Clear transition to high-$T_e$ state with an electron internal transport barrier creation in EC Heated LHD plasmas

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Abstract. A transition to a high electron temperature state in the core accompanied by an electron internal transport barrier (eITB) was clearly observed in neutral beam (NB) sustained plasmas with strongly focused on-axis electron cyclotron heating (ECH) in Large Helical Device (LHD). During stepwise injection of ECH power, the core electron temperature started to build up spontaneously and became high temperature in the core (high-$T_e$ state), while the temperature outside of $\rho \sim 0.3$ drastically decreased. The transition dynamics of the core temperature is analyzed by the time evolution of electron temperature profiles and heat flux changes based on the data from multi-channel electron cyclotron emission. Effect of an initial island size ($m/n = 2/1$) on the high-$T_e$ transition was experimentally investigated by controlling the width by an external coil field. The results show that the island size possibly affects a threshold value of ECH power and collisionality on the high-$T_e$ transition.

1. Introduction

In LHD, transition phenomena to a high electron temperature state (high-$T_e$ state) in the core region has been observed by centrally focused ECH injected into a plasma sustained by NBI. The transition to the high-$T_e$ state is sometimes accompanied by a formation of an electron internal transport barrier (eITB). This is characterized by strongly peaked electron temperature profiles and large positive radial electric field, $E_r$, in the core region, which is the common feature observed in many helical devices [1, 2, 3, 4]. These phenomena are interpreted as a transition to the "electron root" solution of the ambipolarity condition for $E_r$ under the neoclassical transport. Recently this improved confinement has been called "core electron-root confinement (CERC)" [5, 6].

Main features of the high-$T_e$ transition in LHD are summarized as follows [7, 8]. It is characterized by a high central electron temperature up to 10 keV and steep temperature gradient around $\rho$ (normalized minor radius) $\sim 0.3$. The appearance of those states depends on the injection direction of NBI. Heat transport analyses by using ECH power modulation clarified that the structure of the ITB existed only in the counter-injected NBI sustained plasmas. There is a threshold ECH power for the transition to the high-$T_e$ state. Sudden transitions to the high-$T_e$ state are triggered by external perturbations, such as additional ECH power, decrease in density, a small pellet injection, and so on. The presence of $m/n = 2/1$ island or $\iota/2\pi = 0.5$ ($q = 2$) rational surface in the counter-NBI plasma configuration possibly facilitates the transition to the high-$T_e$ state and the formation of the ITB with a steep temperature gradient.
In this paper, a clear transition of a high-$T_e$ state are reported, in which the time evolution of the electron temperature was spatially resolved by using a multi-channel ECE diagnostic. Such transition with an eITB has been clearly observed in neutral beam (NB) sustained plasmas with strongly focused on-axis ECH. During stepwise injection of ECH power, the core electron temperature started to build up spontaneously and became high temperature in the core, on the other hand the temperature outside of $\rho \cong 0.3$ drastically decreased. This phenomenon helps to understand the temporal and spatial behavior of a formation process of eITB in the helical device. The transition phenomena to the high-$T_e$ state with an ITB formation were mainly observed in plasmas sustained with counter-injected NBI \[8\]. It is speculated that this process includes the first expansion of a magnetic island ($m/n = 2/1$) by low power ECH injection, subsequent disappearing or healing of the island by additional ECH power and final transition to high-$T_e$ in the core and eITB formation by realization of so called \[\uparrow\uparrow\] electron-root \[\downarrow\downarrow\].

We tried to contract and expand the island by the external coil field to investigate the effect of the seed island size on the transition. The results show that the island size possibly affects the threshold values of ECH power and collisionality on the high-$T_e$ transition. During ECH power injection, some crashes in the core temperature and flattening of temperature profile frequently occurred and they inhibit attainment of higher central electron temperature. Clarification of the eITB formation process contributes an achievement of higher electron temperature and high performance plasmas by ECH.

