High-Beta (Hot Electron) Plasma in Ring Trap 1 (RT-1)

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Abstract. The Ring Trap 1 (RT-1) experiment has succeeded to produce a magnetosphere- like high-beta (hot electron) plasma in a dipole magnetic field. Magnetic levitation of the super-conducting magnet, freeing it from mechanical supports, brought about significant improvement of plasma parameters (density, temperature, confinement time, etc.). The maximum (local) beta exceeds 0.1, which is primarily contributed by energetic (>1 keV) component of electrons ($n \sim 10^{16}\,\mathrm{m}^{-3}$) produced by ECH.

1. Introduction

Ring Trap 1 (RT-1) is a “laboratory magnetosphere” (FIG. 1) that confines plasma in a dipole magnetic field produced by a levitated super-conducting magnet. The principal mission of the project is to demonstrate very high-beta (~1) confinement [1,2], which may enable to burn advanced fusion fuels. The equilibrium state produced by the RT-1 device simulates Jupiter's magnetosphere that is known to have beta greater than unity. We may explain the mechanism of Jupiter’s plasma confinement by the hydrodynamic pressure due to a fast plasma flow (the homogeneous distribution of the total energy densities, consisting of thermal and coherent flow energies, may be viewed as a generalized Bernoulli law) [3-6]. On RT-1, we have succeeded to produce an appreciably high beta (~0.3) in a hot-electron mode of electron-cyclotron heated (ECH) plasma, which may be accounted by the Bernoulli law for the hot electrons.

The RT1 device is endowed with a super-conducting ring magnet that produces a dipole magnetic field to trap high-temperature plasma [7-9]. Figure 2 shows the geometry and dimensions of the device. The field strength in the confinement region varies from 0.3T to 0.01T. The high-Tc superconductor (Bi-2223) is first cooled down to 20K in the maintenance chamber (located at the bottom of the plasma chamber), and, then, charged to 0.25MA (the coil consists of 12 pancakes and has a total of 2160 turns) turning off a persistent current switch. After detaching the current leads and coolant (He gas) transfer tubes, the ring is moved up to the mid-plane of the plasma chamber, and is then levitated by a feedback-controlled magnet installed on the top of the device. Three-cord laser sensors measure the position of the levitated

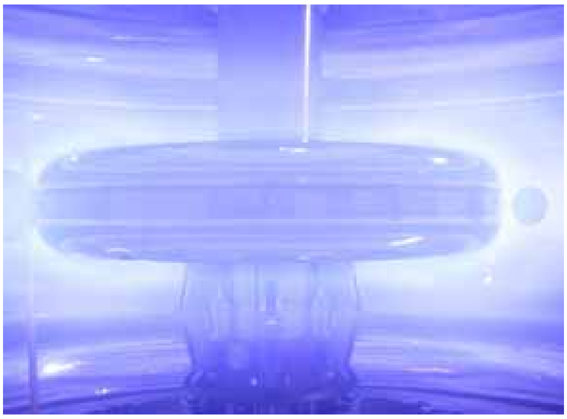

FIG.1. Magnetospheric plasma produced on the RT-1 device (viewed from a side window). A superconducting magnet is levitated in a vacuum chamber, which generates dipole magnetic field. Plasma is produced by ECH.

ring. We can continue the super-conducting operation for 7 hours before the coil temperature increases up to 30K. The current decay is less than 1% after 7 hours.

The plasma is produced by electron cyclotron resonance heating (ECH) by injecting 2.45GHz (< 20 kW) and/or 8.2 GHz (< 25 kW) microwaves. The electron cyclotron resonance occurs in a stronger field place (the resonant magnetic fields are, for 2.45GHz, B=875G, and for 8.2GHz, B=2930G), while the plasma is confined in the weaker field region (see FIG. 2).

