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Collisionality Dependence of Electron Energy Confinement in the Mantle Region of Plasmas with the Electron Internal Transport Barrier

電子内部輸送障壁プラズマ マントル部における電子系エネルギー閉じ込めの衝突周波数依存性

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A working hypothesis that good confinement will be maintained even in high-density and/or high-collisionality plasmas around the density limit, as long as the central heating is applied, has been examined in the plasma experiment using electron cycrotron heating in LHD. As a result, this hypothesis has been proven. A weak negative collisionality dependence was also recognized. These are favorable for the helical fusion reactor that will be operated with the low collisionality plasma near the density limit sustained by the alpha heating intrinsically peaked on the plasma center.

1. Introduction

In magnetic plasma confinement experiments, regardless of tokamak or helical, degradation of the energy confinement time near the density limit has been often observed. It is also the case in the Large Helical Device (LHD). However, it has been pointed out in LHD that this confinement degradation is presumably due to the shallow penetration of heating beams in high-density plasmas [1]. In LHD, the main heating is the neutral beam injection (NBI), of which the injection direction is tangential to the plasma torus. In spite of the high beam energy reaching ~180 keV of the LHD-NBI, the heating profile becomes hollow at high-density of the order of 10^{20} m^{-3}. Then, the energy confinement time compared with the gyro-Bohm scaling becomes degraded. The energy confinement in helical plasmas including LHD shows the gyro-Bohm type parameter dependence as summarized in the International Stellarator/heliotron Scaling 1995 (ISS95) and 2004 (ISS04) [2]. Then, a working hypothesis emerges; "As long as the central heating is applied, good confinement will be maintained even in high-density plasmas".

To examine this, the plasma experiment using Electron Cyclotron Heating (ECH) has been carried out in LHD.

2. Energy Confinement in ECH Plasmas

It is possible to realize central heating in the plasma near the density limit, by setting the ECH cutoff density much higher than the density limit. In LHD, the density limit is reached when the electron density around the plasma edge exceeds a value predicted by a semi-empirical scaling called the Sudo limit, n_c^{Sudo}, given by n_c^{Sudo} (10^{19} m^{-3}) = 2.5 (P

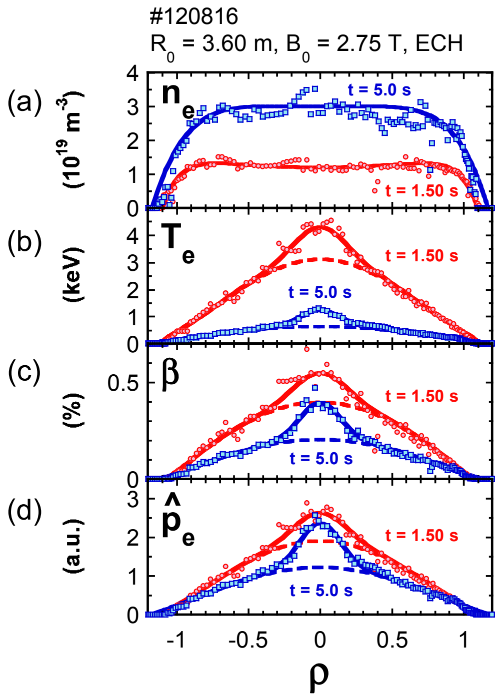

Fig. 1. Radial profiles of (a) n_e, (b) T_e, (c) β, and (d) $\hat{p}_e$, at t ~ 1.50 s (P ~ 2 MW, n_c^{Sudo} ~ 5 × 10^{19} m^{-3}) and t ~ 5.0 s (P ~ 0.3 MW, n_c^{Sudo} ~ 2 × 10^{19} m^{-3}) in an ECH discharge.

B / (a^2 R))$^{1/2}$, where P, B, a, and R are the heating power in MW, the magnetic field strength in T, the plasma minor radius in m, and the plasma major radius in m, respectively. In this study, this requirement has been realized using 154 GHz – 0.3 MW 2nd harmonic X-mode heating at B = 2.75 T. Then, n_c^{Sudo} is ~2×10^{19} m^{-3}. This is much lower than the cutoff density of ~1.5×10^{20} m^{-3} of the 154 GHz ECH. When the ECH focused on the plasma center is applied in LHD, the so-called electron Internal Transport Barrier (e-ITB) is formed and the electron temperature profile becomes sharply peaked. In other words, observation of a strongly peaked electron temperature profile with the e-ITB can be clear evidence of the central heating by ECH.

