21st IAEA Fusion Energy Conference
Chengdu, China, 16 - 21 October, 2006

IAEA-CN-149/ EX/P7-7

# Formation of Radial Electric Field Shear at Boundary of Magnetic Island in LHD

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NIFS-852

Oct. 2006

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**Abstract.** Active control of a radial electric field shear by a combination of pellet injection and a magnetic island induced by external perturbation coils is demonstrated in the Large Helical Device (LHD). In this experiment, the radial electric field shear at the boundary of the magnetic island reaches 0.3 MV/m$^2$ and is sustained by repetitive injection of the pellet and the improvement of ion transport is observed near the boundary of the magnetic island.

## 1. Introduction

Since the radial electric field, $E_r$, and its shear has been recognized to play an important role in the improvement of transport, the effects of the $E_r$ and its shear on the transport have been investigated in various magnetic confinement devices. Active control of the radial profile of the radial electric field is one of the important tools to investigate the effects of the $E_r$ and its shear. In low temperature plasmas, biased electrodes experiments have been performed to investigate effects of radial electric field and/or its shear on fluctuations and anomalous transport in linear devices [1-3], in torus devices [4] in order to change radial electric field actively. There is a difficulty to insert the electrode into plasmas to control the radial electric field because of the high heat flux to electrode from the plasma in high temperature plasmas. Therefore there is few biased electrodes experiment in large toroidal confinement devices where the plasma temperature is too high to insert the electrode. In tokamak plasmas, the transition of the radial electric field and the formation of radial electric field shear are observed associated with the transition from L-mode to H-mode plasma [5, 6]. In helical plasmas, the radial electric field is expected to reduce the neoclassical ripple loss in low collisional regime. The reduction of the ion thermal diffusivity due to the large positive electric field is observed associated with the transition from small $E_r$ to large positive $E_r$ in the LHD when the neoclassical ion loss is dominant loss [7]. On the other hand, the strong $E_r$ shear in the plasma with an internal transport barrier (ITB) contributes to the reduction of turbulent transport as observed in the compact helical system (CHS), Wendelstein-7AS and the LHD [8-12] by the local heating with center focused ECH. In the plasma with the internal transport barrier in the LHD, the reduction of electron thermal diffusivity is observed associated with the appearance of the $E_r$ shear near the boundary between the electron root in the core and ion root in the edge with the combination of center focused ECH and NBI. Thus, the effect of $E_r$ shear in the electron root is well investigated in helical systems related with the ITB. The effect of the $E_r$ shear in ion root on thermal diffusivity has not been much investigated. We demonstrate an active control of the radial electric field shear between large negative $E_r$ in the core and small $E_r$ in the edge in the ion root regime by a combination of pellet injection and a non-rotating magnetic island induced by external perturbation coils in LHD.

## 2. Scheme of $E_r$ Shear formation in an Ion root plasma

In general, the radial electric field determined by the neo-classical non-ambipolar ion and electron flux can be controlled by changing the magnitude of helical ripples [13] and collisionality [14] in helical plasmas. The radial electric field becomes positive (in

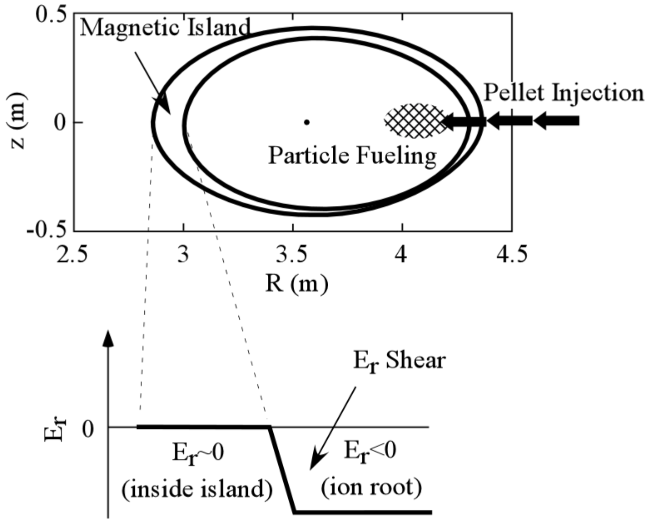


*FIG. 1. Schematic view of poloidal cross section of magnetic flux surface near the magnetic island induced by external perturbation coil and the $E_r$ profile by pellet injection.*

