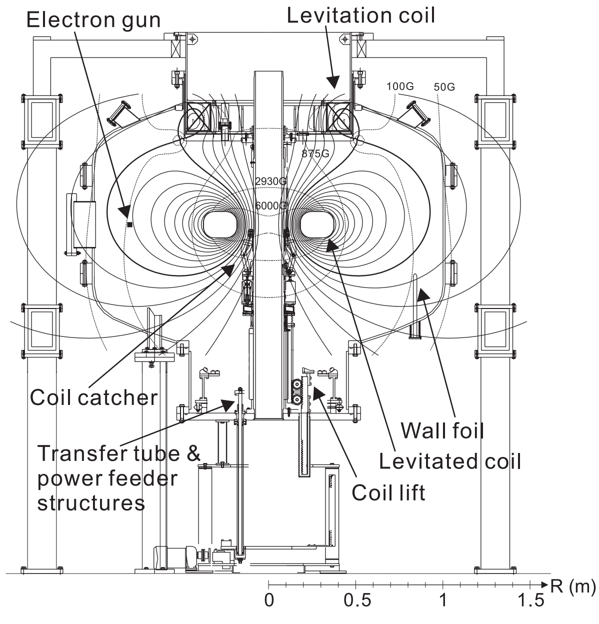

Fig. 1 Cross-sectional view of RT-1, showing magnetic flux contours and field strength. Magnetic field is generated by combination of levitated superconducting coil and levitation coil.

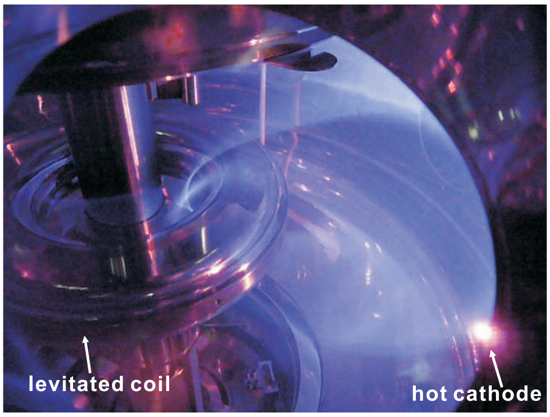

Fig. 2 Visualization of magnetic surfaces in RT-1 chamber. Electrons were injected into hydrogen gas with V_{acc} = 500 V at a pressure of 10^{-2} Pa.

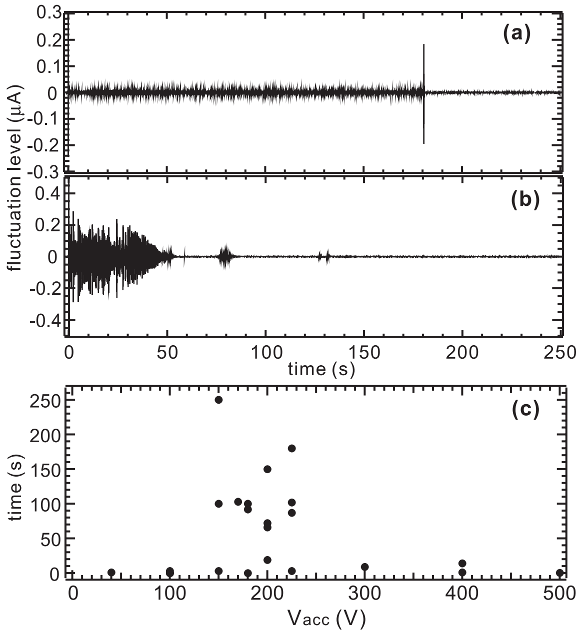

Fig. 3 Typical waveforms of electrostatic fluctuations (a) with stable oscillation and (b) with repeated growth and decay of amplitude. (c) Lifetime of plasma as function of electron acceleration voltage V_{acc}.

chamber to generate a low-density neutral plasma. In experiments where the superconducting coil was slightly levitated (~ 25 mm) and the coil support lift was placed inside the confinement region, the light emitting region was limited to the area between the hot cathode and the coil support. Removing the coil lift created a torus-shaped emitting region in the RT-1 chamber, indicating that the support structure was a critical obstacle to the electron beams.

