Improved beta (local beta > 1) and density in electron cyclotron resonance heating on the RT-1 magnetosphere plasma

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Abstract: This study reports the recent progress in improved plasma parameters of the RT-1 device. Increased input power and the optimized polarization of electron cyclotron resonance heating (ECRH) with an 8.2 GHz klystron produced a significant increase in electron beta, which is evaluated with an equilibrium analysis of Grad-Shafranov equation. The peak value of the local electron beta β_e was found to exceed 1. In the high beta and high-density regime, the density limit was observed for H, D, and He plasmas. The line average density was close to the cut off density for 8.2 GHz ECRH. The density limit exists even at the low beta region. This result indicates the density limit is caused by the cutoff density rather than by the beta limit. From the analysis of interferometer data, the uphill diffusion produces a peaked density profile beyond the cutoff density.

The ring trap 1 (RT-1) device is a "laboratory magnetosphere" created by a levitated superconducting ring magnet, which is dedicated to studying physical processes in the vicinity of a magnetic dipole. An inhomogeneous magnetic field creates interesting properties of plasmas that are degenerate in homogeneous (or zero) magnetic fields. The RT-1 experiment has demonstrated the self-organization of a plasma clump with a steep density gradient; a peaked density distribution is spontaneously created through "uphill diffusion" [1-3]. Without direct ion heating, the ions remain cold being virtually decoupled with the hot component (> 10 keV) and low density ($< 10^{18}$ m^{-3}) electrons.

For the study of two-fluid effects on the plasma flow in a high ion beta plasma, two scenarios are investigated to realize ion heating. Scenario A is an ion heating by an ion cyclotron resonance heating (ICRH). Scenario B is a collision relaxation between electrons and ions. In both cases, achieving the electron density $> 10^{18}$ m^{-3} as a target plasma is essential. The operation regime of the RT-1 device has been investigated and extended to a higher electron density and beta by an increase of the ECRH power up to ~ 50 kW with an 8.2 GHz klystron [4]. The ECRH beams from two launchers L#1 and L#2 were injected with both O-modes. The result is shown as the "conventional operation regime" (gray area) (see Fig. 1).

After an upgrade in the ECRH system, the polarizations of millimeter waves from two launchers L#1 and L#2 were changed to optimize the deposition and heating efficiency. A twisted waveguide was inserted in the transmission line to rotate the polarization direction of 90 degrees from O- to X-modes. In the case of L#1 X-mode and L#2 O-mode injections at the ECRH power of 50 kW,
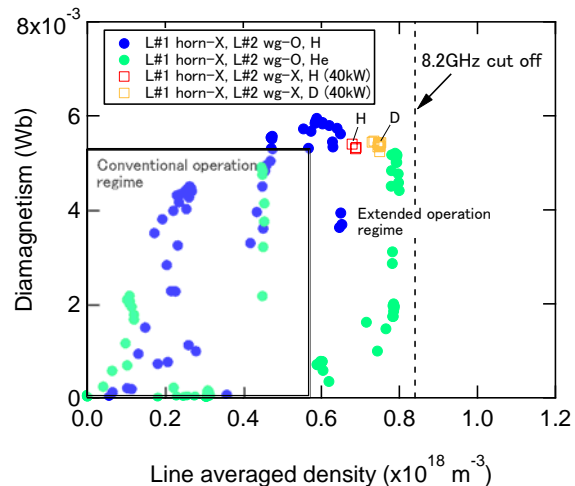

Fig.1 Extended plasma parameters for H, D, and He (W_p and $\bar{n}_e$) in the dipole configuration by the levitated superconducting coil of RT-1. The conventional (gray area) and extended operational regimes are plotted.

the diamagnetic flux W_p increases by about 10%, and the line averaged electron density $\bar{n}_e$ increases by 30%, compared with the conventional operation regime. The core chord of the interferometer reaches the maximum line averaged electron density $\bar{n}_e = 6.9 \times 10^{17}$ m^{-3} for H, 7.5×10^{17} m^{-3} for D, and 8×10^{17} m^{-3} for He. In the case of both L#1 and L#2 X-modes, the achievable density improves slightly, with no observable increase in W_p. In the high beta regime, the lower bound of β_e is estimated by fitting magnetic measurements at nine different positions and Grad-Shafranov solutions. Here the lower bound is given by the extrapolation of the linear relation $\beta_e = 18\, W_p$ that holds in the regime of $W_p < 3$ mWb. In the higher beta regime, the nonlinear effect of the self-magnetic field diminishes W_p, thus the linear relation underestimates the beta. The possible anisotropic electron pressure (due to resonance heating of the perpendicular component) also provides an underestimate of the beta in the MHD fitting [5].

At the high beta and high density regime, $\bar{n}_e$ did not exceed the cutoff density for 8.2 GHz millimeter wave. The density limit does not originate from the beta limit because the low beta and high density regime still shows the density limit. The high beta plasma in a dipole magnetic field is characterized by a strongly peaked density profile [2, 4, 6], which is explained by kinetic equilibrium theory [3, 7]. In the high density regime for $\bar{n}_e = 7.8 \times 10^{17}$ m^{-3} in the He plasma, the density profile was reconstructed in Fig. 2 from three-chord interferometer data. Even though the density limit exists in $\bar{n}_e$, the profile of electron density forms a central peaking that exceeds the cutoff density of 8.2 GHz-ECRH; hence, the peaked density ($> 10^{18}$ m^{-3}) is produced by inward diffusion.

The isotope effect of H and D plasmas was investigated at the ECRH power of 40 kW (see Fig. 1). The W_p does not show a clear difference between H and D plasmas, and $\bar{n}_e$ for the D plasma increases 8%. The isotope effect fails to show a drastic enhancement of the plasma performance in this operation regime.

In the high-density regime, the electron density fluctuation level was investigated to provide the density and beta limit. We observed fluctuations in the electron density that has a discrete spectrum of cascade modes at the frequencies less than 1 kHz. The fluctuations are spatially localized in the edge of the confinement region, and do not crush the produced plasma.
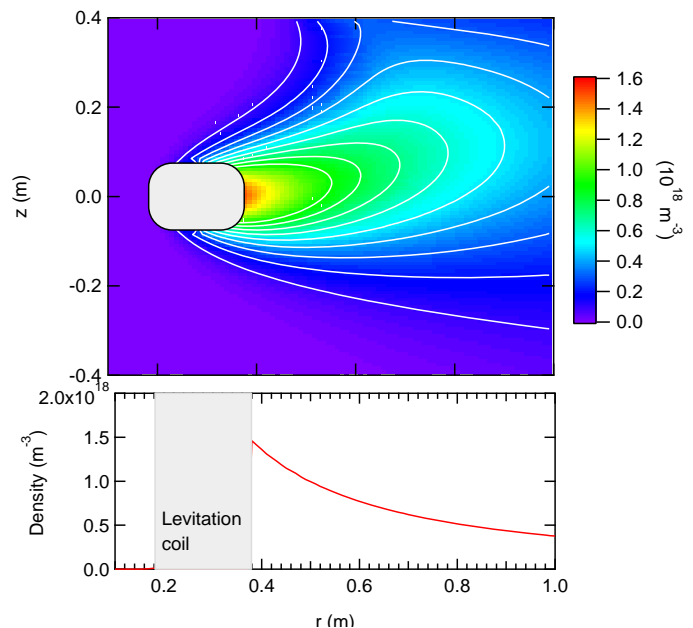

Fig.2 Radial profile of electron density in RT-1, which is reconstructed from three chord interferometer data. The lower graph shows the radial density profile at z=0.

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