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Electric Field Effect on Energy Transport in Electron Cyclotron Heated NBI Plasma on CHS

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Abstract

An improvement of plasma confinement by the addition of electron cyclotron heating (P_{inj} ~ 130 kW) to neutral beam injection sustained plasmas has been observed on the CHS heliotron/torsatron device. In the core region inside $\rho = 0.5$, the temperature is increased for both electrons (2300 eV from 300 eV) and ion (400 eV from 200 eV). The change of the electric field structure by transition from ion to electron root is correlated to the improvement of the plasma performance. The condition for this phenomenon occurring depends sensitively on the plasma density.

Keywords:

electric field, E_r shear, ECH, NBI, CHS, improved confinement

1. Introduction

It is important to investigate the relation between the electric field and transport phenomena of helical plasmas in Heliotron/torsatron device. For example, an internal transport barrier (ITB) for electrons has been formed by electron cyclotron heating (ECH) (53 GHz, P_{inj} ~ 200 kW) on the Compact Helical System (CHS). In the previous experiments [1], a large E_r shear has been observed at the position of the ITB fromation. Density fluctuations are clearly reduced at the position of the E_r shear, which is confirmed by the measurement with a heavy ion beam probe (HIBP).

The electrons inside the transport barrier have a considerably high temperature ($T_e(0)$ ~ 2.3 keV), which is confirmed by the extension of the measurable temperature range of the YAG Thomson scattering system [2]. These results show importance of the electric fields on transport phenomena in helical plasmas.

The purpose of this paper is to report on the effects of electron cyclotron heating on neutral beam injection (NBI) plasma and to investigate the correlation between the electric field and transport characteristic of the helical plasma.

2. Experimental Set-Up

CHS is a Heliotron/Torsatron type device, whose magnetic structure has a periodicity of l = 2 and m = 8 respectively, and the major and averaged minor radii are 1.0 and 0.2 m respectively. This device is equipped with two NBI systems (maximum power of each NBI is ~ 1 MW) and two gyrotrons (53 GHz, 106 GHz). It is possible to investigate a wide variety of plasmas that have a wide range of plasma parameters by combining ECH and NBI for plasma heating.

In these experiments, the plasma profile is measured with CXS, HIBP, and YAG Thomson scattering systems. The ion temperature profile is measured with CXS with fully striped carbon [3]. The

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profiles of the electron temperature and the electron densities are measured with YAG Thomsonscattering system which has 24 spatial channels, and the spatial resolution is 1–2 cm at the plasma center [4]. The profile can be measured in 10 ms intervals. The amount of scattered light from low density ($< 0.8 \times 10^{13}$ cm^{-3}) plasma is too weak to get enough S/N ratio for deriving an accurate value. Therefore, we accumulate the scattering light of 5–15 shots with an identical conditions.The profiles of radial electric field are derived from plasma potential profiles measured with HIBP and from poloidal rotation velocity profile measured with CXS.

3. Experimental Results

3.1 Profiles of Electron Cyclotron Heated NBI Pasma

The introduced experiments are performed at a magnetic field strength of 0.88 T at the coil center (R = 100 cm) with a magnetic axis position of R = 92 cm. The target NBI plasma is initiated by ECH, then heated and sustained by NBI heating ($P_{inj} \sim 0.7$ MW) for t = 40–160 ms. A second pulse of the same gyrotron is superposed on the NBI plasma for purpose of the changing the plasma potential for t = 60–100 ms ($P_{inj} \sim$ 130 kW). The direction of the NBI injection is co-direction. The gyrotron frequency is 53.2 GHz, and the resonance zone is located exactly at the magnetic axis. The injected EC wave is focused by a focusing mirror. The beam waist (width is ~ 2.5 cm) is located at the resonance zone. The minor radius of CHS is ~ 20 cm. The beam path crosses the resonance zone inside ρ = 0.1. Therefore, the ECH power is only absorbed inside $\rho = 0.1$.