Figure 3 shows typical electrostatic oscillation waveforms and electron plasma lifetimes. The superconducting coil was magnetically levitated, thus minimizing the loss channel caused by the support structures. Temporal evolutions of the electron plasma were measured with a wall probe. The wall tip was a cylindrical stainless steel foil, 1 cm in diameter and 20 cm in long, and was placed outside the separatrix at R = 84 cm as shown in Fig. 1. The tip was insulated from electrons by an alumina tube and grounded to the chamber through a current amplifier. The wall was capacitively coupled to the plasma, and electrostatic fluctuations of the plasma were observed as a flow of induced image charge on the wall tip. In Fig. 3 (a), a fluctuation with approximately constant amplitude was observed until a rapid growth of instability, and the resultant loss of electrons, at t = 181 s. In some cases, the oscillation signal decayed without a transition to larger amplitude fluctuations. Another typical fluctuation signal is also shown in Fig. 3 (b). In this case, the amplitude of the fluctuation signal repeatedly underwent a series of growths and decays with time constants of the order 10 s. As shown in Fig. 3 (c), the lifetime of the electron plasma peaked at $V_{\mathrm{acc}} \sim 175$ V, and order of minutes confinement of a toroidal electron plasma was realized. At higher V_{acc}, the initial large fluctuations quickly decayed without entering a quiet confinement phase. In this case, the last moment, at which the fluctuation signal was observed, was identified as the lifetime of plasmas.

During the stable confinement phase, the typical frequency of the fluctuation was 10 kHz. Assuming that the observed oscillation is a diocotron mode propagating in the toroidal direction with frequency $f_{\mathbf{E}\times\mathbf{B}}$, we can estimate the trapped charge of electrons. For a poloidal magnetic field strength of $B \sim 10^{-2}$ T at $R = 0.8$ m, the radial electric field strength at the plasma edge is $E_{\mathrm{r}} \sim 2\pi RBf_{\mathbf{E}\times\mathbf{B}} = 500$ V/m. Using a cylindrical approximation of the plasma shape, with a major radius $R = 0.8$ m and a minor radius $a = 0.25$ m, the total trapped electron number was evaluated as follows: $N \sim 4\pi^2\varepsilon_0 aRE_{\mathrm{r}}/e = 2\times10^{11}$.

This work was partially supported by the Grant-in-Aid for Scientific Research 19340170 from JSPS. The work of H.S. was supported in part by the Grant-in-Aid for Young Scientists 18740360 from JSPS.

[1] M.R. Stoneking, M.A. Growdon, M.L. Milne and R.T. Peterson, Phys. Rev. Lett. **92**, 095003 (2004).
[2] J.P. Kremer, T.S. Pedersen, R.G. Lefrancois and Q. Marksteiner, Phys. Rev. Lett. **97**, 095003 (2006).
[3] Z. Yoshida, Y. Ogawa, H. Himura *et al.*, in *Non-neutral Plasma Physics III*, AIP Conf. Proc. **498**, 397 (AIP, New York, 1999).
[4] H. Saitoh, Z. Yoshida, C. Nakashima *et al.*, Phys. Rev. Lett. **92**, 255005 (2004).
[5] Z. Yoshida, Y. Ogawa, J. Morikawa *et al.*, Plasma Fusion Res. **1**, 008 (2006).
[6] S.M. Mahajan and Z. Yoshida, Phys. Rev. Lett. **81**, 4863 (1998).
[7] Z. Yoshida and S.M. Mahajan, Phys. Rev. Lett. **88**, 095001 (2002).