

High Confinement Plasma Produced by Lower Hybrid Current Drive on the HT-7 Superconducting Tokamak

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Abstract. A high confinement plasma produced by using lower hybrid current drive (LHCD) has been obtained on the HT-7 superconducting tokamak. An internal transport barrier in the core plasma was formed. The energy confinement time increases from 14.6 (OH phase) to 24.5 ms (LHCD phase), which is near the value of the ITER93 ELM free scaling. The H_{99} -factor was increased from 0.78 (OH phase) to 1.42 (LHCD phase). The experimental results were in good agreement with the simulations calculated with a ray tracing code and a 2-dimensional Fokker-Planck equation. The edge plasma characteristics around the last closed flux surface were investigated using Langmuir probes. Turbulence and transport of the edge plasma were suppressed significantly by the lower hybrid wave. Studies show that the high confinement plasma is mainly attributable to a sheared flow resulting from the varying radial electric field.

1. Introduction

Recently, LHCD has become an important means to modify the plasma current profile and to improve plasma confinement for advanced tokamak operation, and many significant results in JT-60U and Tore-Supra have been studied[1,2]. In the 2001 campaign of the HT-7 tokamak[3], a high confinement plasma was obtained by means of LHCD.

In this paper, some preliminary characteristics of high confinement plasmas are studied. A possible mechanism of the confinement improvement is also discussed.

2. Core Plasma Characteristics

High confinement performance by using LHCD is obtained at the following parameters: $I_p=220$ kA, toroidal magnetic field $B_T=2.0$ T, central line averaged plasma density $n_c=1.5 \times 10^{19}$ m^{-3} , lower hybrid wave (LHW) frequency $f=2.45$ GHz, LHW power $P_{LHW}=260$ kW, and the peak of the parallel refractive index $N_{\parallel}^{peak}=2.9$. Figure 1 shows a typical waveform of LHCD experiments (#46693). During the discharge, when LHCD is applied, the plasma loop voltage drops quickly to a certain value, which suggests that part of the plasma current is sustained by LHW power. In addition, the central

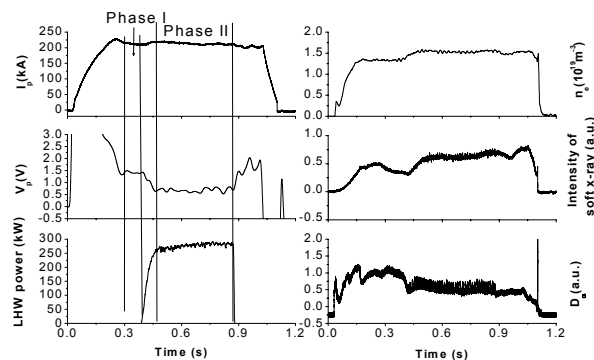


Fig. 1. Typical waveforms of LHCD experiments (#46693).

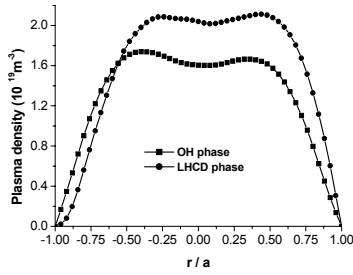


Fig. 2. Radial plasma density profile.

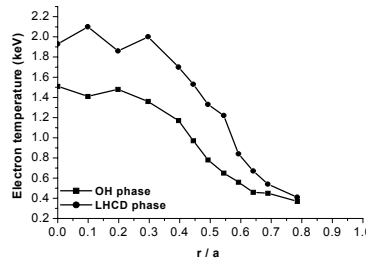


Fig. 3. Radial electron temperature profile.

