Regime of Electron Internal Transport Barrier in High-Density NBI Heated Plasmas of Heliotron J

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Here, we report on the first observation of electron internal transport barrier (e-ITB) formation in the high-density plasmas heated only by NBI in Heliotron J [1]. The high-density ($n_e \sim 8\times10^{19}$ m^{-3}) e-ITB plasma is produced by introducing high-intense gas puffing (HIGP) at the magnetic field strength $B >$ 1.2 T and by controlling the plasma current using balanced NB. Under the condition, a steep T_e gradient at the core region and a peripheral steep n_e gradients are observed at the same time, resulting a simultaneous improvement in the core electron heat transport and global energy confinement exceeding the ISS04 scaling. The operational regime of the high-density e-ITB plasmas is 50 times higher normalized collisionality (plateau regime) than that of conventional e-ITB ($1/\nu$ regime) observed in low-density and high-power ECH plasmas. A different ITB formation mechanism to that of the conventional e-ITB case is expected because (1) dynamics of the high-density e-ITB formation has a time scale of the energy confinement time and (2) negative radial electric field E_r is predicted by a neoclassical (NC) transport calculation.

The plasma operation for the conventional e-ITB formation in Heliotron devices has been limited by the electron density and the ECH power, because it is strongly connected to the transition to Core Electron-Root Confinement (CERC) with a positive NC radial electric field. Moreover, since it has been widely observed that the foot-point of the ITB has been related to the rational surface in Heliotron configuration as well as in Tokamak, control of the rotational transform is essential for better control of ITB formation in low magnetic shear devices. Therefore, the development of the operational scenarios for the high-density ITB formation is indispensable to realizing Heliotron-type reactor.

In this study, we carried out e-ITB plasma discharge experiments in the standard configuration of Heliotron J by changing the magnetic field strength from B = 0.8 to 1.4 T to find the operational regime of the e-ITB formation. As shown in Fig. 1, the plasma was heated only by balanced NB (co-NB: 0.3MW, ctr-NB: 0.3MW) with assistance of the pre-ionization using 2.45 GHz microwave [2]. A high-density plasma with the line-averaged electron density $\bar{n}_e \sim 7\times10^{19}$ m^{-3} was achieved by HIGP with pulse timing of t = 230-245 ms. As a result, the reduction in hydrogen recycling was observed by the H_α measurement, which contributed to controlling the charge exchange and radiation loss. The plasma current was almost

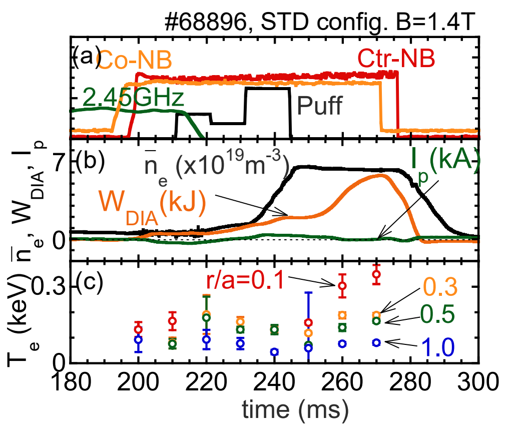

Fig. 1. Time evolution of heating, fueling and plasma parameters obtained in high-density e-ITB plasmas.

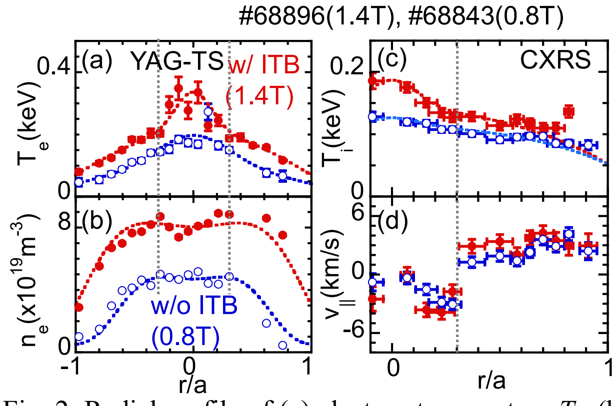

Fig. 2. Radial profile of (a) electron temperature T_e, (b) electron density n_e obtained by YAG-TS and (c) carbon ion temperature T_i and (d) flow velocity parallel to magnetic field line $v_{\parallel}$ measured by CXRS.

zero due to the balanced NB injection. The time evolution of the T_e profile represents a dynamic change of the T_e gradient during the recovery phase after HIGP has a time scale of the energy confinement time (~10 ms). Finally, the formation of ITB with a steep T_e gradient was seen at $t = 260$ ms. This experimental observation indicates that the dynamics of the high-density e-ITB formation differ from that of the conventional e-ITB formation which is characterized by the CERC transition represented by a fast change from negative (ion-root) E_r to positive (electron-root) E_r.