We compare the EC heated NBI plasma (t = 70 ms, ECH phase) with the NBI plasma after the ECH is switched off (t = 110 ms, 30 ms after ECH phase). Though we compare with the NBI phase after the ECH, the effect of ECH does not remained. That is because the time (~ 30 ms) between the ECH phase and no ECH phase is sufficiently longer than the confinement time (~ 2 ms) and the radial electric field measurements show that a transition occurred from the electron root to the ion root. A clear difference has been observed in the electron temperature profiles between both plasmas. As shown in Fig. 1(a), the electron temperature of the NBI plasma (~ 2.3 keV) in the ECH phase is considerably higher than that (~ 0.26 keV) in the no ECH phase. On the other hand, the temperature of the outer region ($\rho(r/a) > 0.5$) in the ECH phase is almost same as that in the no ECH phase. Therefore, the temperature increases only inside $\rho = 0.5$, and the shape of the electron temperature profile in ECH phase is bell like. Though the electron density is increases in the no ECH phase, this characteristic is consistent with the pressure profile for electrons, the plasma pressure increases in the central region as shown in Fig. 1(e). Therefore, these data show the possibility that the energy confinement for electrons is improved inside ρ = 0.5.

In the ECH phase, as shown in Fig. 1(g), the ion temperature is also higher than that in NBI only phase.We have observed the prominent characteristics of the ion profile; the steep increase of the ion temperature (dT_i/dr = 40 eV/cm) exists arround $\rho = 0.6$ that has not been observes in the no ECH phase. However, the ion pressure in the ECH phase is less than that in the no ECH phase, as shown in Fig. 1(i). This show that the energy confinement for ions in ECH phase is less than that in no ECH phase, because the plasma density is decreased. In no ECH phase, moreover, the plasma density is peaked, as shown in Fig. 1(e), so that the plasma confinement is improved by the high T_i mode of the helical plasma [5].

3.2 Density Dependence of Electron Cyclotron Heated NBI Plasma

The condition for these phenomena in EC heated NBI plasma has a density dependence. We compare the plasma profile in the higher density $n_e(0) \sim 0.46 \times 10^{13}$ cm^{-3} with that in the low density $n_e(0) \sim 0.35 \times 10^{13}$ cm^{-3} that is the same as the above mentioned plasma. The other plasma parameters (e.g. the magnetic field strength, the magnetic axis position, and the injected power of ECH and NBI) are the same between both plasmas. Though the difference of the density is considerably small, clear differences in the temperature have been observed.

As shown in Fig. 1(b), the central electron temperature ($T_e(0) \sim 0.9$ keV) in the high density plasma is rather smaller than that ($T_e(0) \sim 2.3$ keV) in the low density plasma. The plasma pressure of the electrons is also smaller than that in the low density plasma, as shown in Fig. 1(e)(f). Therefore, the improvement of electron confinement by ECH is small in high density plasma.Though there is a large increase of the ion temperature in the ECH phase in low density plasma, the ion temperature slightly increases from that in the no ECH phase in high density, as shown in Fig. 1(h). The ion pressure in the high density plasma is lower than