the electron root) when the plasma collisinality is low enough, while it becomes negative (in the ion root) at higher collisionality. The collisionality can be increased large enough to make the plasma to be in the ion root by increasing the electron density using gas puffing or pellet injection. Since the radial electric field tends to be zero inside the magnetic island [15], the large radial electric field shear will be produced at the boundary of the magnetic island in the ion root regime where the $E_r$ is negative outside of the magnetic island. Figure 1 show the schematic view of this experiment. The radial electric field shear near the boundary of a n/m=1/1 non-rotating magnetic island induced by external perturbation coils (Local Island Divertor coils: LID coils) is expected to be produced and sustained with continuous fueling by the repetitive pellet injections.

## 3. Target discharge and pellet injection for $E_r$ formation

The experiment was performed in an NBI sustained plasma with a magnetic axis of 3.6m, averaged minor radius of 0.6m and the magnetic field strength of 2.5T on the LHD. Figure 2 (a) shows heating scheme by the NBI and ECH which used to start up of the plasma. Six pellets with a volume of 12 mm³ are injected with a repetition time of 0.15 sec at the timing indicated by arrow in Fig. 2(b) to produce negative $E_r$ in the ion root plasma. The electron density at the plasma center and the stored energy is increased up to $3.7 \times 10^{19}$ $m^{-3}$ and 400 kJ at t=1.86sec associated with the repetitive pellet injection as shown in Fig. 2(b) and (c). The deposition power of NBI, which is depend on the density, is 4.2 MW at t=1.86sec. The radial electric field is derived from the poloidal rotation velocity at the mid-plane of the vertically elongated cross section with the charge exchange spectroscopy (CXS) [14,16] using the charge exchange line of fully ionized Neon. The Neon impurity is injected by gas puff before the pellet injection to make CXS available during the formation of $E_r$ as shown in Fig. 2(b). Figure 2(d) shows the time evolution of the radial electric field at R=4.04m measured with the charge exchange spectroscopy with the time-resolution of 150msec. The increase of the electron density is small enough to keep the plasma to stay in the electron root with the Neon puff. The radial electric field changes from positive (electron root) to negative (ion root) associated with increasing the electron density with repetitive injections of pellet. The critical density of the transition between positive and negative is about $1.5 \times 10^{19} m^{-3}$. The strong negative $E_r$ (ion root) is achieved at t=1.4 sec by the repetitive pellet injection and sustained up to the end of the NBI. Figure 3 shows the time

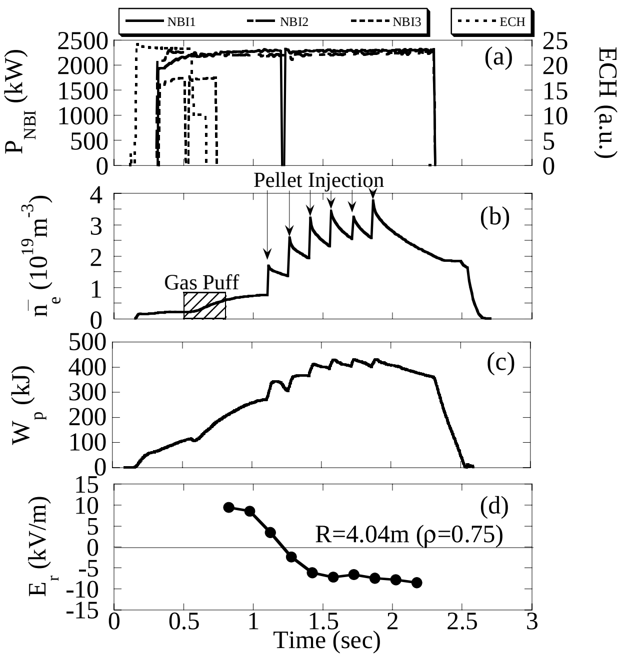


*FIG.2. Time trace of (a) port through power of NBI and the timing of ECH, (b) line averaged electron density and timing of gas puffing and pellet injection, (c) stored energy, (c) radial electric field at $\rho$=0.75.*

