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Fast electron dynamics in lower hybrid current drive experiment on HT-7 tokamak*

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The dynamic behaviour of fast electron in lower hybrid current drive (LHCD) experiments is a crucial issue in the sense of enhancing plasma performance. A new hard x-ray diagnostic system on HT-7 allows the investigation of the lower hybrid wave dynamics. The behaviour of fast electron is studied in several kinds of LHCD experiments, including long pulse discharges, high performance discharges and counter-LHCD experiments.

Keywords: fast electron, hard x-ray, lower hybrid waves
PACC: 5225, 5250G, 5225F

1. Introduction

Non-inductive current drive is an important subject in tokamak fusion research. The experiments in many tokamaks have shown that lower hybrid current drive (LHCD) is one of most efficient methods to drive non-inductive current in tokamak plasma.[1] The LHCD is a powerful means for controlling the current profile to stabilize MHD instability and to improve plasma confinement, and in this respect many significant results in Tore Supra, FTU, JET and JT-60U have been achieved.[2−6] Some significant results of LHCD experiment are also obtained in the HT-7 superconducting tokamak, to which a series of technical improvements have been made,[7] according to the experimental schedule in a period of Nov. 2001–Jan. 2002. In the long pulse discharge with a duration up to 10s, T_e ∼1keV and central density $\sim 1\times10^{19}\mathrm{m}^{-3}$ are achieved. The well confined plasma with an internal transport barrier (ITB) is obtained by means of LHCD.

Fast electron behaviour in LHCD experiment is a crucial issue in the study of LHW plasma physics. With a new hard x-ray diagnostic system on HT-7, the behaviour of fast electron is investigated in this paper. It is found that plasma performance is closely related to the non-inductive driven current profile.

2. Experimental setup

HT-7 is a medium-sized superconducting tokamak with limiter configuration.[8] The machine is normally operated under the plasma current I_p= 150–220kA, the toroidal magnetic field strength B_T=2T, and the minor radius a=27cm. Its main limiter is made of specially doped graphite, coated with a thickness of SiC film.[7] Twenty-four ferritic steel plates are located inside the vacuum vessel, so that the magnetic ripple is reduced from 4% down to 1.6% at the edge of the lower field side, which is useful in suppressing the fast electron and ion ripple-loss, especially, in an auxiliary heating discharge.[9] The LHCD system[10] with 1.2MW power at a frequency of 2.45GHz can be operated in continuing work (CW) mode. The LHW is launched into the tokamak plasma by a 3×16 multijunction grill type of antenna. The power spectrum of the launched wave can be adjusted in the range $1.25 \leq N_{//}^{\mathrm{peak}} \leq 3.45$ by means of the feedback control of phase difference between adjacent waveguides of the coupler, where $N_{//}^{\mathrm{peak}}$ is the peak value of parallel refractive index of launched wave.

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The hard x-ray radiation in the energy range under consideration is emitted by fast electrons, and can be used to diagnose their spatial distribution and temporal dynamics. In many tokamaks, hard x-ray diagnostics is applied to study LHCD and ECRH in physics.[11−17] The profile of fast electron bremsstrahlung can well approximate the one of the driven LH current and absorbed LHW power.[18] A multi-chord hard x-ray (HXR) pinhole diagnostics[19] (Fig.1) is used in HT-7 to study the spatial and spectral distribution of bremsstrahlung emission in the 10–200keV range. Photon detection is carried out by a linear array of CdTe detectors with an intrinsic energy resolution of 7keV. The 128 energy channels are available for each detector. The time and space resolutions of the diagnostics are respectively 5ms and 4cm.

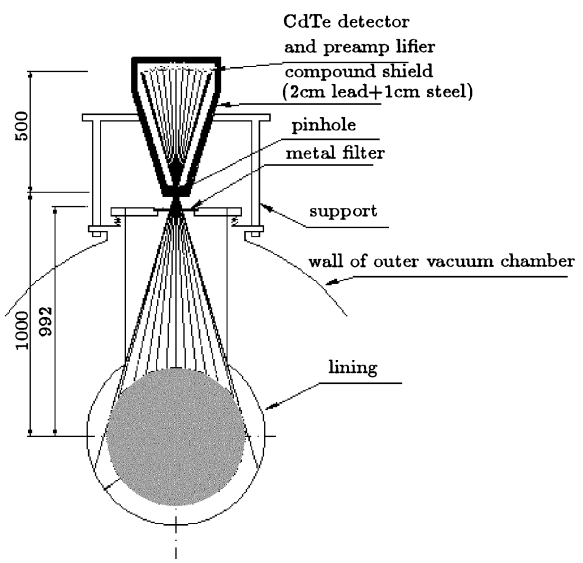


Fig.1. Schematic diagram of multi-chord hard x-ray diagnostics.