Figure 3 shows the typical waveforms of 2.45GHz RF discharge of RT-1. Microwave was injected from t=0 to 1s. In the initial phase (t=0 ~ 0.15s), soft X-ray count and diamagnetic flux increased, while visible light emission dropped rapidly. At the same time, a small drop of the line integrated density n_l (measure by 75GHz microwave interferometry) was observed. After the termination of 2.45GHz RF, about 10% ($\sim 2\times10^{16}\mathrm{m}^{-3}$) of the density of the main discharge was sustained. The soft X-ray measurement shows that the high temperature electrons, generated by 2.45GHz ECH, survived as long as 1.4s. The decay of the diamagnetic flux signals also has a slow component.

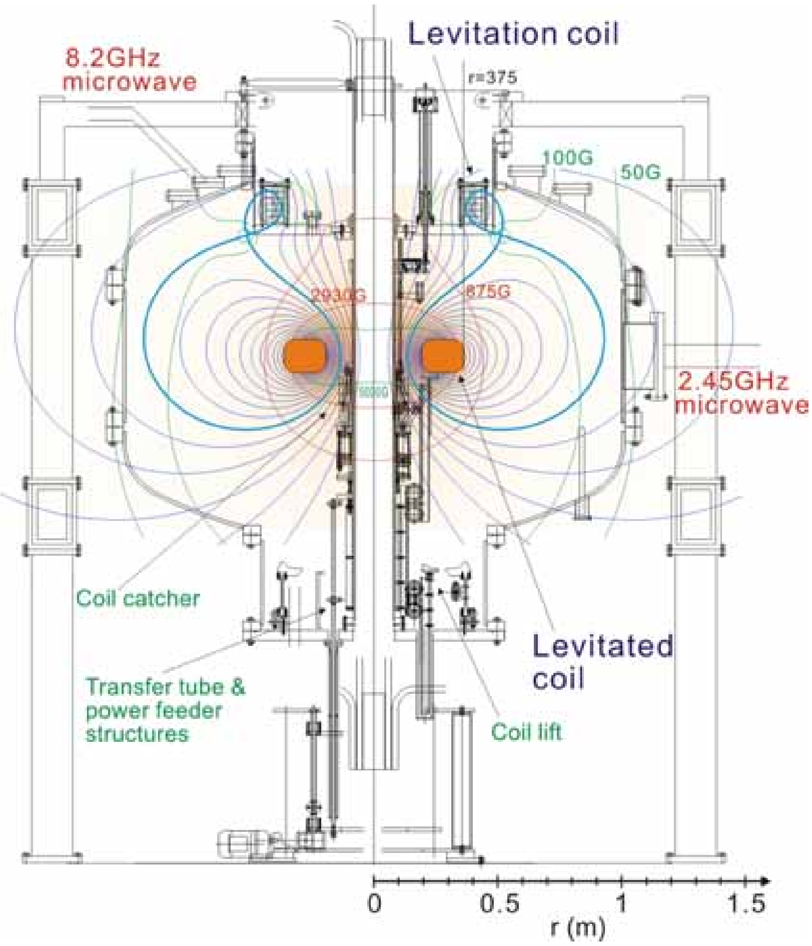

FIG. 2. The RT-1 device. A high-Tc super-conducing magnet (Bi-2223) is levitated by an external feedback-controlled magnet. The lifting magnetic field produces a separatrix in the poloidal magnetic field. The resonances of the 2.45GHz and 8.2GHz ECH occur near the internal magnet.