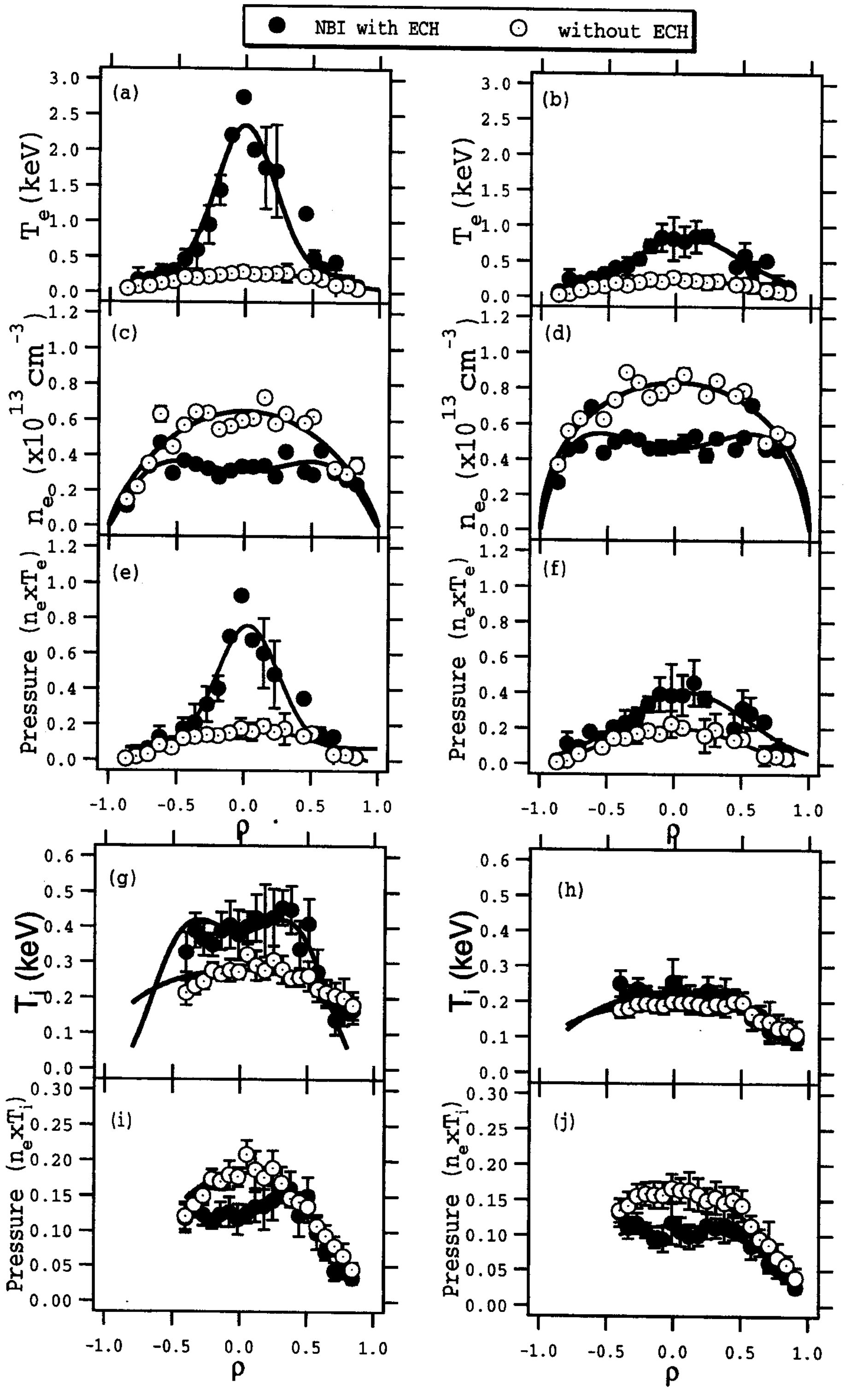

Fig. 1 Radial profiles of ECH heated NBI plasma in two different densities. (a)(c)(e)(g)(i) are $n_e(0) \sim 0.35 \times 10^{13}$ cm^{-3}. (b)(d)(f)(h)(j) are $n_e(0) \sim 0.46 \times 10^{13}$ cm^{-3}. (a)(b) are electron temperature profiles. (c)(d) are electron density profiles. (e)(f) are pressure profiles for electrons. (g)(h) are ion temperature profiles. (i)(j) are pressure profiles for ions. Closed circles denote profile in NBI with ECH. Open circle denote profile in NBI after ECH.

that in low density plasma, as shown in Fig. 1(i)(j).

In conclusion, the plasma performance in the low density plasma is better than that in the high density plasma.

4. Estimation of Confinement Time

Under the condition for the above mentioned experiments, we estimate the absorbed power by the formula from I. Fidone and G. Granata [6]. In the low density plasma with the high electron temperature, all the injected gyrotron power (P_{inj} ~ 130 kW) reaches the resonance zone and is absorbed at the plasma center. Even in the high density plasma with the low temperature, the absorption rate is more than 90%. That is because the plasma temperature (~ 0.9 keV) is somewhat lower than that (~ 2.3 keV) in low density plasma, though the density difference is small for both plasmas ($n_e(0)$ ~ 0.46 × 10^{13} cm^{-3} in the high density plasma, $n_e(0)$ ~ 0.35 × 10^{13} cm^{-3} in the low density plasma).