In the experiment, the plasma was generated by ECH of ~2 MW in total. Then the heating power was reduced to ~0.3 MW. In Fig. 1, typical radial profiles of (a) the electron density, $n_e(\rho)$, (b) the electron temperature, $T_e(\rho)$, (c) the plasma beta, $\beta(\rho) \equiv (2n_e(\rho)T_e(\rho))/(B^2/(2\mu_0))$, and (d) the gyro-Bohm normalized electron pressure, $\hat{p}_e(\rho) = 1.6n_e(\rho)T_e(\rho)/(P^{0.4}B^{0.8}n_e(\rho)^{0.6})$ with $P \sim 2$ MW ($t \sim 1.50$ s) and $P \sim 0.3$ MW ($t \sim 5.0$ s) are shown. In both cases, $T_e(\rho)$, $\beta(\rho)$, and $\hat{p}_e(\rho)$ are sharply peaked at the center. In LHD, the typical shape of $\hat{p}_e(\rho)$ is parabolic and can be fitted by zero-order Bessel function, as shown in Fig. 1(d). In the center region of $\rho < 0.3$, $\hat{p}_e(\rho)$ is larger than the broken curve denoting the Bessel function, $\alpha_0 J_0(2.4\rho/\alpha_1)$, fitted to $\hat{p}_e(\rho)$ at $0.6 < \rho < 1.0$. This means that the energy confinement in the central region is improved compared with the typical plasmas following the gyro-Bohm scaling. The thick curve in Fig. 1(a) denotes a fitting function of $[n_{e0}/(1 - \alpha_2)][(1 - (\rho/\alpha_1)^{\alpha 3}) - \alpha_2(1 - (\rho/\alpha_1)^2)]$, fitted to $n_e(\rho)$ at $0.6 < \rho < 1.0$. The broken curve for $T_e(\rho)$ shown in Fig. 1(b) is then given by $P^{0.4}B^{0.8}\alpha_0 J_0(2.4\rho/\alpha_1)/[1.6n_e(\rho)^{0.4}]$. As seen in the figure, this does not include the sharply peaked temperature in the core region. Hereinafter, the central value of the fitting curve for $T_e(\rho)$ is treated as the central electron temperature without e-ITB, $T_{e0\_w/o\_e\text{-}ITB}$.

From top to bottom in Fig. 2, shown are (a) $\hat{p}_{e0}$ (= $\hat{p}_e(0)$) and α_0, (b) the kinetic energy confinement time normalized by ISS95, $\tau_E^{kin}/\tau_E^{ISS95}$, or by ISS04, $\tau_E^{kin}/\tau_E^{ISS04}$, (d) the central electron temperature, T_{e0}, and the ion temperature measured by the Doppler broadening of ArXVII, $T_i^{ArXVVII}$, and $T_{e0\_w/o\_e\text{-}ITB}$, respectively. The abscissa is the collisionality defined by $\nu_{ei}/(\nu_{e,th}/R)$ (= $\nu_{p*} \times ι$), where ν_{ei}, $\nu_{e,th}$, ν_{p*}, and $ι$ are the electron-ion collision frequency, the electron thermal speed, the plateau collisionality, and the rotational transform, respectively. As seen in Figs.

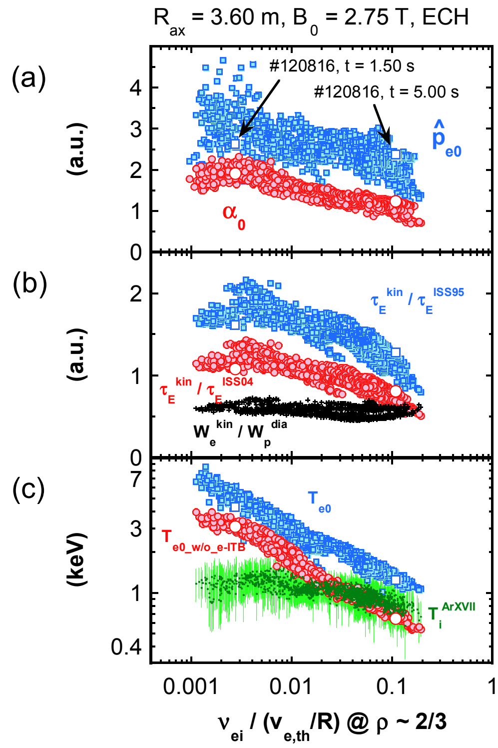

Fig. 2. Collisionality dependences of (a) $\hat{p}_{e0}$ and α_0, (b) $\tau_E^{kin}/\tau_E^{ISS95}$, $\tau_E^{kin}/\tau_E^{ISS04}$, and the ratio of the kinetic electron energy to the diamagnetic plasma energy, W_e^{kin}/W_p^{dia}, (d) T_{e0}, $T_i^{ArXVVII}$, and $T_{e0\_w/o\_e\text{-}ITB}$.

2(a) and 2(c), the central values of $\hat{p}_{e0}$ and T_{e0} are larger than those without e-ITB of α_0 and $T_{e0\_w/o\_e\text{-}ITB}$, respectively, even at high-collisionality including the cases near the density limit as was shown in Fig. 1 (t ~ 5.0 s). At the same time, the energy confinement time is larger than the ISS95 prediction (Fig. 2(b)). It should be noted that both $\tau_E^{kin}/\tau_E^{ISS95}$ and $\tau_E^{kin}/\tau_E^{ISS04}$ gradualy decreases as the collisionality increases. A change of collisionality of the two orders of magnitude leads to a change of a factor ~2 in confinement. This was already pointed out in [2]. This is a good news for the helical fusion reactor [1] that will be operated at low collisionality of ($\nu_{ei}/(\nu_{e,th}/R)$ at $\rho \sim 2/3$) ~ $\nu_{p*\_2/3} \sim 0.01$.

3. Conclusion

As long as the central heating is applied, good confinement comparable to, or better than the conventional energy confinement scalings together with the core confinement improvement with e-ITB can be maintained even in the plasmas of $\nu_{p*} \sim 0.1$.

The energy confinement time gradually increases as the collisionality decreases. This is favorable for the helical fusion reactor designed at $\nu_{p*\_2/3} \sim 0.01$.

References

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[2] H. Yamada et al.: Nucl. Fusion **45** (2005) 1684.