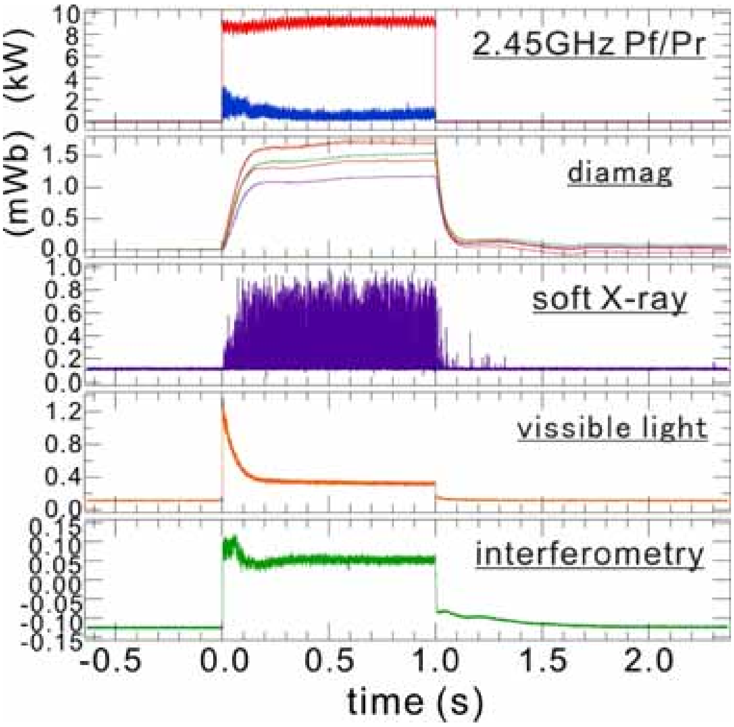

FIG. 3. Typical waveforms of (from the top to the botom) (1) injected and reflected microwave power, (2) diamagnetic signals from different loops, (3) soft X-ray, (4) visible light emission strength, and (5) interferometry fringe shift.

2. Improved Confinement with Levitated-Magnet Operation

The RT-1 device produced the first plasma in 2006 [7]. After about one year of the initial-phase operations with mechanically supported ring magnet, we started experiments with perfectly levitated magnet in 2007. By levitating the ring magnet, the plasma is freed from interactions with mechanical structures. With magnetic levitation, a separatrix is created in the poloidal magnetic field (FIG. 2). In comparison with supported-magnet operations, we observed significant improvements of various plasma parameters [10].

In FIG. 4, we compare the line-integrated density n_l, in the variation of input power of 2.45GHz ECH, for the discharges by the levitated operations (triangles) and supported operations (circles). Without the levitation, n_l saturated around the cut-off density of the RF. However, n_l increased above the cutoff density when the magnet was levitated. Assuming a parabolic distribution of the electron density profile, the peak electron density is estimated to be n_{peak}=2.0×10^{17}m^{-3} (when P_{f} =15kW), which is at least two times higher than the cut-off density. This result suggests the mode conversion of microwave into the electron Berstein wave. Indeed, on the Mini-RT experiment, we have detected the EBW by small monopole antenna inserted near the resonant point [11].

We also observe strong diamagnetism in the levitated operations. The diamagnetic loop signals are enhanced by one order of magnitude, indicating appreciably high beta values. In the next section, we describe the characteristics of high-beta hot electron mode created by ECH.

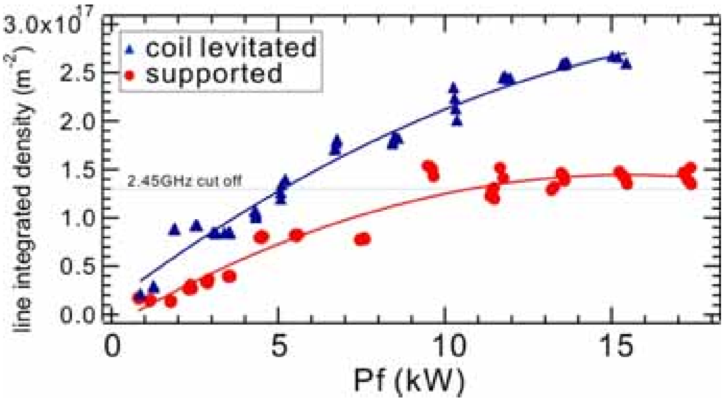

FIG. 4. Line integrated electron densities in the variation of 2.45GHz RF power. When n_e was equal to the 2.45GHz cutoff density of $7.4\times10^{16}\mathrm{m}^{-3}$ inside the separatrix, n_l was $1.3\times10^{17}\mathrm{m}^{-3}$, as noted in the figure.