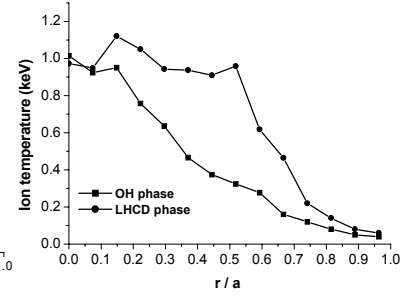


Fig. 4. Radial ion temperature profile.

line averaged plasma density (n_e) increases and the neutral deuterium radiation (D_α) decreases. The plasma density profile, as shown in Fig. 2, shows that the electron density increases from $1.5 \times 10^{19} \text{ m}^{-3}$ to $2.0 \times 10^{19} \text{ m}^{-3}$ because of LHCD near the region of $r/a \sim 0.5$ (r is the radius of the magnetic surface and a is the minor radius of the plasma column). All these phenomena indicate that particle confinement was improved.

The achieved profiles of $T_e(r)$ and $T_i(r)$ are plotted in Fig. 3 and Fig. 4. These two figures tell us that, during the LHCD phase, T_e and T_i increase and their profiles become broad, implying that the profile of plasma current is also broadened. Furthermore, the gradients of $T_e(r)$ and $T_i(r)$, especially $T_i(r)$, were increased very prominently near the region of $r/a \sim 0.5$. This means an internal transport barrier (ITB) was formed.

The experimental results are in good agreement with the code simulations. Figure 5 shows a simulated LHW power deposition profile using a ray tracing code with the experimental parameters. The LHW power mainly deposits at the position around $r/a \sim 0.5$, which is consistent with the position of the ITB. Since the LHW power mainly deposits at the position of $r/a \sim 0.5$, the driven current is farther away from the plasma center than that induced by Ohmic heating. The plasma current profile became broadened during the LHCD phase, which is seen from the simulated current profiles before LHCD (OH phase) and after LHCD (LHCD phase) shown in Fig. 6.

The energy confinement time was estimated according to the expressions

$$\tau_E = W/P_{\text{tot}}, \quad (1)$$

$$\text{and } P_{\text{tot}} = P_{\text{OH}} + P_{\text{LHW}}, \quad (2)$$

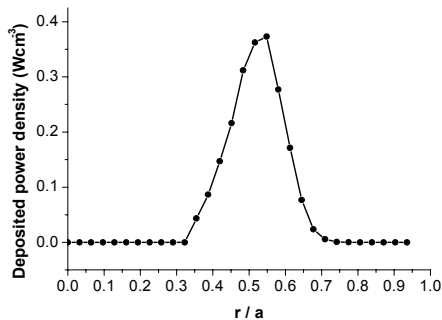


Fig. 5. LHW power deposition profile calculated with a ray tracing code.

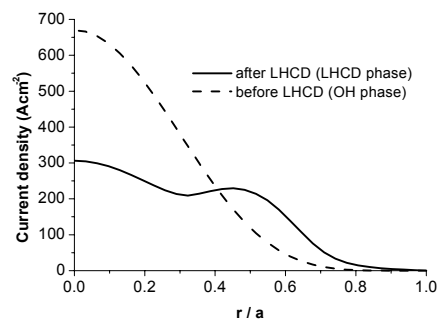


Fig. 6. Simulated current profiles before LHCD and after LHCD.

where W is the total plasma energy, which is calculated from the expression

$$W = (3/2) \cdot \int (n_e T_e + n_i T_i) \cdot dV, \quad (3)$$

where n_e , n_i , T_e , T_i are the electron density, the ion density, the electron temperature and the ion temperature, respectively. V is the volume of the plasma column. P_{OH} and P_{LHW} are the OH heating power and the LHW power absorbed by the plasma, respectively.

The OH heating power was estimated by the equation

$$P_{OH} = I_p \cdot V_p, \quad (4)$$

where I_p is the plasma current, and V_p is the plasma loop voltage.

According to equations (1), (2), (3) and (4), the estimated experimental energy confinement times during phase I (OH phase) and during phase II (LHCD phase) are 14.6 and 24.5 ms, respectively, demonstrating that the energy confinement was improved greatly.