3. Experimental results and discussion

3.1. Typical LHCD experiment

In LHCD experiments in HT-7, the LHW power is usually launched into the plasma during the plateau of plasma current waveform. A group of typical waveforms of LHCD discharge with a moderate LHW power is shown in Fig.2. The LHW driven current is about 80kA roughly estimated from the drop of loop voltage. A two-dimensional ray-tracing Fokker–Planck simulation code[21] is developed to calculate the profiles of LHW power deposition and driven current in HT-7. The effect of fast electron radial diffusion on the current drive is taken into account in this code. The calculation made by use of this code shows that the radial diffusion of fast electron will make the profile of driven current flat and broad. Both driven current and current drive efficiency decrease due to the radial diffusion of fast electron.[20] The profile of current driven by fast electrons can be estimated by investigating the hard x-ray emission profile.[2,4,15−18,21] The non-thermal HXR emission profile between 50 and 60keV is used to investigate the LHCD in this paper.

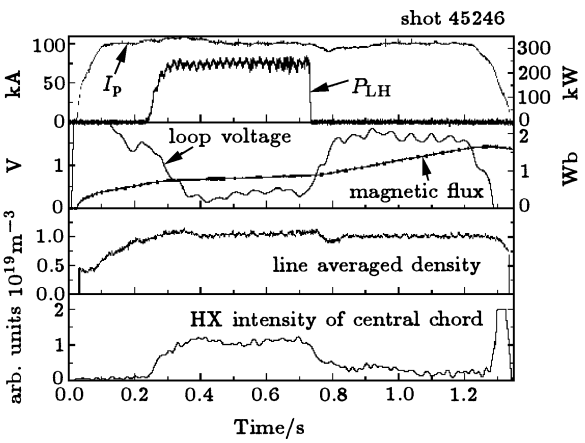


Fig.2. Typical waveforms of LHCD discharge.

The Abel inverted profile of hard x-ray is shown in Fig.3. In order to make a comparison with the simulation results, the Abel inverted data are normalized by electron density. Three values for the diffusion coefficient of fast electron (1, 2 and $5m^2/s$) are tried. It can be seen that the best match is obtained for $2m^2/s$ and the total non-inductive current calculated by the simulation code is in accord with the measurements. This result of diffusion coefficient of fast electron is tentative as the loop voltage is not zero during LHCD, and this result has yet to be accounted for in the modelling.

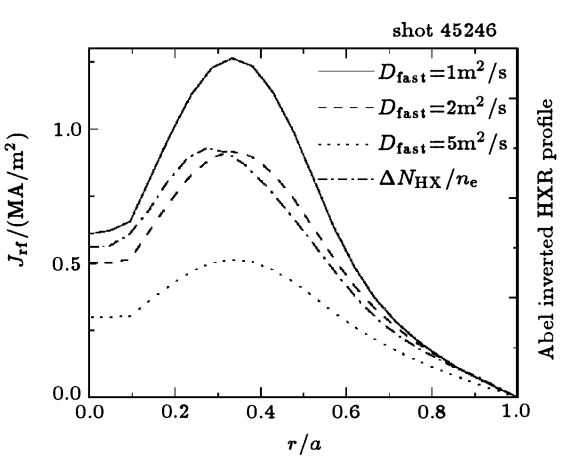


Fig.3. Abel inverted profile of hard x-ray from LHCD discharge.