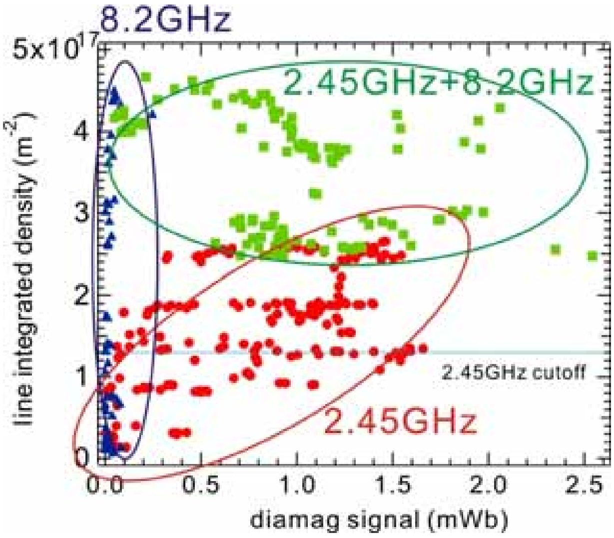

FIG. 5. Diamagnetic signals and line integrated density for the cases of RF injections of single frequency of 8.2GHz and 2.45GHz, and multiple frequencies.

3. Hot-electron High-beta Mode

By decreasing the filling gas pressure, we can produce a hot electron component that yields an appreciably high beta value (similar behavior was observed in the LDX experiment [12]). In levitated-magnet operations, the maximum (local) beta exceeds 0.3 (estimated by the diamagnetic flux compared with two-dimensional Grad-Shafranov analysis [6]).

The parameter regime (span by the densities and temperatures of the bulk and hot electron components) is appreciably extended by the combination of two different frequencies of ECH,

Figure 5 plots the diamagnetism and line-integrated density of ECH plasmas for three cases: single-frequency microwave injections with 8.2GHz (triangles) and 2.45GHz (circles), and multiple-frequency injection (squares). In comparison with the group of 8.2GHz RF discharges, those with 2.45GHz RF have much higher diamagnetic fluxes (up to around 2mWb that correspond to more than 10% of the vacuum-field fluxes). One possible reason for the advantage of the 2.45GHz RF is that the corresponding resonance layer (875G line in FIG. 2) does not interact with the internal magnet, which is not the case for the 8.2GHz RF (2930G line in FIG. 2). While the 8.2GHz RF is not effective to produce hot electrons, it helps to increase the bulk density n_e (measured by the interferometer). By the combination of two RFs, both high density and large diamagnetism can be obtained simultaneously.

By matching multiple diamagnetic signals with Grad-Shafranov equilibrium analyses, we estimate the beta value. Figure 6 plots the relation between the diamagnetic flux (given in FIG. 5) and the estimated beta value. The fitting of fluxes at five different position shows that the (hot electron) pressure has a peak near *R*=0.5m. The maximum local beta (that appears in a weaker magnetic field place near *R*=0.7) is around 0.3.

Figure 7 shows the energy spectra of soft-X ray emissions. The hot electron component, produced by 2.45GHz ECH, has a typical temperature 1~10 keV and density ~10^{16} m^{-3}, while the bulk plasma component has a density 10^{17}~$10^{18}m^{-3}$ and much lower temperatures (of order 10 eV, estimated by spectroscopy).