This paper organized as follows. In Sec. 2, experimental devices and configuration including magnetic and heating condition are briefly summarized. In Sec. 3, experimental observations will be given in detail, together with the analyses of heat flux change. Experimental results of an effect of the initial island size on high-$T_e$ transition are also described. Finally, a summary will be presented in Sec. 4.

2. Experimental setup and configuration

![Figure 1](image-url)  
**Figure 1.** (a) Configuration of ECH injection. Magnetic flux surfaces, ECR layer and injection direction of millimeter-waves from each antenna are illustrated. (b) Time sequence of NBI and ECH pulses. Direction of beam-driven currents could be changed by switching NB injectors in co- and counter-direction.

LHD is a heliotron-type device ($\ell = 2, m = 10$) with superconducting helical coils and poloidal coils. In this experiment the major and the averaged minor radii of the produced plasmas are typically 3.5 m and 0.6 m, respectively. The ECH system consists of two 82.7 GHz and two 84 GHz gyrotrons for the fundamental resonance heating, and four 168 GHz gyrotrons for the second harmonic heating at 3 T \[9\].
In the present experiments, 82.7 GHz and 168 GHz power were injected from the antenna installed in the upper port (U-antenna), and 84 GHz power was launched from the antenna in the lower port (L-antenna), as shown in figure 1 (a). The electron cyclotron resonance (ECR) layers for each frequency are located near the magnetic axis on the equatorial plane, which are denoted by ECR in this figure. The ECR layers are almost the same for each frequency. That is the fundamental resonance for 84 GHz and 82.7 GHz and is the second harmonic resonance for 168 GHz. The U- and L-antennas were installed in the toroidal section with a vertically elongated cross section. The beam waist radii at the focal point were 15 mm in the radial direction for the U-antennas, and 30 mm for the L-antennas.

The experiments were performed at the magnetic configuration with magnetic field $B_0 = 2.829T$ and the magnetic axis of $R_{ax} = 3.5m$. A schematic of the time sequence in NBI and ECH is illustrated in figure 1 (b). The target plasmas were produced and sustained by NBI with the port-through power of about 2.4MW, and an additional ECH was turned on at the flat top of the discharge in figure 1 (b). Direction of beam-driven currents could be changed by switching NB injectors in co- and counter-direction. The ECH power was additionally injected into a plasma in the steady state with the electron temperature of about 2 keV and the electron density of $6.6 \times 10^{19} m^{-3}$. The ECH pulse formed a stair-like pattern such that 84GHz power (0.4MW) was turned on from $t = 1.3 s$ and 82.7GHz and 168GHz powers (0.72MW) were turned on from $t = 1.5 s$, and both pulses were terminated at $t = 2 s$.

The electron temperature profiles were measured by using a Thomson scattering system at about 130 positions in the equatorial plane of the horizontally elongated toroidal section with a spatial resolution of 20 – 35 mm [10]. For electron temperature measurements with a higher time resolution, a multi-channel radiometer system was used to detect electron cyclotron emission (ECE) radiated from the low magnetic field side (30 channels, spatial resolution: 10 – 70 mm) [11]. The absolute error of $T_e$ determined by the absolute calibration of ECE is about 20 % and the relative error of the $T_e$ determined by the noise levels of ECE is only 1 %.

