Quasi-steady State High Confinement at High Density by LH Waves in the HT-6M Tokamak

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Abstract

The quasi-steady-state (t_H> 10 τ_{Eoh}) H-mode with high plasma density (ELMy and ELMy free) was routinely obtained by the injection of Lower Hybrid Heating (LHH) and Lower Hybrid Current Drive (LHCD) with a power threshold of 50 kW . The antenna spectrum was scanned in wide range and τ_E was about 1.5~2.0 times of the L-mode scaling. The density increases almost three times during the H-phase by gas puffing and the particle confinement time increases more than two times even with a line average density of $3x10^{13}cm^{-3}$, which is about 60% the Greenwald density limit. A hollow T_e profile was achieved in the high density case. The experimental results reproducibly show a good agreement with the theoretical prediction for the LH off-axis power deposition profile. When a certain of fraction of the plasma current is non-inductively sustained by the LH waves, a hollow current density profile is formed and the magnetic shear is reversed. This off-axis hollow current profile and enhanced confinement improvement are attributed to a strong reduction of electron thermal diffusivity in the reversed shear region.

1.Introduction:

The improvement of tokamak plasma confinement under non-inductive steady-state conditions is a key issue for magnetic confinement fusion research. The advanced tokamak concept appears promising for reducing the size of the device. The confinement of the tokamak plasma could be improved by optimizing the current density profile. One of the improved confinement configurations is the reversed magnetic shear in the plasma core, which is predicted by theory and observed by experiments[1]-[5]. The reversed magnetic shear could be obtained and sustained by lower hybrid current drive. How to make this configuration work under high density and steady-state conditions is still unsolved. For this purpose, experiments have been carried out on the HT-6M tokamak. The quasi-steady-state (t_H> 10 τ_{Eoh}) H-modes with high plasma density (ELMy and ELMy free) were routinely obtained by the injection of Lower Hybrid Heating (LHH) and Lower Hybrid Current Drive (LHCD) with a power threshold of 50 kW .

The plasma parameters were properly chosen to get weak LH wave absorption dormant regimes. LHH and LHCD were applied under high density conditions, in which the waves could not be absorbed in the plasma center so that a large fraction of the non-inductive current was driven in the out part of the plasma column. In these regime, the initial launched spectrum is up-shifted and broadened. The waves make many passes through the plasma and are trapped in the external column of the plasma. An off-axis non-inductive current profile is generated.

2.Experimental results:

For H-mode experiments with LH waves, the HT-6M tokamak is operated in a circular limiter configuration in D_2 working gas with major radius 65cm, minor radius 20cm, toroidal field 1 T and plasma current less than 100 kA . The plasma density is around $1\sim3x10^{13}cm^{-3}$ that is measured by 7-channel HCN interferometer. Electron temperature is obtained by ECE and soft x-ray energy spectrum. The other standard diagnostics give the information on the impurities, particle recycling and edge parameters. Two LH wave systems are used. One is mainly for current drive with a launching spectrum $n_{||}$ = 3.0±0.5 (2.45GHz). The second one could be used for either heating or current drive with a narrow changeable launching spectrum. For all the experimental conditions, the Stix-Golant accessibility limit, $n_{||\ acc}$, is about 2.4 ~ 3.0 (B_T = 1.0T, n_e = $1\sim3x10^{13}cm^{-3}$). The fixed $n_{||}$ = 2.4±0.3 (2.45GHz) is used for most shots. So the weak absorption regimes are realized.

