First observation of an electron internal transport barrier in Heliotron J

N. Kenmochi[1, 2], T. Minami[3], C. Takahashi[3], S. Tei[1], K. Nishioka[1], T. Mizuuchi[3], S. Kobayashi[3], K. Nagasaki[3], Y. Nakamura[1], H. Okada[3], S. Kado[3], S. Yamamoto[3], S. Ohshima[3], S. Konoshima[3], G. M. Weir[3], Y. Otani[1], F. Sano[3].

[1] *Graduate School of Energy Science, Kyoto University, Gokasho, Uji, Japan*

[2] *Research Fellow of Japan Society for the Promotion of Science*

[3] *Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Japan*

Introduction

Electron Internal Transport Barrier (ITB) formation is reported in many helical devices from the viewpoint of Core Electron-Root Confinement (CERC), which is characterized by highly peaked electron temperature profiles together with large positive ambipolar radial electric fields (neoclassically defined as the electron-root solution) [1]. In Heliotron J, an ITB with a peaked electron temperature profile caused by improved thermal transport has recently been observed with on-axis Electron Cyclotron Heating (ECH).

This paper is the first report on the characteristics of the observed ITB plasma in Heliotron J. The experimental transport analysis and a comparison with neoclassical calculations are carried out, and the results are discussed.

Experimental Setup

Heliotron J is a medium-sized helical-axis heliotron device (the averaged plasma major radius is R = 1.2 m, the averaged minor radius is a = 0.17 m, the averaged magnetic field strength at the magnetic axis is B_{ax} = 1.35 T) with an L/M = 1/4 helical coil, where L is the pole number and M is the pitch number of the helical coil [2, 3]. Figure 1(a) shows the time evolution of plasma parameters, the line averaged electron density, $\overline{n_e}$, and the plasma stored energy, W_p^{dia}, with ECH injection power, P_{ECH}. The second-harmonic 70 GHz ECH beam with the extraordinary mode is perpendicularly injected and focused on the magnetic axis. The field strength is adjusted to the resonance condition of the microwaves at the focused magnetic axis. In this experiment, P_{ECH} is controlled to be gradually reduced from 330 kW to 120 kW after t = 210 ms. The line averaged electron density is kept approximately constant and equal to $\overline{n_e} \sim 1.0 \times 10^{19}$ m^{-3}. The stored energy slightly decreases with reduced P_{ECH}.

Experimental Results

Figures 1(b) and 1(c) show typical electron temperature (T_e) and density (n_e) profiles respectively for two heating powers, P_{ECH} ~ 240 kW and 175 kW. Here, the T_e and n_e profiles are measured using a Nd:YAG Thomson scattering system (YAG-TS)[4, 5]. Reduction of P_{ECH} causes decreased T_e gradient in the core region (r/a < 0.3), while $T_e(r/a)$ in the outer region (r/a > 0.3) is almost the same between the two heating powers. The maximum value of $T_e(0)$ reaches 1.5 keV with a steep gradient of 30 keVm^{-1} at r/a = 0.2.