### 3. Experimental results

#### 3.1. Spontaneous $T_e$ transition and crash

During additional ECH pulse, a spontaneous transition to the high-$T_e$ state was clearly observed in a counter-NBI sustained plasma with an ITB formation. Figure 2 shows a time evolution of some plasma parameters. A target plasma was initiated by co- and counter-NBI at first, then co-NBI pulse was switched off at $t = 0.5 s$ while counter-NBI pulse was extended to $t = 2.1 s$. ECH power was injected from $t = 1.3 s$ and from $t = 1.5 s$ stepwisely. A plasma current in the counter direction continued to increase up to the end of the NBI pulse. As shown in $T_e$ measured by ECE, a transition to high-$T_e$ in the core region is obviously noticed at $t = 1.67 s$, when a rapid increase of core temperature and a little step-down of temperature in outer region ($\rho > 0.34$) occurred almost simultaneously. The inversion radius of the temperature change is about $\rho \approx 0.3$. Precise time evolution of the electron temperature profile by ECE is shown in figure 3. The plasma sustained by counter-NBI has a rather flat profile in the core region ($t = 1.6 s$). The second peak of the temperature appeared around $\rho \sim 0.4$ just before the transition ($t = 1.65 s$). After the transition, the central temperature was growing up, while the second peak was shrinking. This behavior of the temperature profile looks to be inverted at $\rho \approx 0.3$. Position of a transport barrier seems to be the position of the inversion radius $\rho \approx 0.3$ inside which temperature increases and outside which it decreases.

In a co-NBI sustained plasma, a big crash of electron temperature in the core region was observed. Figure 4 shows a time evolution of some plasma parameters. A target plasma was initiated and sustained by co-NBI only. ECH power was injected in the same manner as counter-NBI case. Plasma current in the co-direction continued to increase up to the end of the NBI pulse. The final attained absolute value of the plasma current is almost the same as that in counter case, though the direction of current was inverted. As shown in $T_e$ measured by ECE, a big $T_e$ crash in the core region suddenly occurred at $t \sim 1.79 s$, when a drastic decrease of core temperature and a little step-up of temperature in outer region occurred.
Figure 2. Time evolution of some plasma parameters for counter-NBI plasma with ECH. Spontaneous transition to the high-\(T_e\) state occurred at \(t = 1.67\) s. Figures show NBI pulse, ECH pulse forms, plasma current \(I_p\), line-averaged electron density \(n_e\), plasma stored energy \(W_p\) and electron temperature by ECE (normalized radial position is indicated in the figure) from top to bottom.

Figure 3. (a) Time evolution of electron temperature profile measured by ECE during the transition (from \(t = 1.6\) s to 1.9 s). The relative error determined by noise level are typically plotted for the data points of \(t = 1.65\) s. (b) Contour plot of electron temperature profile.

almost simultaneously. Precise time evolution of the electron temperature profile is shown in figure 5 from \(t = 1.6\) s to 1.9 s. The plasma sustained by co-NBI has a rather peaked profile in the core region with higher temperature than in counter-NBI case at \(t = 1.6\) s from the beginning. The inversion radius of the temperature behavior is about \(\rho \approx 0.23\) as shown in the figure. It is obviously smaller than that in the counter-NBI case. The difference of the inversion radius is supposed to arise from the position of a lower order rational surface, \(\iota/2\pi = 0.5\), in special, induced by plasma current.

3.2. Temporal and spatial analyses of electron heat flux
During ECH pulse, ECH power is assumed to be constant. Ray tracing calculation shows that it is absorbed within \(\rho \lesssim 0.2\). Then variation of an electron heat flux through a given normalized radius, \(\rho\), and at time, \(t\), will be given by a following equation outside of the ECH deposition layer.

\[
\delta Q_e(\rho, t) \propto -\frac{1}{\rho} \int_{0}^{\rho} \left( \frac{3}{2} \right) \frac{\partial}{\partial \rho} \left[ n_e(\rho', t) T_e(\rho', t) \right] \rho' dp'
\]  

(1)

This corresponds to a time derivative of the total kinetic energy stored within a given radius \(\rho\). Using temperature data measured by ECE and density data by FIR interferometer, temporal and spatial variation
Figure 4. Time evolution of some plasma parameters for co-NBI plasma with ECH. A sudden crash of core $T_e$ occurred at $t \sim 1.79 \text{s}$. Figures show NBI pulse, ECH pulse forms, plasma current $I_p$, line-averaged electron density $n_e$, plasma stored energy $W_p$ and electron temperature $T_e$ by ECE (normalized radial position is indicated in the figure) from top to bottom.

