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Improved Mode by Lower Hybrid Current Drive on HT-7 Tokamak

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Abstract A transition from low confinement mode (L-mode) to high confinement mode (H-mode) is realized by lower hybrid current drive (LHCD) on HT-7 superconducting Tokamak. The energy confinement time increases from 14.6ms (Ohmic phase) to 24.5ms (LHCD phase), which is consistent with calculation using the H-mode scaling law of ITER93ELM free. By using LHCD, an internal transport barrier (ITB) is formed and the confinement factor H up to 2.11 is obtained. Results indicate that plasma confinement is improved greatly.

1. Introduction Nuclear fusion experiments have made a rapid progress since 1980's in many tokamaks by using lower hybrid wave (LHW). Recently, many results on improved confinement in JT-60U and Tore-Supra have been reported[1, 2]. In 2001 campaign with high plasma parameters on HT-7, improved confinements are obtained by means of LHCD.

In LHCD experiment on HT-7, the plasma current is built up firstly by Ohmic (OH) discharge, then LHW is switched on to sustain the plasma current. The experiments are performed with a feedback control system adjusting the input power from the OH transformer to keep plasmas current I_p as a constant[3]. The energy confinement time is defined as $\tau_E = \dfrac{W}{P_{tot}}$ (1), $P_{tot}=P_{OH}+P_{LHW}$ (2), $P_{Oh} = I_P \cdot V_p$ (3), where, I_p is the plasma current, and V_p is the plasma loop voltage. W is the total plasma energy calculated from the expression $W = \dfrac{3}{2}\int (n_e T_e + n_i T_i) dV$ (4), n_e, n_i, T_e, T_i are the electron density, the ion density, the electron temperature and the ion temperature. V is the volume of plasma column. P_{OH} and P_{LHW} are OH heating power and the LHW power absorbed by plasma, respectively.

In this paper, some preliminary experimental results of improved plasma and the interpretation for the confinement improvement are discussed.

2. Experimental results High confinement performances by using LHCD are carried out with the parameters: I_p=220kA, a toroidal magnetic field B_T=2.0Tesla, a central line averaged plasma density $n_e=1.5\times10^{19}m^{-3}$, LHW frequency f=2.45GHz, LHW power

P_{LHW}=260kW, the peak of parallel refractive index $N_{//}^{peak}$=2.9. Fig.1 shows a typical waveform of LHCD experiments (#46693). In the discharge, when LHCD is applied, the plasma loop voltage drops quickly to a certain value, suggesting that part of the plasma current is sustained by LHW power. The central line

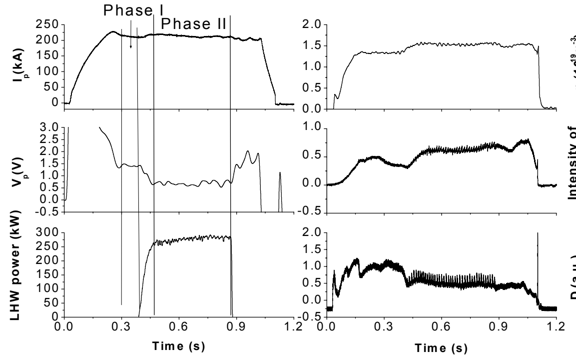

Fig. 1 Typical waveforms of LHCD experiments (#46693)

averaged plasma density (n_e) increases and neutral deuterium radiation (D_α) decreases. The plasma density profile measured by HCN laser is shown in Fig.2. The electron density increases from 1.5 to 2.0×10^{19}m^{-3} because of LHCD near the region of r/a~0.5 (r is the radius of the magnetic surface and a is the minor radius of plasma column). Also, the density profile broadens and the gradient becomes steeper in the outer region. All these phenomena indicate that the particle confinement is improved.

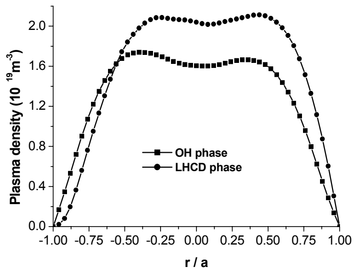

Fig. 2 Radial plasma density profile

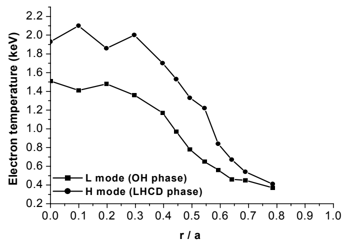

Fig. 3 Radial electron temperature profile

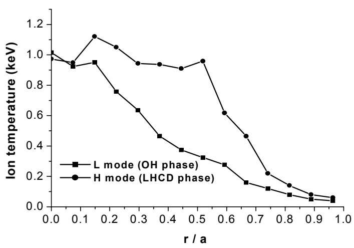

Fig. 4 Radial ion temperature profile

On HT-7 Tokamak, electron temperatures $T_{e,}$ are measured by the soft x-ray spectrum analyzer and ion temperatures T_i are diagnosed by the neutral particle analyzer. The achieved profiles of T_e(r) and T_i(r) are plotted in Fig.3 and Fig.4. These two figures show that the values of T_e and T_i increase obviously. Also, the profiles of T_e(r) and T_i(r) become broad, from which we can infer that the profile of plasma current also broadens. Furthermore, the gradients of T_e(r) and T_i(r) become steeper near the position r/a ~0.5 or so, which means a core internal transport barrier (ITB) is achieved. All above results show that an improved confinement with ITB has been obtained.