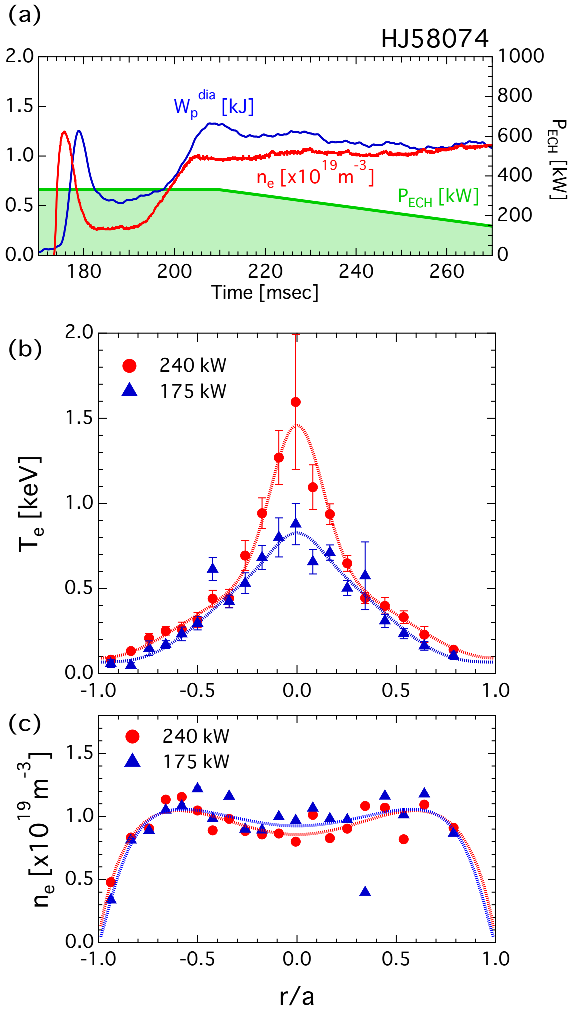

Figure 1. (a) Time evolution of the plasma stored energy, line averaged electron density and injection power of ECH. Profiles of (b)T_e and (c)n_e with ECH (injection power: 175 kW and 240 kW).

Heat Transport Analysis using Experiential Results

The effective electron thermal diffusivity profiles ($\chi_e^{eff} = (Q_{ECH}/n_e)/\nabla T_e$) are evaluated by using $T_e(r/a)$, $n_e(r/a)$ and the single-pass ECH deposition profiles (Q_{ECH}) for the cases of P_{ECH} ~ 240 kW and 175 kW (Fig. 2). Here, Q_{ECH} is calculated using the TRAVIS ray tracing code [6, 7]. In this estimation of χ_e^{eff}, we neglect the electron-ion energy transfer and impurity radiation losses, whose contributions are negligible especially in the core region. The uncertainty in χ_e^{eff} comes from that in the T_e and n_e profile measurements. For the low injection power of 175 kW, the χ_e^{eff} is approximately constant in the whole confinement region, which reflects the constant T_e gradient of entire region. For the 240 kW case, the χ_e^{eff} decreases significantly from 10 m^2/s to 4 m^2/s between r/a = 0.4 and r/a = 0.2; however, the χ_e^{eff} is higher in the outer region of the plasma (r/a > 0.3) than at the lower power. This is come from that, the shape of T_e profile does not change relating to profile stiffness, despite the large difference of P_{ECH} (240 kW and 175 kW). In the core region (r/a < 0.3), the large increase of T_e gradient indicates a reduction of χ_e^{eff} to the lower level than that for the case of P_{ECH} ~ 175 kW.

The transport analysis shows the clear reduction of χ_e^{eff} for r/a < 0.3 in the highly peaked T_e-profile case, which suggests improved confinement in the core region.

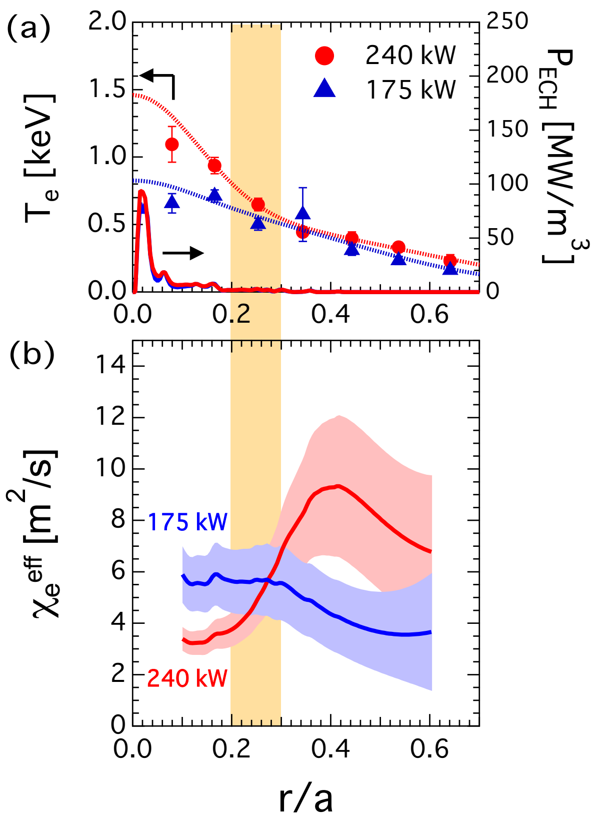

Figure 2. Radial profiles of (a) the T_e, ECH deposition and (b) the electron thermal diffusivity, χ_e^{eff}, for the plasmas with and without electron ITB.