Figure 5. (a) Time evolution of electron temperature profile measured by ECE during the crash (from $t = 1.6 \text{s}$ to $1.9 \text{s}$). The relative error determined by noise level are typically plotted for the data points of $t = 1.7 \text{s}$. (b) Contour plot of electron temperature profile.

of $\delta Q_e$ can be calculated. Difference of in- and out-flux through a thin layer $2\Delta \rho$ between $\rho - \Delta \rho$ and $\rho + \Delta \rho$ was calculated and defined as $\Delta \delta Q_e(\rho, t)$.

The values, $\Delta \delta Q_e(\rho, t)$, are calculated for the high-$T_e$ transition and temperature crash shots described in the previous subsection. In these analyses $\Delta \rho$ was selected to be 0.01. Difference between in- and out-heat fluxes at $\rho$ is plotted as a function of time for the shot of the high-$T_e$ transition in figure 6. Electron temperature is gradually increasing after on-timing of the second ECH pulse ($t = 1.5 \text{s}$), keeping a flat profile in the core region. From about 20 ms before a jump of core electron temperature at $t \sim 1.67 \text{s}$, the value $\Delta \delta Q_e$ is increasing gradually between $\rho = 0.25$ and 0.45 (from $t = 1.65 \text{s}$ to $1.67 \text{s}$). More precisely, the slow decrease of temperature between $\rho = 0.3$ and 0.55 is observed as shown in figure 3 (b). This fact implies that a recovering of confinement has been already begining around the central part of the plasma from $t = 1.65 \text{s}$ gradually. Then abrupt dip of $\Delta \delta Q_e$ up to $\rho \sim 0.3$ and its increase at $\rho > 0.45$ can be noticed. It is suggested that a kind of transport barrier of electron heat transport was established at $\rho \sim 0.3$ at this moment and that the confinement of the electron energy was improved within $\rho \sim 0.3$. The first small crash of the core temperature happened at $t = 1.8 \text{s}$, when the reverse process occurred, that is, increase of $\Delta \delta Q_e$ in the core ($\rho < 0.31$) and a rapid dip of flux deference in $\rho > 0.45$. The inversion radius of these phenomena such as the transition and crash is the same.

A opposite behavior of heat flux difference $\Delta \delta Q_e$ was noticed in the core temperature crash of the co-NBI sustained plasma case. A rapid build-up and slow relaxation of the heat flux occurred within
ρ < 0.23 at t ∼ 1.79 s. On the contrary, a rapid decrease and its relaxation were observed in the outside region (ρ > 0.25) as shown in figure 7. The minimum of the flux difference has a time delay of several milliseconds in the outer region. This implies that a heat flux flowing out from the core propagates outward.

These temporal and spatial behavior of the heat flux helps to understand a dynamics that occurs in plasmas with extremely localized ECH.

3.3. Effect of seed island size for high $T_e$ transition

It is noticed that the presence of $m/n = 2/1$ island or $\iota/2\pi = 0.5 (q = 2)$ rational surface in the counter-NBI plasma configuration may facilitate the transition to the high-$T_e$ state and the formation of the ITB with a steep temperature gradient [8, 9].
There are some natural islands produced by existing error fields in LHD. Using an electron gun as the electron beam source and the multiple probe array, their position, width, and phase at a given toroidal section can be successfully identified in a high magnetic field state \((B=2.75 \, \text{T})\). Calculations based on the magnetic field line tracing can reproduce these islands if the given error field sources are assumed.

**Figure 8.** Time evolution of electron temperature during stair-like ECH power injection for (a) with enlarged \(2/1\) island and (b) with reduced island. The measured positions of the temperature correspond to \(\rho = 0.015, 0.114, 0.190, 0.283, 0.407, 0.546, 0.644, 0.757\) from top to bottom.