The low confinement mode (L mode) energy confinement time scaling law of ITER89P is defined as[4]

$$\tau_E^{ITER89P} = 0.048 I_p^{0.85} B_T^{0.2} P_{tot}^{-0.5} n_e^{0.1} M^{0.5} R^{1.2} \epsilon^{0.3} \kappa^{0.5}, \quad (5)$$

with units of s, MA, T, MW, $10^{20} m^{-3}$, and m. The energy confinement factor H_{89} , which is regarded as a criterion for whether a high confinement mode (H mode) plasma is achieved, is defined as[5]

$$H_{89} = \tau_E / \tau_E^{ITER89P}, \quad (6)$$

where τ_E is the experimental energy confinement time. The energy confinement times calculated with equation (5) during phase I and during phase II are 18.7 and 17.2 ms, respectively. Thus, the corresponding H_{89} factors of 0.78 and 1.42 are achieved. This suggests that an improved confinement plasma was obtained by LHCD.

In addition, we estimate the energy confinement according to the H mode scaling law of ITER93 (edge localized mode (ELM) free)[6, 7]

$$\tau_E^{ITER93ELM\ free} = 0.036 I_p^{1.06} B_T^{0.32} P_{tot}^{-0.67} n_e^{0.17} M^{0.41} R^{1.79} \epsilon^{-0.11} \kappa^{0.66}, \quad (7)$$

with units of s, MA, T, MW, $10^{19} m^{-3}$, and m. The value predicted by equation (7) is about 27 ms, which is near to the experimental value during the LHCD phase. From the above data, it seems that the energy confinement times during the OH phase and during the LHCD phase are nearly in agreement with those predicted by $\tau_E^{ITER89P}$ and $\tau_E^{ITER93ELM\ free}$, respectively. This suggests again that a high confinement plasma was achieved.

Theory and experiments[8] show that the flow of $\mathbf{E}_r \times \mathbf{B}$ (E_r is the radial electric field, and B is the magnetic field) is responsible for plasma transport improvement. The radial electric field is crucial to form a sheared flow. To determine the radial electric field, it is often sufficient to specify and solve the radial force balance. The equilibrium of the radial force balance for ions is given by[8]

$$E_r = [1/(Z_i e)] \cdot (\partial p_i / \partial r) + [m_i / (Z_i e)] \cdot (\partial \langle \delta u_{r_i} \delta u_{r_i} \rangle / \partial r) - u_{\theta i} B_\phi + u_{\phi i} B_\theta \quad (8)$$

where Z_i is the charge state of the ions, e is the electron charge, n_i is the ion density, p_i is the ion pressure, m_i is the ion mass, and the subscripts θ and ϕ indicate the components of the mean poloidal and toroidal ion flow and magnetic field. Since the diagonal Reynolds stress contribution (the second term of the right side) is often neglected[8,9], it is evident that the radial electric field is governed by the ion pressure force, the poloidal and toroidal ion flows. Owing to a lack of diagnostics for measuring the poloidal and toroidal ion flows, we only consider the contribution of the ion pressure force to the radial field, which is described as follows. Due to the contribution of LHCD, the fast electron profile is affected greatly by LHW power deposition. Consequently, the ion temperature profile is also greatly modified as

shown in Fig. 4 because of the collisions of the ions with the high-energy particles. Owing to the variations of ion density profile and ion temperature profile, the ion pressure profile also changes greatly. According to Eq. (8), due to the effect of the ion pressure force on the radial electric field, the transport coefficients, including the electron transport coefficient and the ion transport coefficient, may decrease because of the flow shear generated by $\mathbf{E}_r \times \mathbf{B}$. Therefore, a high confinement plasma with ITB is achieved.

3. Edge Plasma Characteristics

The edge plasma characteristics around the last closed flux surface (LCFS) were investigated using the Langmuir probes. Figure 7 shows typical results (#46283). The fluctuation of the edge plasma was suppressed greatly by LHW. The turbulent particle flux and heat flux were greatly reduced after inputting LHW, as shown in Fig. 8(a) and Fig. 8(b).

All of the above data indicate that turbulence and transport of the edge plasma were suppressed, which suggests that the edge plasma was improved due to LHW.