Steady-state high-temperature plasma operation is one of the very important issues in HT-7 experiments. The waveform of a 10sec-discharge is shown on the left in Fig.4, where the LH power of 130kW is injected into the plasma by a new multijunction launcher with a narrow $n_{//}$-power spectrum which peaked at $n_{//\mathrm{peak}}$=2.9 with FWHM $\Delta n_{//}$=0.3, plasma centre electron density $n_{\mathrm{e}0} \sim 1\times10^{19}\mathrm{m}^{-3}$, I_{p}=100kA, and B_{T}=2T. Since a feedback control system keeps the plasma current constant, the loop voltage decreases down to 0.1V due to the injection of LH power. The time evolution of line-integrated hard x-ray emission profile is shown on the right in Fig.4. The improvement on global confinement and increase of temperature take place after the broadening of hard x-ray emission profile. This phenomenon in our long-pulse discharge is very similar to that in the LHEP long-pulse discharge of TORE SUPRA.[2,22,23] The broadening of the HXR profile augments with the increase of central electron temperature. The hard x-ray emission profile is a good measure of the fast electron density profile (driven current density profile). Figure 5 shows the Abel inverted HXR profiles at different times. It can be seen that the profile becomes more off-axis at 6 sec. The current density profile will affect the global confinement and the local transport, as discussed in Ref.[23]. Unfortunately, only the electron temperature in the central region instead of its profile can be obtained in the long-pulse discharge on HT-7, which makes further analysis of heat transport very difficult. The total current profile becomes broader, leading to the formation of a hot electron core region in the LHEP long-pulse discharge of TORE SUPRA.[2,22,23] The modification of current density profile may also be an important cause of the increase of central electron temperature in HT-7.

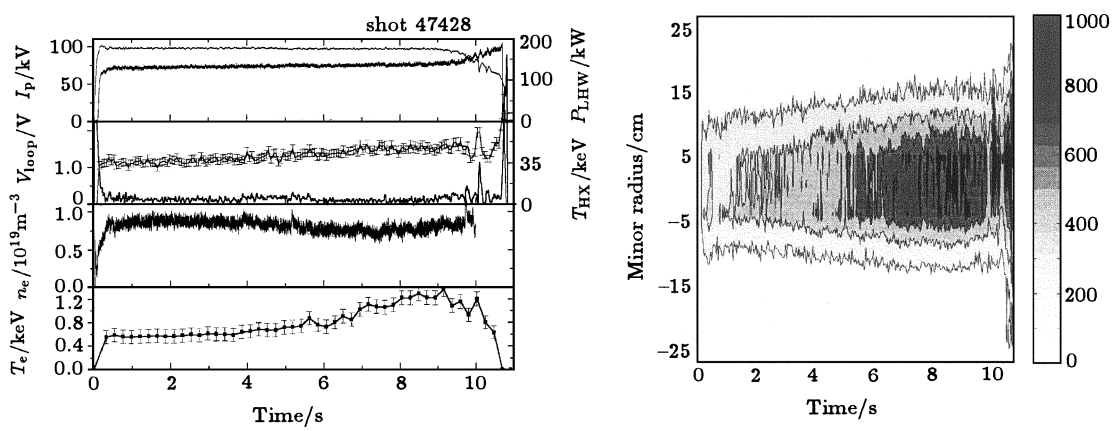


Fig.4. Waveform of a 10sec discharge and the time evolution of line-integrated hard x-ray emission profiles.

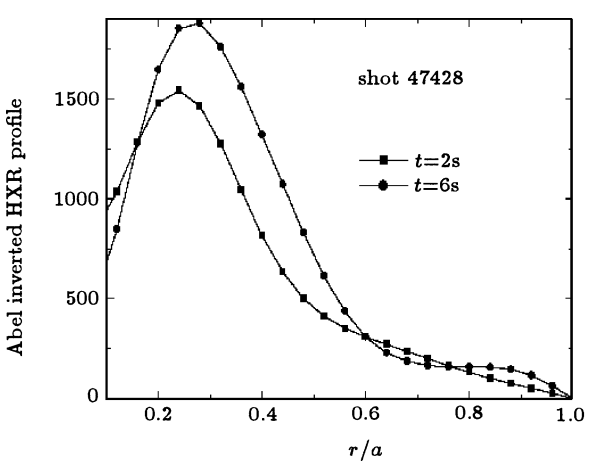


Fig.5. The Abel inverted HXR profile at different time.