We calculate the NBI deposition with PROCTR-MOD [7]. In this calculation, we do not take into account orbit losses from the plasma. The calculated NBI deposited power is shown in Fig. 2(a). The total deposited power of the ECH phase is ~ 220 kW in the low density case, and ~ 280 kW in the high density case. In the no ECH phase, these are ~ 340 kW and ~ 400 kW, respectively.

The calculations of the confinement time are shown in Fig. 2(b). The results are plotted as a function of the $P^{-0.59}n^{0.51}$ dependency from the ISS95 scaling law [8]. These data show that the confinement time is improved in the ECH phase, and is more improved in the low density plasma. Therefore, additional ECH can improve the plasma performance with NBI heating in low density.

These estimations are preliminary results. For a more accurate estimation of the deposited power, it is necessary to consider the orbit losses and other factors. We plan to carry out these calculations in the future.

5. Electric Field Measurement and Discussions

We investigate the change of the electric field structure to understand the improvement in the confinement. Fig. 3(a) shows the results of E_r and E_r shear measured with HIBP and CXS in the low density plasma. The data of HIBP and CXS are denoted by the circles and the broken line, respectively. Both results have good agreement. First, in the NBI phases for both

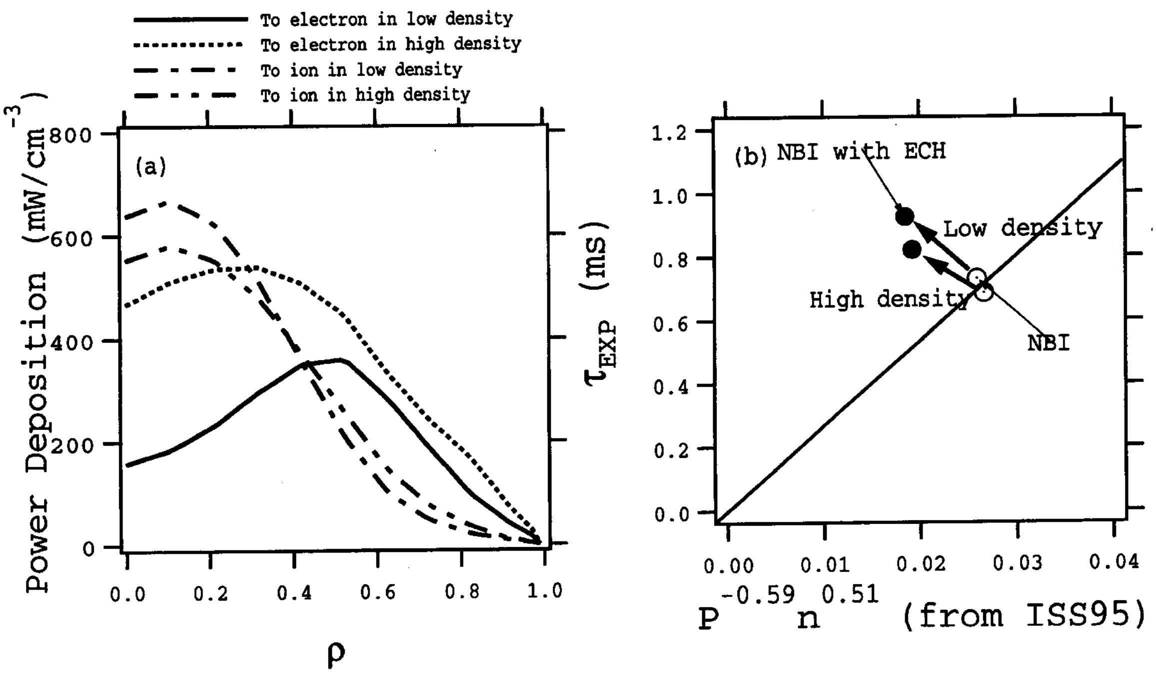

Fig. 2 (a) NBI Power deposition profile to electrons and ions that is calculated by Proctr-Mod. Calculation is done for low density plasma ($n_e(0)$ ~ 0.35 × 10^{13} cm^{-3}) and for high density plasma ($n_e(0)$ ~ 0.46 × 10^{13} cm^{-3}). (b) Confinement time v.s. ISS95 scaling low for power and density.