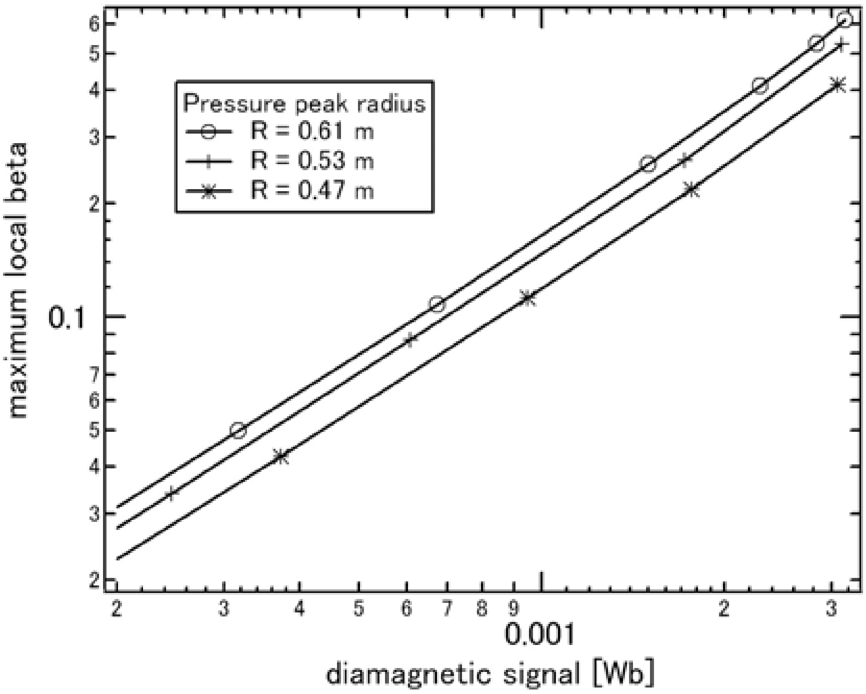

FIG. 6. Numerical estimate of the beta value as a function of the diamagnetic signal. The horizontal axis gives the diamagnetic signal corresponding to FIG. 5. Three different profiles of the hot electron pressure are compared. Fitting the equilibrium magnetic fields and the diamagnetic signals at five different places, the curve for *R*=0.47 (the position of the pressure peak) gives the best estimate.

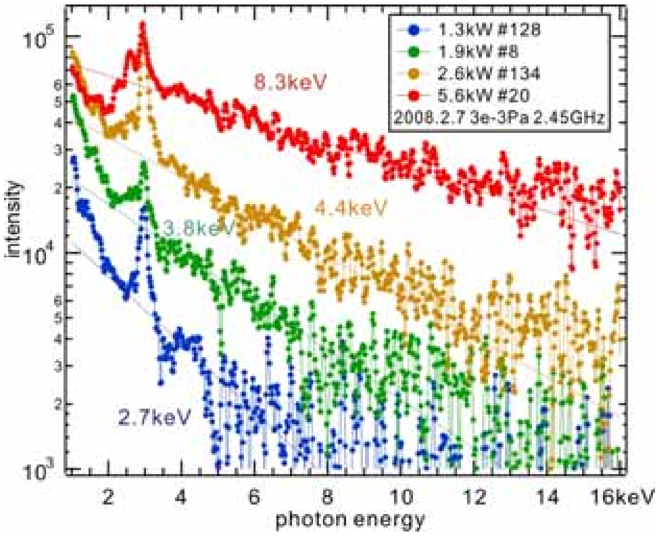

FIG. 7. Soft-X ray energy spectrum of the hot electron component (measured by Si(Li) detector pulse height analysis system). The plasma was produced by 2.45GHz ECH.