3.2. High performance LHCD experiment

When the plasma current is as high as around 200kA, it is very easy to enhance confinement with a LHW power threshold of 250kW. Figure 6 is a group of typical waveforms for the LHEP (LHCD enhanced performance) discharge. When the LHW is injected into the plasma, the H_α drops down and the electron temperature in the central region increases from 1.5keV to 2.2keV. In the LHEP discharge, an ITB-like structure (where ITB stands for internal transport barrier) is formed at $0.55a$ (where a is the minor radius) as indicated from the profile of electron temperature in Fig.7.

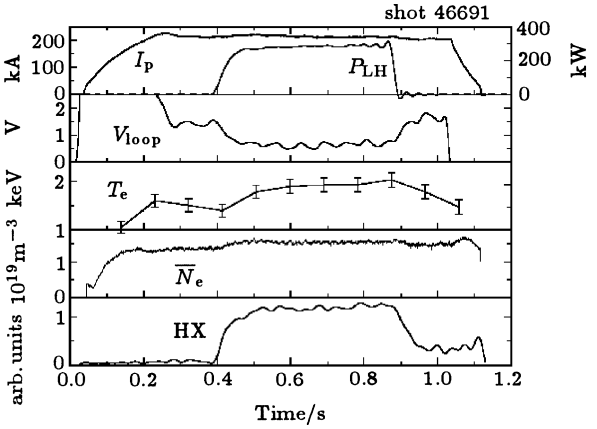


Fig.6. A typical waveform for the LHEP discharge.

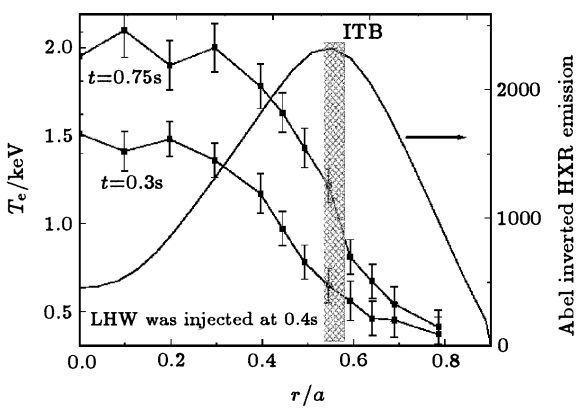


Fig.7. ITB-like structure in the electron temperature profile.

The local thermal electron heat can be analysed from the power balance equation. Here, we give the integro-differential form of electron balance equation as follows:

$$\frac{\partial W_e(r)}{\partial t} + P^e_{cond}(r) + P^e_{conv}(r) = P_{OH}(r) + P^e_{LHW}(r) - P_{rad}(r) - P_{ei}(r). \quad (1)$$

Here $W_e(r)$ denotes the total electron energy inside a flux surface. P_{OH} denotes the ohmic heating power inside the flux surface. P_{rad} is the radiation loss and can be obtained from XUV measurements. P_{ei} is the power transfer between electrons and ions due to Coulomb collisions. P^e_{LHW} is the LHW power absorbed by electrons in the flux surface. In our experiments, the ion absorption of LHW can be neglected. LHW power deposition profile is deduced from hard x-ray profile together with ray-tracing Fokker–Planck simulation code. The convective energy flux of electrons is defined as

$$P^e_{conv}(r) = \frac{3}{2} \times 4\pi^2 R r n_e(r) \Gamma_e(r), \quad (2)$$

where R is the major radius. The conductive energy flux of the electrons is given by

$$P^e_{cond}(r) = -4\pi^2 R r n_e(r) \chi_e(r) \frac{\partial T_e(r)}{\partial r}, \quad (3)$$

where χ_e is the electron heat conductivity. So χ_e can be obtained from Eq.(1) by using experimental data. The improvement of energy confinement is clearly observed from the decrease of χ_e in the central region ($0 < r/a < 0.5$) during LHCD (as seen in Fig.8).

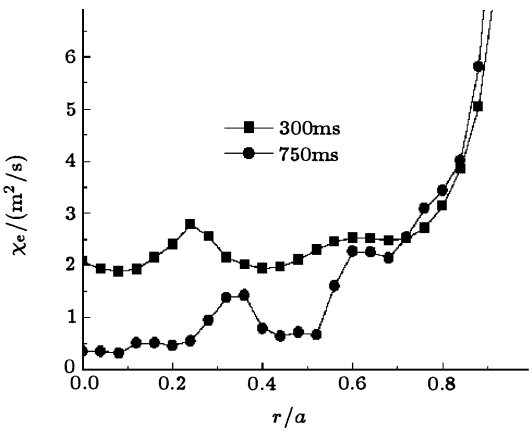


Fig.8. The electron heat conductivity at different time.