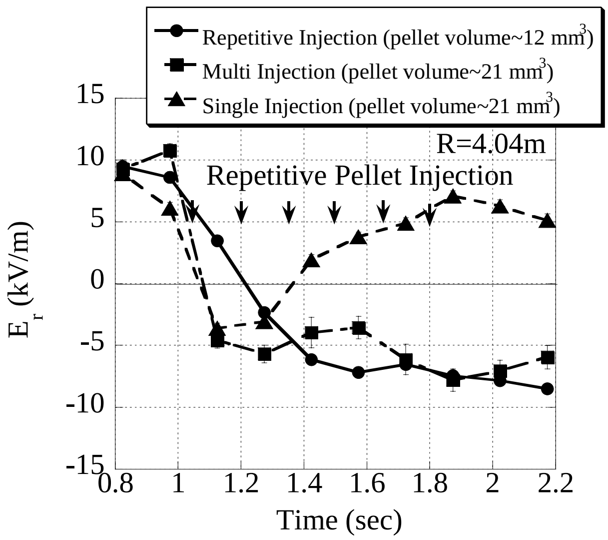


*FIG.3. Time evolution of the radial electric field at the R=4.04 with repetitive (circle), multi (square) and single pellet injection (triangle).*

evolution of the radial electric field with three type of pellet injection. Although the negative $E_r$ is formed near the magnetic island just after the pellet injection at t=1.05 sec, the formation of negative electric field is transient and the negative $E_r$ changes back to positive in the time scale of few 100 msec in the discharge with a single pellet injection. In the discharges with multi pellet injection (inject at t=1.05, 1.2, 1.35sec) and repetitive pellet injection, the negative electric field can be sustained even after the last injection of the pellet. The volume of the pellet used for single injection and multi injection is 21mm$^3$ which is larger than that used for the repetitive injections (12mm$^3$). Faster change of $E_r$ is observed in the discharge with larger pellet injection. It is considered

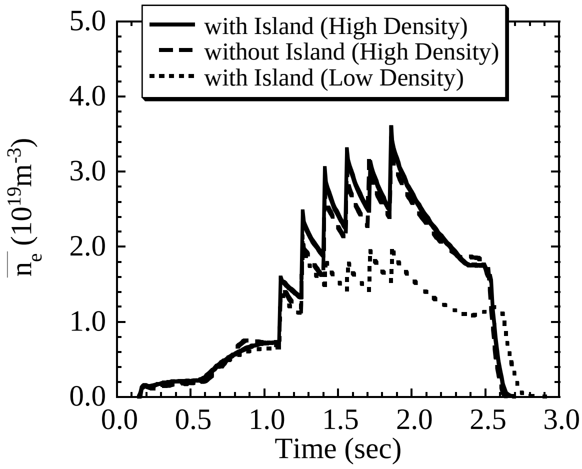


*FIG.4. Time traces of line averaged electron density in the plasmas both with (solid line) and without (dashed line) magnetic island at high density and with magnetic island (dotted line) at low density.*

that the time scale of the $E_r$ formation is related to the amount of the particle fuelling.

## 4 Required condition of $E_r$ shear formation in an Ion root plasma

Figure 4 shows the three time traces of the line averaged electron density in the plasma both with and without magnetic island at high density and with magnetic island at low density. The line averaged electron density is increased up to over the critical density in the high density discharge while the line averaged electron density is lower than the critical density in the low density discharge. The effect of magnetic island on particle transport is relatively small because the two time traces of the line averaged density at high density discharge are almost identical to each others.