By enhanced boronization and helium glow discharge, a very good wall condition is achieved which is optimized for the LH wave coupling with plasma: low edge density (0.3~1.5x10^{12}cm^{-3}), higher electron temperature (T_e >20eV) in the SOL and a suitable distance between the antenna and the plasma (0.5~1.5cm). The ELMy and ELMy-free H-modes are obtained for either LHH or LHCD plasma. Figure 1 shows the ELMy H-mode discharge with the LHH. The ELMy could be seen on the edge H_α monitor during the confinement improvement phase. The edge electrostatic fluctuation is suppressed. The energy and particle confinement times are increased by nearly a factor of two. By combining LHH and LHCD, the H-phase could be easily obtained and sustained for a longer time. The antenna spectrum is scanned in a wide range and τ_E was about 1.5~2.0 times of the L-mode scaling. The density increases almost three times during the H-phase by gas puffing and the particle confinement time increases more than three times even with a line average density 3x10^{13}cm^{-3} which is about 60% of the Greenwald density limit. Figure 2 is a typical H-mode shot achieved by combining off-axis LHH and LHCD. Impurity radiation is reduced for most of the H-phase unless a burst of metal impurities terminate the H-phase. A hollow T_e profile is achieved in the high density case. The transport code is used to simulate the experimental data which shows that impurities (mainly carbon and oxygen) and the electron heat diffusivity χ_e are dramatically suppressed. Figure 3 gives the visible line radiation (H_α, CIII, OV) during the discharge. The full measurements of the impurities show that Z_{eff} drops from 3.2 to 1.8 after LH wave injection and its profile becomes flatter.

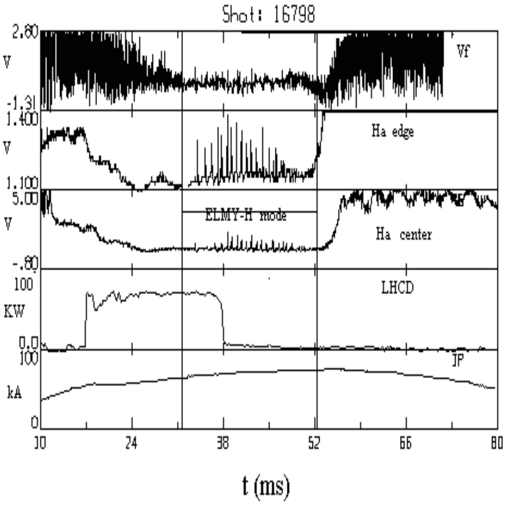

Fig. 1. ELMy H-mode by LH H. $B_T = 0.95T$, $N_{// LHH} = 2.4$, $T_{e0} = 500$ eV, $P_{LH} = 60kW$.

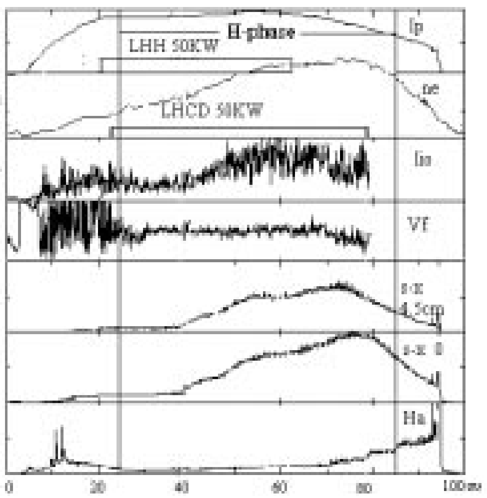

Fig. 2. Typical shot of quasi-steady-state H-mode by LH waves. $B_T = 0.93T$, $N_{// LHH} = 2.4$, $N_{// LHCD} = 3.0$, $f = 2.45$ GHz, $T_{e0} = 550$ eV.

The movable Langmuir probe array and Mach probe are finely scanned from 0.85 normalized radius to the SOL. The edge electrostatic and density fluctuations are reduced dramatically by LH waves during the H-phase. Mirnov coils give the same results. M=2, 3, 4, 5 modes are disappeared during H-phase. Figure 4 shows the temporal behavior of m=2, m=5 coils, ion saturation current and floating potential obtained by the Langmuir probe array. The edge turbulence is suppressed to an ultra-low level by LH waves. Both radial electric field shear and toroidal rotation velocity are changed during the L to H transition. By using the wavelet technique, the edge electrostatic and density fluctuations are analyzed. The coherent structure of the density fluctuations is found at the plasma edge. Higher edge electron temperature and lower density were observed by the LH waves. The edge density and temperature profiles become steeper. The shear of electric field E_r in the edge region was more negative and sustained for long time. It seems that the electric well inside the last closed flux surface plays a key role in suppressing the turbulence in the edge.