In Tore Supra,[2,22,23] JET,[5] FTU[4] and JT-60U,[6] the low or negative magnetic shear caused by LHCD is a very important condition for the enhancement of confinement and formation of ITB. It is found that the ITB is located around the peak position zone of the Abel inverted local emission profile of hard x-ray. This fact suggests that the formation of the ITB is correlated with the LHW driven fast electron current. The current density profiles and q-profiles are shown in Fig.9. The fraction of bootstrap current increases from 7% to 15% after the injection of LHW. The profile of bootstrap current is off-axis just like that of LHW driven current. The off-axis non-inductive driven current makes the total current profile flat or hollow, which may form weak or reversed magnetic shear configuration in the plasma core region and improve the plasma performance. The profiles of current density and safety factor q are roughly estimated by the profile of electron temperature and hard x-ray, and they are shown in Fig.9. It can be seen that the position of the lowest safety factor corresponds to the ITB, which also coincides with the experimental observation.

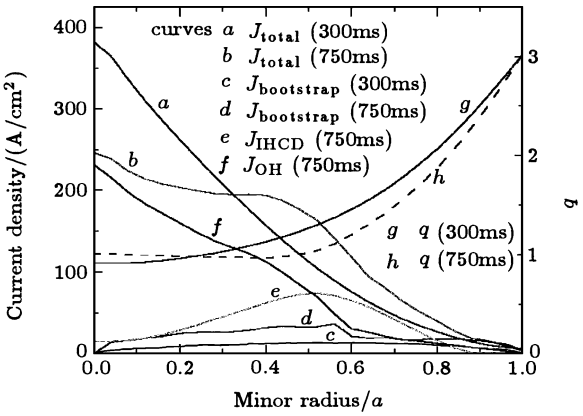


Fig.9. Profiles of current density and safety factor q. $J_{\rm total}$ is the total current density, $J_{\rm bootstrap}$ is the bootstrap current density, $J_{\rm LHCD}$ is the LHW driven current density.

3.3. Counter-LHCD experiment

The waveforms for the counter-LHCD and co-LHCD discharges are shown in Fig.10. The two shots are carried out with the same parameters: a central line averaged plasma density $N_{\rm e}$=1.5×10^{19}m^{-3}, $B_{\rm T}$=2T, $I_{\rm p}$=120kA, the peak of parallel refractive index $N_{//\rm peak}$=2.9 and LHW power $P_{\rm LH}$=180kW. The photon temperature ($T_{\rm HX}$) of hard x-ray in counter-LHCD is obviously lower than that in the co-LHCD (as seen in Fig.10). The lower $T_{\rm HX}$ implies a lower average energy of fast electrons. There exist two causes of the lower $T_{\rm HX}$. In counter-LHCD, the lower $n_{//}$ part of LHW cannot meet as many resonant electrons as in co-LHCD. The upshift of lower $n_{//}$ LHW is necessary to meet enough resonant electrons. The residual electric field will decelerate the fast electrons generated by LHW in counter-LHCD. On the other hand, fast electrons produced by LHW in co-LHCD will be accelerated to higher energy by the residual electric field. So $\eta_{\rm LHCD}$ will be lower in counter-LHCD. The simulation results show that the driven current in counter-LHCD is no more than half of the driven current in co-LHCD (as seen in Fig.11). The decrease of loop voltage in counter-LHCD is not as large as in LHCD. It is found that the core electron temperature measured by soft x-ray PHA increases from 0.8keV to 1.8keV in counter-LHCD, which is the main cause of the decrease of loop voltage. It is difficult to determine the value of driven current in counter-LHCD. The Abel inverted profile of soft x-ray becomes peaked in counter-LHCD (as seen in Fig.12(b)). The profile of hard x-ray shows that the power of LHW is mainly deposited in the core. Although fast electrons cannot drive current efficiently in counter-LHCD, more fast electrons slow down because of electric field and collisions, causing the plasma heating.