Figure 5 shows the radial profiles of $E_r$ after the pellet injection (t=1.7s) measured by charge exchange spectroscopy with time resolution of 400 msec which can be measured with wide range in space compared with the CXS system with high-time resolution (150msec). The radial electric field is already close to zero in the plasma near the critical density and therefore there is no $E_r$ shear at the boundary of magnetic island in the low density discharge. In the plasma with the electron density higher than the critical density, the small negative $E_r$ is observed at the inner region of the plasma ($\rho$<0.74) and its magnitude gradually increases toward the plasma edge when there is no magnetic island. On the other hand, when there is a magnetic island, the large negative $E_r$ is observed except for the inside of the magnetic island, where the $E_r$ vanishes because of damping of the poloidal flow, and large $E_r$ shears are observed at the boundaries of the magnetic island.

Figure 6 shows the radial profiles of the ratio of electron density 0.1 sec after (t=1.15 sec) the start of the pellet injection (t=1.05 sec) to that 0.1 sec before (t=0.95 sec) the start of pellet injection in the plasma with and without the magnetic island. Although the ablation location indicated by the peak of $H_\alpha$ intensity is at r=0.68-0.86, the peak of increase in density appears at r=0.82-0.94 because the ablation cloud moves outward due to $E_\theta$xB force. The larger increase of the density is observed in the plasma with the magnetic island as compared with it in the plasma without the magnetic island and the more negative $E_r$ is produced in the plasma with the magnetic island as compared with it in the plasma without the magnetic island at the inner region of the plasma. These observations clearly show that both the magnetic island and high density plasma by pellet injection are necessary for formation of the $E_r$ shear in an ion root.

## 4. Time evolution of $E_r$ shear and gradient of ion pressure

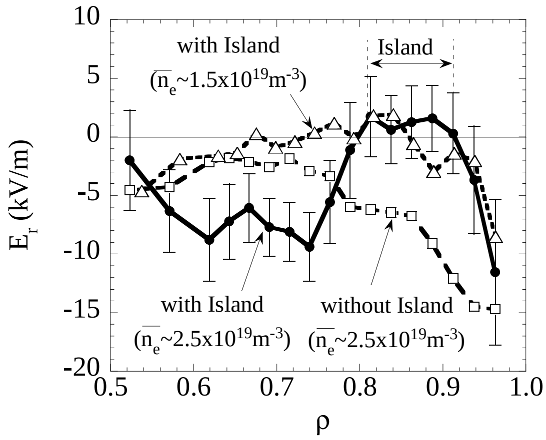


*FIG.5. Radial profiles of $E_r$ after the pellet injection in the plasmas with (closed circles) and without (open squres) magnetic island at high density and with magnetic island (open triangles) at low density.*

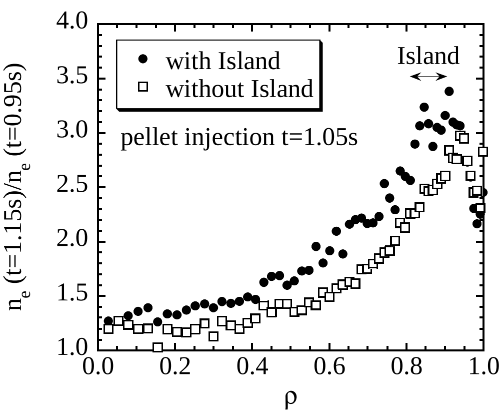


*FIG.6. The radial profile of the ratio of electron density 0.1 sec after the pellet injection to that 0.1 sec before the pellet injection (t=1.05sec) in the plasma with and without the magnetic Island.*