Figure 8(c) shows the evolution of the turbulent poloidal phase velocity, which was obtained with a two-point correlating technique by using the two spatially separated floating potentials. The fluctuation changes its direction due to LHW. The radial electric field was changed to positive during LHW. Also, since the change of the poloidal phase velocity of the turbulence is nearly simultaneous with the evolution of the radial electric field, it may be considered that the change of poloidal phase velocity of the turbulence mainly resulted from the effect of $\mathbf{E}_r \times \mathbf{B}$.

The flow shear resulting from the radial electric field was thought to be an important reason for the improved edge plasma confinement. In our experiments, the observed radial electric field has an obvious tendency to change from a negative value to a positive value after the application of LHW. This suggests that the loss of fast electrons generated by LHW plays a dominant role in changing the radial electric field, which shows good agreement with the model proposed by Voitsekhovich[10]. In the model, it is suggested that the

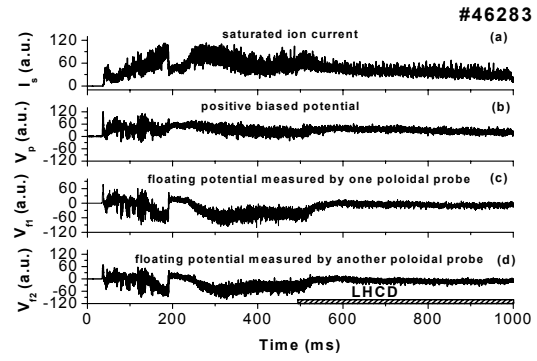


Fig. 7. Langmuir probe signals.

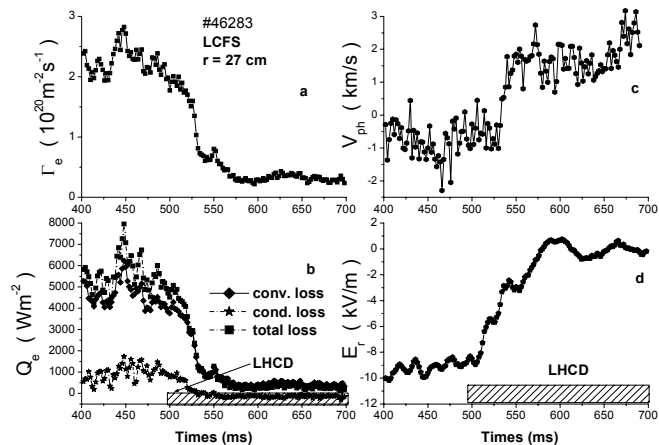


Fig. 8. Evolution of (a) electron flux, (b) heat flux, (c) turbulent poloidal phase velocity, (d) radial electric field.

confinement is improved by the increased drift flow resulting from $\mathbf{E}_r \times \mathbf{B}$. The formation of the radial electric field due to energetic electron loss is considered to be responsible for improving confinement.

Since the fast electrons generated by LHW, including those from the core and the edge, will undergo transverse diffusion during their longitudinal motion, this kind of longitudinal draining off of the fast particles towards the region beyond the limiter results in the emergence of a positive potential at the plasma edge. So, as shown in Fig. 8 (d), the radial electric field is changed by LHW just due to the very energetic electron loss. Due to the change of the radial electric field, it is possible to form a sheared flow in the edge region. Therefore, the transport of the edge plasma is reduced and the plasma confinement is improved because of the poloidal sheared flow resulting from the varying radial electric field.

4. Conclusion

An enhanced plasma performance produced by LHCD was achieved on the HT-7 superconducting tokamak. The H_{89} factor was increased from 0.78 to 1.42. A core ITB was formed near the region ($r/a \sim 0.5$) of LHW power deposition modeled by the ray tracing code. The experimental results are in good agreement with simulations. Simultaneously, the turbulence and transport at the plasma edge were suppressed greatly by LHW, which means that the edge plasma confinement was also improved. Analysis shows that a flow shear generated by $\mathbf{E}_r \times \mathbf{B}$ may be the reason for the improved plasma confinement.

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