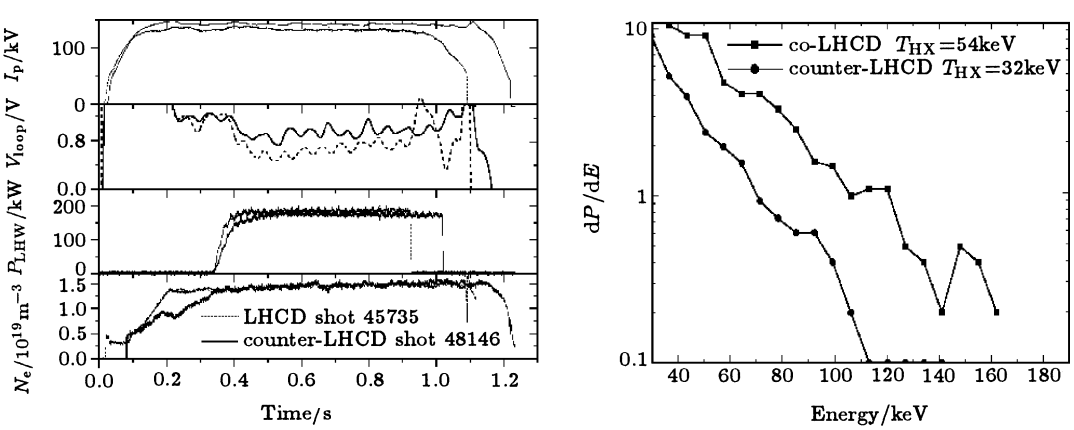


Fig.10. Waveforms of a count-LHCD discharge and co-LHCD discharge, the photon temperature ($T_{\rm HX}$) of hard x-ray in counter-LHCD and co-LHCD.

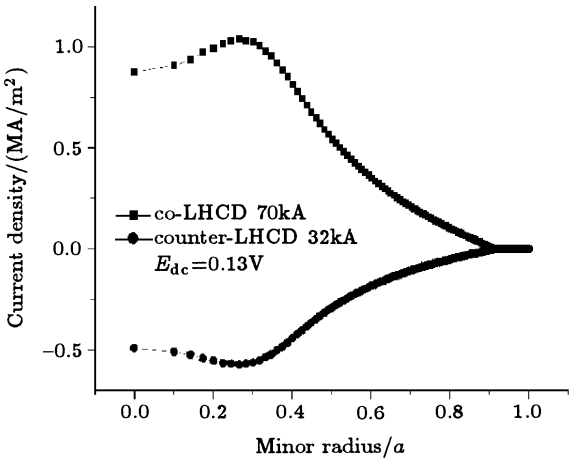


Fig.11. Simulation results of driven current from counter-LHCD and co-LHCD.

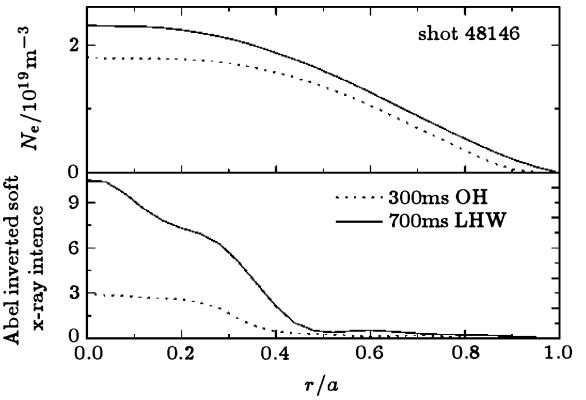


Fig.12. Electron density profile and the Abel inverted profile of soft x-ray.

4. Conclusion

The new hard x-ray diagnostic system on HT-7 allows the investigation of the fast electron dynamics. The main experimental results can be summarized as follows. Good agreement between the profile of hard x-ray and result of Fokker–Planck modelling is obtained when the value for diffusion coefficient of fast electron is equal to $2\text{m}^2/\text{s}$. Based on the hard x-ray diagnostic and other diagnostic information, the improvement of plasma confinement in LHCD experiment on HT-7 has been analysed. The results show that the hollow or flat driven current density profile favours the improvement of plasma performance. The profile of driven current density can affect the formation and position of internal transport barrier (ITB). The LHW can heat the core plasma in counter-LHCD with a moderate LHW power.

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