For local island divertor experiments, LHD has ten pairs of perturbation coils located above and below the LHD vacuum vessel. Arranging the perturbation coil currents from the calculated expectations can change the size of these natural islands. With an arrangement of the perturbation coil currents, the width of these islands can be changed by a factor of two. The maximum width of the \(2/1\) island is controlled from 58 mm that is the natural island size to 29 mm (reduced island) and to 83 mm (enlarged island) by the application of the external magnetic field produced by the perturbation coils. Target plasmas were produced and sustained by counter-NBI power and ECH power was additionally injected stairlikely as shown in figure 8. Figures show time evolutions of electron temperature measured by ECE for the EC heated plasma with enlarged \(2/1\) islands in figure 8 (a) and with reduced islands in (b). ECH power was turned on by each 0.2s from \(t = 1.2 \, \text{s}\) and the power level increased from 0.38 MW \((t = 1.2 – 1.4 \, \text{s})\), 0.87 MW \((t = 1.4 – 1.6 \, \text{s})\) and finally to 1.26 MW \((t = 1.6 – 1.8 \, \text{s})\). Although the time period of 0.2 s was insufficient so that the temperature might attain a steady value, temperature values just before the next power steps were adopted as data for power dependence. Those timings are indicated by arrows in figure 8 (a).

ECH power normalized by line-averaged electron density \(P_{\text{ECH}}/\bar{n}_e\) is plotted as a function of electron temperature gradient at \(\rho = 0.25\) as a representative of ITB foot position in figure 9. Because \(P_{\text{ECH}}/\bar{n}_e\) represents a product of heat diffusivity \(\chi_e\) and temperature gradient in steady state, a slope of a straight line drawn from the origin to data point roughly expresses the heat diffusivity \(\chi_e\).

All curves show almost the linear increase of \(T_e\) gradient as the ECH power increases at low power level. However, there are specific power ranges where the temperature gradient stays almost constant or even decreases (which means an increase of heat diffusivity). The larger is the island size, the wider the power range becomes. These phenomena stem from the extreme flattening of the core temperature profile as observed at \(t=1.6s\) in figure 8(a). The spontaneous expansion of the \(m/n=2/1\) island towards the
plasma center is speculated as one of causes. Then a jump in the temperature gradient occurs at higher density-normalized ECH power, which implies a recovery of the heat diffusivity or a change towards another confinement state. There are threshold power at which temperature gradient suddenly increases. It is not clear in the case of reduced island. The natural island case looks to have the minimum threshold power among three cases. The optimum size of the island possibly exists to facilitate such transition.

4. Summary

During stepwise power injection of centrally localized ECH in the plasma sustained counter-NBI, the core electron temperature within $\rho \approx 0.3$ started to build up spontaneously and became high temperature (high-$T_e$ state) in the core, on the other hand the temperature outside of $\rho \approx 0.3$ drastically decreased. This phenomenon directly shows temporal and spatial behavior of the formation process of an eITB (or CERC) in the helical device. The transition phenomena to the high-$T_e$ state with an ITB formation were mainly observed in plasmas sustained with counter-injected NBI. The second peak of the temperature appeared around $\rho \sim 0.4$ just before the transition. After the transition, central temperature was growing up, while the second peak was shrinking. It is suggested that this process is affected by the change of heat flow around a magnetic island ($m/n = 2/1$) induced by ECH injection.

There is a noticeable difference in the inversion radius of the electron temperature change between for the high $T_e$ transition in the counter-NBI plasma and for the temperature crash in the co-NBI plasma. This fact is considered to result from a change of the rotational transform profile caused by an NBI-driven current. The exact positions of the inversion radius, however, differ from those of calculated positions based on the assumed current profiles. Determination of current profiles will be required experimentally.

Effect of $m/n = 2/1$ island size on the high-$T_e$ transition was investigated by controlling the island size. The width of the island was reduced and enlarged by external coil field by about factor of two. The results suggested that there is an optimum size of island to facilitate a transition phenomenon in core $T_e$. When increasing ECH power, confinement of electron energy was once degraded and then recovered or changed to another confinement state. This confinement degradation phase relevant to ECH power seems to be wider with the size of the island. Detailed study of a role of islands on the high-$T_e$ transition mechanisms is one of urgent issues.

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