Figure 7 shows the time evolution of the radial profile of $E_r$ in the plasma with a magnetic island. Where the Δt indicates the time difference from the start of the pellet injection (t=1.05sec). The $E_r$ changes from positive (Δt=-0.8s) to negative (Δt > 0.22s) on the inner side of the magnetic island while there are no large changes in the $E_r$ inside the magnetic island as the line averaged electron density increases from 0.7x10$^{19}$m$^{-3}$ to 2.3-3.2x10$^{19}$m$^{-3}$ by repetitive pellet injections. The radial electric field shear ($dE_r/dR$) also changes its sign from negative to positive associated with the change of the $E_r$ sign at ρ=0.79. Thus, the $E_r$ shear can be controlled by changing the collisionality outside of the magnetic island in helical plasmas. Figure 8 shows the time evolutions of the $E_r$ shear ($dE_r/dR$) at ρ=0.79. With the repetitive pellet injection, the positive $E_r$ shear becomes strong and reaches 0.3MV/m$^2$ 0.3sec after the first pellet injection in the plasma with the magnetic island while the no significant $E_r$ shear is observed in the plasma without the magnetic island. This large $E_r$ shear can be sustained during the repetitive pellet injection with a repetition time of 0.15sec. Because the electron density is lower than the critical density before the pellet injection, the $E_r$ inner side of the magnetic island is positive (electron root) and the $E_r$ shear is negative. When the electron density exceeds the critical density by the pellet injection, the $E_r$ is negative

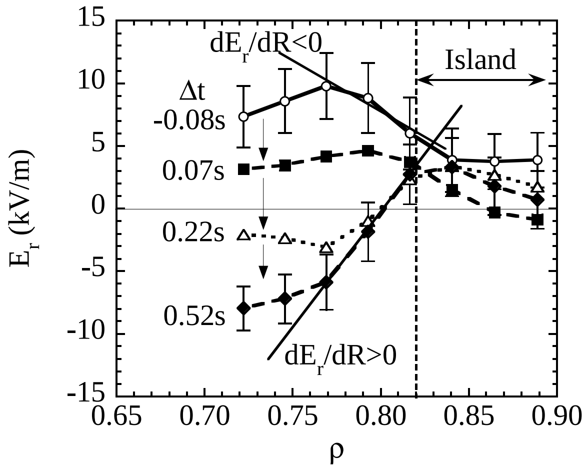


*Fig.7: Radial profiles of the $E_r$ 0.08s before and 0.07, 0.22, 0.52s after the pellet injection.*

(ion root) and the $E_r$ shear is positive after the pellet injection.

Figure 9 shows the time evolution of ion pressure gradient $-n_e dT_i/dR$ at $\rho$=0.77. The gradient of ion temperature, $dT_i/dR$, is derived from the ion temperature profiles measured with the CXS, while the electron density, $n_e$, is measured with an FIR interferometer. As shown in Fig.9, the value of the $-n_e dT_i/dR$ in the plasma with the magnetic island is almost twice that in the plasma without the magnetic island associated with the positive $E_r$ shear formation. This experiment demonstrates that the ion transport is improved associated with an appearance of negative $E_r$ shear. On the other hand, there is no sign of transport improvement due to the positive $E_r$ shear as seen in the ion pressure at t=0.8-1.05. It is noted that there is no difference in ion heat flux in these plasmas because the electron density and NBI power are controlled to be identical. The ion thermal diffusivity $\chi_i$ is estimated to be reduced by a factor of two near the magnetic island within a few cm by creating the large positive $E_r$ shear at the boundary of magnetic island with the assist of pellet injection in ion root plasma. In the ion root, the increase of the ion pressure gradient makes $E_r$ to be more negative. It is considered that there is feed back between the $E_r$ shear, reduction of $\chi$i, and the increase of the ion pressure gradient. When the $E_r$ is negative, the feed back process bocomes positive feedback because the larger ion pressure due to the reduction of $\chi_i$ contributes more negative $E_r$ and larger $E_r$ shear as shown in Fig.10. On the other hand, when the $E_r$ is positive, it becomes negative feedback and no improvement of the ion transport is expected.

## 5. Summary

Large *Er* shear in the ion root regime can be produced and sustained at the boundary of the magnetic island by combination of repetitive pellet injection and a magnetic island induced by external perturbation coils. The electron density which is much higher than the critical density is required to produce the $E_r$ shear in an ion root. The gradient of ion pressure is increased up to twice of that in the plasma without the magnetic island associated with the formation of the positive $E_r$ shear in the ion root plasma, while there is no differences of the ion pressure gradient between with and without the magnetic island in the negative $E_r$ shear in the electron root. It was suggested that there is a positive feedback process between the $E_r$ shear, reduction of $\chi$i, and increase of ion pressure gradient when the $E_r$ is negative (ion root) and $dE_r/dR$ is positive. It may be that the positive feedback process contributes to sustaining the $E_r$ shear. The combination of a magnetic island and pellet injection is considered to be a useful tool to control $E_r$ shear and an ion energy transport near the magnetic island.