Figure 2 shows a comparison of the electron density, electron and ion temperature, and flow velocity profiles between $B = 1.4$ and 0.8 T cases. In the case at $B = 1.4$ T, radial profile of T_e with e-ITB had a foot-point of r/a around 0.3, while almost the flat n_e profile with a maximum n_e of 8×10^{19} m^{-3} was observed. Note that the steep n_e gradient at the peripheral ($r/a > 0.7$) region was formed as well as the core e-ITB. In the HIGP fueled plasma, the E_r shear in the peripheral region measured by poloidal CXRS has been a candidate of the steep n_e gradient formation [3]. Thus, the operational scenario in this study simultaneously improves the core electron heat transport and the peripheral particle transport. A steep T_i gradient was only observed at the core region of $B = 1.4$ T case. The parallel flow velocity $v_{\|}$ shown in Fig. 2(d) had a shear at the ITB foot-point. In the case of the no-ITB plasmas at $B = 0.8$ T, on the other hand, no clear steep gradients were observed in the T_e profile, while the flow velocity shear at $r/a = 0.3$ was observed as well as that of the ITB case. As a result, the normalized collisionality ν^* observed in the ITB plasmas is plateau regime, which is 50 times higher than that of the conventional e-ITB plasmas.

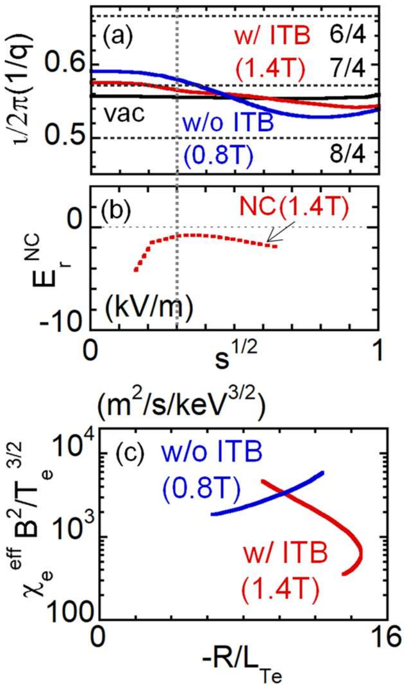

Fig. 3. Radial profile of (a) rotational transform and (b) neoclassical E_r as a function of square root of normalized toroidal flux s, and (c) $\chi_e^{eff}B^2/T_e^{3/2}$ in the radial location of $0.1 < r/a < 0.3$ as a function of R/L_{Te} for with and without ITB cases.

The equilibrium calculation by VMEC (fixed boundary condition) indicates the existence of a low-order ($m/n = 7/4$) rational surface around $r/a = 0.25$~0.35 for both cases as shown in Fig. 3(a). Then the presence of rational surface and the flow shear might not be sufficient conditions for the e-ITB formation. On the other hand, the appearance of e-ITB is dependent on the magnetic field strength. The e-ITB was observed in the range of $B > 1.2$ T. In these conditions, the density was more than 7×10^{19} m^{-3}, resulting in the beam absorption fraction around 0.6, while, in the lower magnetic field less than 1.0 T, the achieved density was less than 5×10^{19} m^{-3} and absorption fraction was 0.4 due to larger drift orbit of beam ions. Due to its high-density condition, the neoclassical E_r is predicted to be negative in the range of −1 ~ −4 kV/m both inside/outside of e-ITB (see Fig. 3(b)), which contradicts the ordinal e-ITB formation mechanism relating to the CERC transition.

The transport characteristics of the e-ITB plasma based on NB absorption analysis were investigated by comparing the gyro-Bohm scaling. Figure 3(c) shows the effective electron thermal diffusivity χ_e^{eff} normalized by the gyro-Bohm scaling factor ($T_e^{3/2}/B^2$) in the radial location $0.1 < r/a < 0.3$ as a function of the inverse scale length R/L_{Te}, where R and L_{Te} are the major radius of Heliotron J and the scale length of the T_e profile. As compared with the no-ITB case, a reduction in the normalized thermal diffusivity by 1/10 is obtained in the case with e-ITB (see Fig. 3(c)). Since the thermal diffusivity of the gyro-Bohm scaling is expected as $T^{3/2}/B^2$, χ_e^{eff} of the e-ITB case is smaller than that predicted by the T_e dependence of the gyro-Bohm scaling, which is similar to that observed in the conventional e-ITB plasmas. Note that the e-ITB plasmas have a global energy confinement time (19 ms) surpassing the empirical ISS04 scaling (15 ms), which indicates that the improvements in the core local transport and the global energy confinement were achieved simultaneously in the high-density e-ITB plasmas.

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