3. Analysis and discussion According to equations (1), (2), (3) and (4), the estimated experimental results are as follows: during phase I (OH phase, see Fig. 1), W=4.8kJ, P_{OH}=330kW, P_{LHW}=0kW, $\tau_E \approx$14.6ms; and during phase II (LHCD phase, see Fig. 1), W=9.5kJ, P_{OH}=130kW, P_{LHW}=260kW, $\tau_E \approx$24.5ms. The data demonstrate that the energy confinement is improved greatly by means of LHCD.

An energy confinement factor H, which can be regarded as a criterion (H>2) whether an H mode plasma is formed or not, is defined as[4]$H = \tau_E / \tau_E^{ITER89P}$, where, τ_E is the experimental energy confinement time and $\tau_E^{ITER89P}$ is the confinement time predicated by the L mode scaling law of ITER89P[5] $\tau_E^{ITER89P} = 0.048 I_p^{0.85} B_T^{0.2} P_{tot}^{-0.5} n_e^{0.1} M^{0.5} R^{1.2} a^{0.3} k^{0.5}$, with units of s, MA, T, MW, $10^{20}m^{-3}$, and meters. The predicated energy confinement times during phase I and during phase II are 12.6ms and 11.6ms, respectively. The corresponding H factors of 1.16 and 2.11 are achieved. The estimated energy confinement according to H mode scaling law of ITER93ELM free [6, 7] $\tau_E^{ITER93ELMfree} = 0.036 I_p^{1.06} B_T^{0.32} P_{tot}^{-0.67} P_{tot}^{-0.67} M^{0.41} R^{1.79} a^{-0.11} k^{0.66}$, with units of s, MA, T, MW, $10^{19}m^{-3}$, and meters, is about 27ms, which is near to the experimental value during LHCD phase. The experimental energy confinement times during OH phase and during LHCD phase coincide with those predicated by $\tau_E^{ITER89P}$ and $\tau_E^{ITER93ELM\ free}$, respectively. All above data indicate that the transition of L-H is realized.

The reason of improved confinement is mainly due to the contribution of modified plasma current profile by LHCD. The experimental results show good agreements with the code simulations. A simulated LHW power deposition profile using a ray tracing code with the experiment parameters is shown in Fig.5, showing that LHW power mainly deposits at the position around the r/a~0.5, which is located at the position of ITB. At the deposition of LHW, a number of fast electrons are generated due to the interaction between electrons and waves, consequently, a non-inductive current comes into being. Since the LHW power mainly deposits at the position of r/a ~ 0.5, the driven current is farther away from the plasma center than that induced by Ohmic heating. Therefore, the plasma current profile becomes broad during H mode phase. The current profiles modeled by a two-dimensional Fokker-Planck equation before LHCD (OH phase) and after LHCD (LHCD phase) are shown in Fig.6, indicating that plasma current profile broadens because of LHCD, which also coincides with the experimental results.

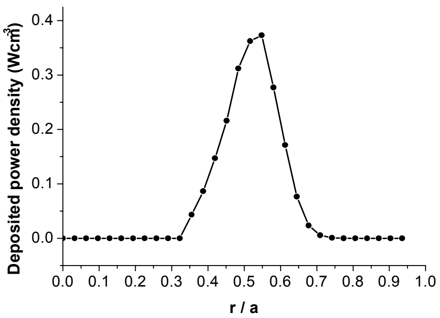

Fig. 5 LHW power deposition profile calculated with a ray tracing code

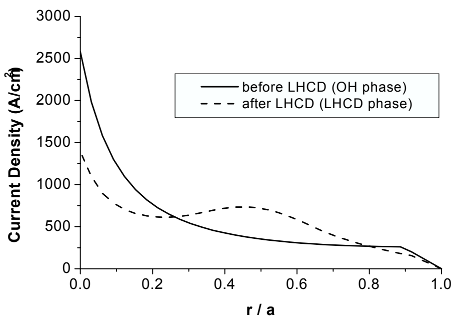

Fig. 6 Simulated current profiles before LHCD and after LHCD

4. Conclusion An H mode plasma produced by LHCD is achieved on HT-7 superconducting Tokamak. The energy confinement time increases from 14.6ms to 24.5ms, and the confinement factor H increases from 1.16 to 2.11. A core ITB is formed near the region (r/a~0.5) of the LHW power deposition obtained from the ray tracing code. Plasma current profile becomes broad due to the contribution of LHCD. The experimental results show good agreements with simulations modeled by 2-dimensional Fokker-Planck equation code.

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