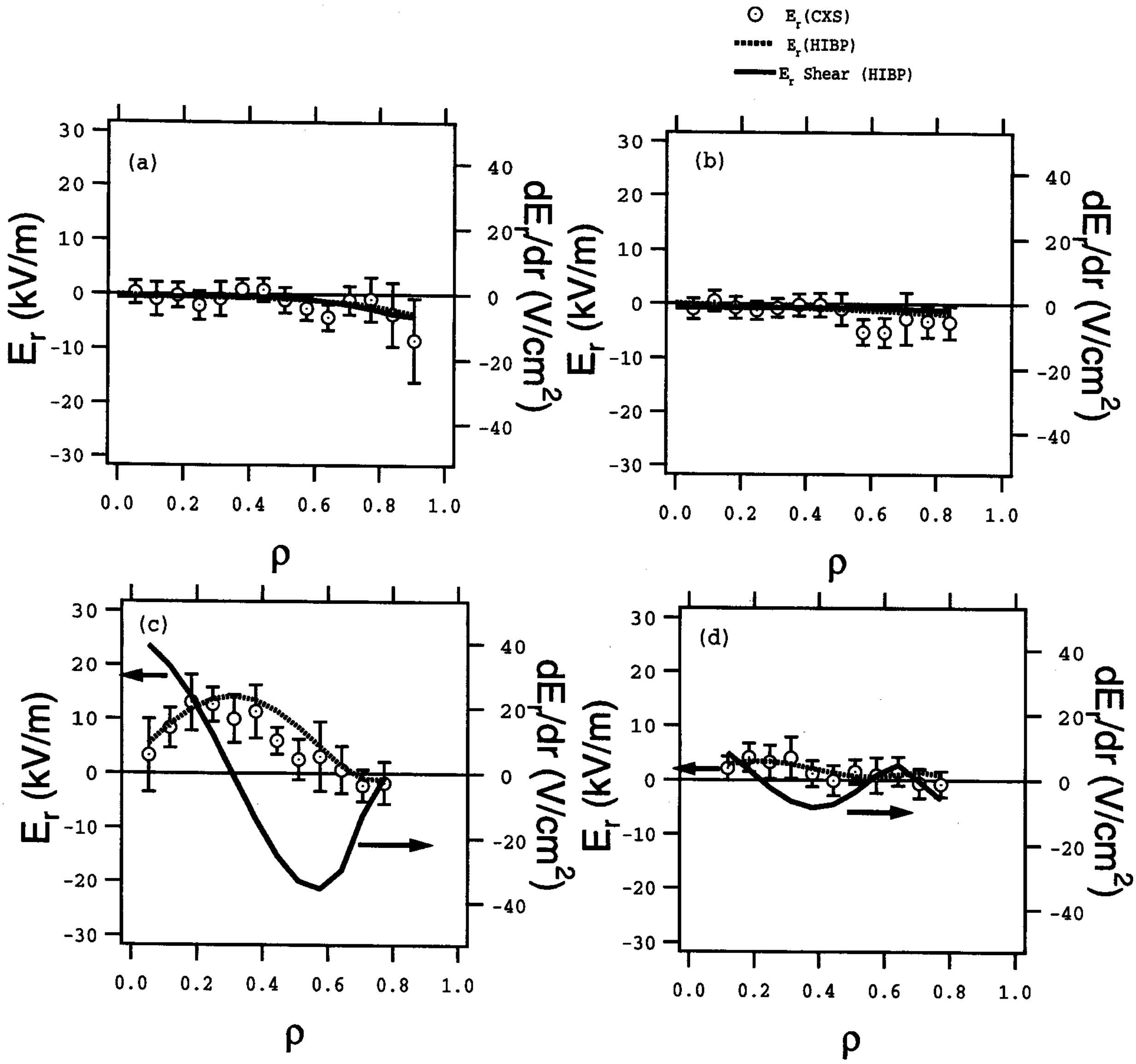

Fig. 3 Radial Electric field and shear profiles of EC heated NBI plasma in two different densities. (a)(c) is $n_e(0)$ ~ 0.35 × 10^{13} cm^{-3}. (b)(d) is $n_e(0)$ ~ 0.46 × 10^{13} cm^{-3}. (a)(b) is NBI only phase (110 ms) (c)(d) is ECH + NBI phase. Open circles and dotted lines denote electric field measured with CXS and HIBP, respectively. Lines denote the electric field shear.

high and low density plasma, the electric field and electric shear are small and negative, as shown in Fig. 3(a)(b). The plasma flows of these NBI plasmas are in the ion root. For the transition to the electron root from the ion root occur, it is necessary that the temperature be increased over the threshold value. In ECH+NBI phase, the plasma radial flow changes to the electron root inside ρ ~ 0.5 through electron heating. However, the flow outside ρ ~ 0.5 remains in the ion root. Therefore, the large electric field (~ 15 kV/m) exists around ρ ~ 0.3. We can calculate the E_r shear that is denoted by the line on the graph. In the ECH phase, there is also a large E_r shear (~ −40 V/cm^2) in the neighborhood of ρ ~ 0.5. This structure of the radial electric field caused by a transition from ion to electron root.

On the other hand, the value of the E_r (~ 5 kV/m) and the E_r shear (~ −8 V/cm^2) in the high density plasma are less than that in the low density plasma, though they are considerably larger than that in the NBI phase, as shown in Fig. 3(d). Therefore, even though the difference in the density is small for both cases, the confinement time is improved in the low density plasma. It is noted that the positive electric field is created by ECH in even high density plasma, therefore confinement is improved from the NBI phase.

We think that the reason plasma performance is improved is related to the structural change of the electric field. In the central region inside ρ = 0.5, the plasma confinement is improved by the creation of a large electric field. Moreover, from the suggestion of the previous experiments the internal transport barrier is formed at ρ = 0.5, which reduces the anomalous transport. These data show that good plasma performance is correlated to the structural change of the electric field.