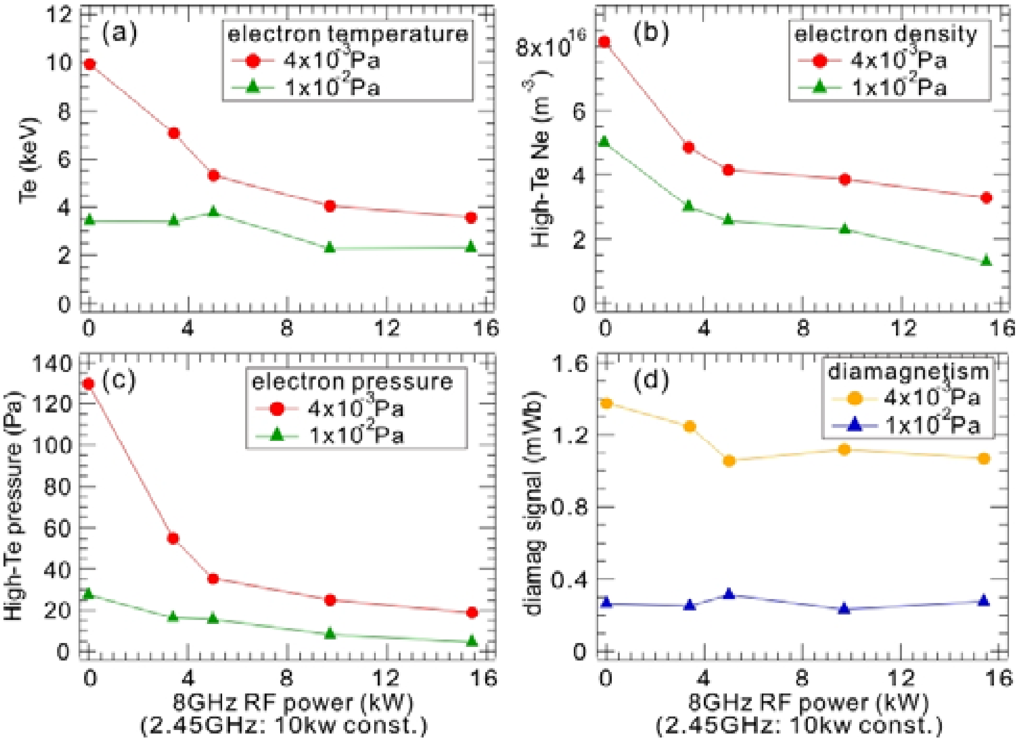

FIG. 8. Combination of 2.45GHz ECH and 8.2GHz ECH. (a) Electron temperature T_e, (b) density n_e, and (c) electron pressures $p_e=n_e k_B T_e$ of high-energy component electrons. 2.45GHz RF power was 10kW for all cases, and measurement was done for two neutral gas pressures. (d) Diamagnetic signals measured by a magnetic loop.

For the plasma with 2.45GHz ECH only, the pressure of the hot electrons accounts well for the beta value estimated by the diamagnetic measurement (see FIG. 8). However, adding the 8.2GHz ECH and increasing the bulk plasma density, the pressure due to the hot electrons underestimates the diamagnetism, suggesting that the energy of the intermediate energy electrons is increased. The energy confinement time (total stored energy / total RF power) is about 0.5ms, which is primarily dominated by the radiation from the cold bulk component.

4. Discussions

We have succeeded to produce high-beta hot-electron plasmas on the RT-1 device. Magnetic levitation of the internal superconducting magnet freed the plasma from interactions with mechanical structures, and the achievement of closed-surface magnetospheric configuration brought about significant improvement of the plasma parameters. The demonstration of the steady-state high-beta (~0.3) confinement encourages our challenge to the advanced fusion.

The high beta value is primarily due to the pressure of the hot electrons produced by ECH in a relatively low-density plasma. To heat the bulk component of the electrons, we have to increase the density. Because of relatively small magnetic field, the cut-off density is rather low for available ECH microwaves, so that the bulk plasma heating needs some innovation. In the 2.45GHz ECH plasma, we have obtained the bulk plasma density n that is about double of the cut-off density, which indicates the mode-conversion into the Electron Bernstein Wave (EBW). By the combination of 2.45GHz and 8.2GHz ECH, we can change the bulk plasma density n within the range span by the corresponding cut-off densities ($10^{17} < n < 10^{18}$ m^{-3}). At higher n, the pressure (both the temperature and the density) of the hot electrons decreases, while the diamagnetism is kept strong (FIG. 8). Further studies are needed to demonstrate high beta confinement of the bulk electrons as well as ions.

Acknowledgements
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