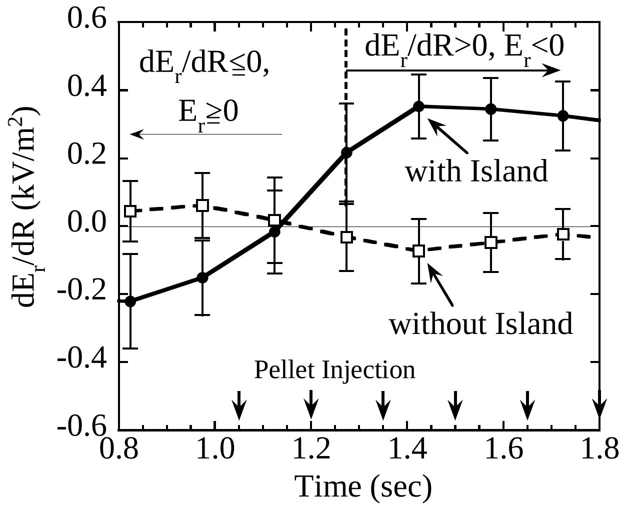


*Fig.8: Time evolutions of the $E_r$ shear in plasmas with (circle) and without (square) a magnetic island. Arrows indicate the timings of pellet injection.*

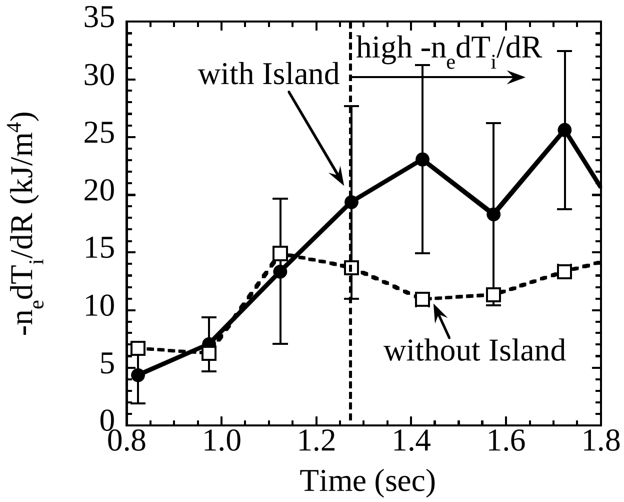


*Fig.9: Time evolutions of the ion pressure gradient at $\rho$~0.77 in plasmas with (circle) and without (square) a magnetic island.*

**Acknowledgement**

The authors would like to thank the LHD technical staff for their effort to support the experiments in LHD. They also acknowledge continuous encouragement and support of Director-General O. Motojima. This work is supported by NIFS05ULBB512 and partly supported by a grant-in-aid for scientific research of MEXT Japan.

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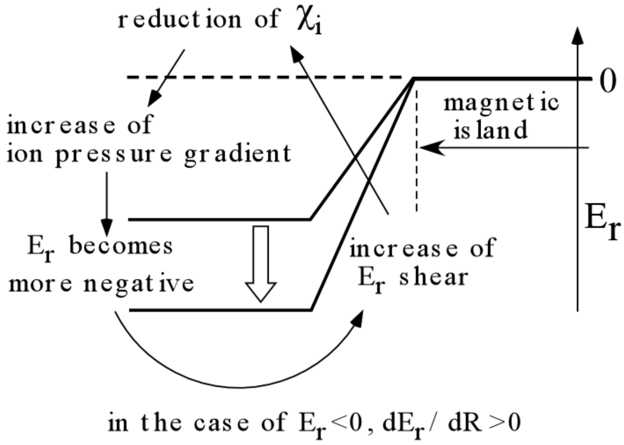


*FIG.10. Positive feed back between the $E_r$ shear, reduction of ion diffusivity, and increase of ion pressure gradient.*

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