In the previous experiments [9], we show that it is possible to change the electric field of the plasma by ECH injection, and the internal transport barrier is formed. We compare EC heated NBI plasma to ECH plasma with ITB. The density dependence of this experiment is similar to the ECH plasma with an ITB [2]. In the ECH plasma experiment, the phenomena have a bifurcative nature, and the threshold density is < ~ 0.4×10^{13} cm^{-3} when the injected ECH power is ~ 170 kW. In these experiments, the transition may occurr at ~ 0.4×10^{13} cm^{-3} when the injected ECH power is ~ 130 kW. This value is almost the same value as that in the ECH plasma.

On the other hand, there are two differences. (1) the ion temperature is increased by ECH in NBI plasma, because the ion heating is carried out. (2) The location of a large electron temperature gradient for the NBI plasma with ECH is ρ ~ 0.5 which is wider than the location of the ITB created (ρ ~ 0.3) in the ECH plasma. The region of improvement is larger than that in the previous ECH plasma experiments. The EC heated NBI plasma is more effective for improving confinement.

6. Conclusions

We present the EC heated NBI plasma experiments. Conclusions are as follows.

(1) We have observed a large increase of ion and electron temperature inside ρ ~ 0.5 by EC heating to NBI plasma.The shape of the plasma profile is changed only in the core region.

(2) We have also observed the creation of a large electric field in the plasma core region, and the large E_r shear also exist at ρ = 0.5.

(3) The condition for the occurence of this phenomenon depend sensitively on the plasma density.

(4) We have confirmed that additional ECH can improve the electron transport of NBI plasma. The change of the electric field structure by transition from the ion to the electron root is correlated to these phenomena.

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