Comparison with Neoclassical Theory

A neoclassical (NC) calculation using the DKES code [8, 9] with the measured n_e and T_e profiles is carried out for the plasma shown in Fig. 1 to compare the experimental results to NC theory. Figures 3(b) and 3(c) show the theoretically expected ambipolar radial electric field, E_r, and the neoclassical prediction of the electron thermal diffusivity (χ_e^{NC}), respectively. For both ITB and non-ITB plasmas within r/a ~ 0.3, only the electron root (large positive E_r) is predicted, while electron and ion roots are predicted to coexist in the outer region (0.3 < r/a < 0.6). This discussion focuses on the core region where only the electron root is expected, while experimental measurements of E_r is required to determine which root is realized in the outer region. At r/a ~ 0.2, a strong positive E_r (12 kV/m) is expected with the ITB plasma while the value of E_r reduces to almost half its value for the non-ITB plasma as shown in Fig. 3(b). The E_r shear also increases around the plasma center (0.2 < r/a < 0.3) for the plasma with ITB, which could suppress fluctuation leading to the reduction of anomalous transport.

Within r/a < 0.3, the predicted values of χ_e^{NC} for the ITB plasma and the non-ITB plasma are almost the same and much smaller than the values of χ_e^{eff}. In addition, the difference of the χ_e^{eff} between the ITB and non-ITB plasma is much larger than that of χ_e^{NC}. Since the experimentally obtained χ_e^{eff} contains both neoclassical and anomalous transport effects, the difference in χ_e^{eff} is attributed to a reduction of anomalous transport in the core region with ITB formation.

Summary

In Heliotron J, an ITB caused by improved thermal transport in the core region was observed with centrally focused ECH microwaves injected into plasma for the first time. The T_e exceeds 1.5 keV in the core region, and the heat transport analysis shows significant improvement of the effective electron thermal diffusivity χ_e^{eff} in plasma with an ITB over that without the ITB. The DKES calculation predicts that a large positive E_r is formed in the core region, although a transition from ion- to electron- root has not yet been experimentally observed and verification will be required. The expected E_r profile should have a strong E_r shear around $r/a \sim 0.3$, which can lead to suppressed anomalous thermal transport and improved confinement.

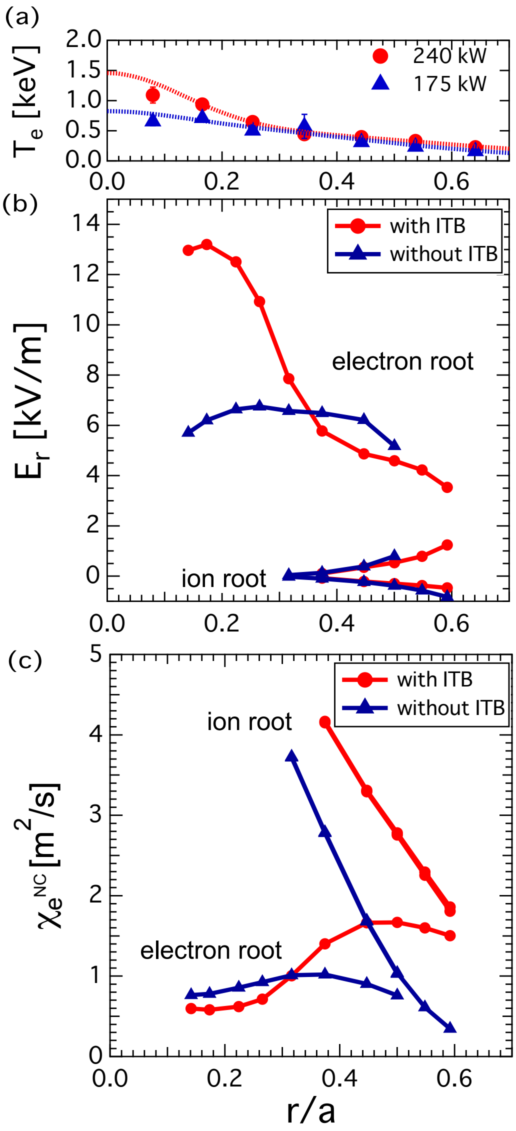

Figure 3. Results of the neoclassical calculation using the DKES code for the plasmas with and without ITB formation. (a) Radial profiles of (a) the T_e, (b) electric-field, and (c) electron thermal-diffusivity profiles.

Acknowledgments

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