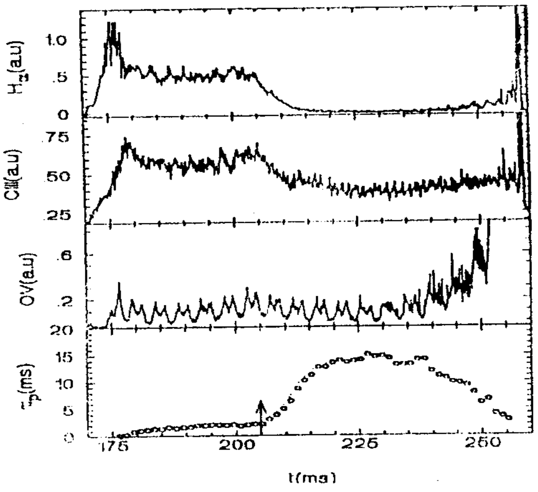

Fig. 3. Temporal behavior of H_α, CIII and OV for the LHCD+LHH H-mode.

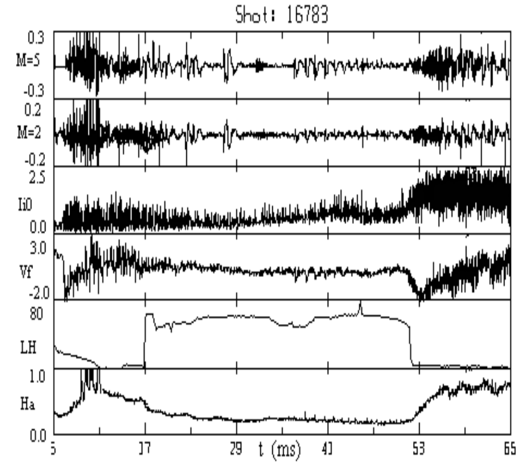

Fig. 4. The MHD and edge fluctuations were suppressed to an ultra-low level during H-phase.

3.Simulation and discussion:

To full understand the mechanism of the LH deposition profiles in the weak absorption regimes, the wave diffusion/Fokker-Planck (WD/FP) mode was used, which is derived from the phase averaging of the wave kinetic equation[6]. In this multipass absorption regime, the initial $n_{||}$-spectrum is broadened and upshifted to very high $n_{||}$ values. The power is absorbed. The electromagnetic energy density U(r,k,t) tends to be uniform. The diffusion equation for <U>(m,t) could be obtained by averaging the wave kinetic equation over the wave orbit as follow:

$$(\tau\frac{\partial}{\partial t}-\frac{\partial}{\partial m}D_{wave}\frac{\partial}{\partial m}+2\tau<\gamma>)<U>=\tau<S>$$

Where <…> denotes the orbit averaging. $D_{wave} = \Delta m^2/2$ and m is the RM S step in m per transit time. τ, γ are the damping rate and S is the RF source term which is assumed to have a δ-like form. By simplifying and integrating the Fokker-Planck equation, the 1-D current density diffusion equation could be written as [7]:

$$\frac{dJ_{rf}}{dt}=-v_M J_{rf}+v_M J_{rf0}+\frac{1}{r}\frac{\partial}{\partial r}D_{rr}r\frac{\partial}{\partial r}J_{rf}=0$$

The definition of each term of the equation can be found in the reference [7]. Combining and solving these two equations, the LH wave power deposition, and the current density and safety factor profiles could be obtained. The clear off-axis LH wave power deposition is shown in Fig. 5. The q profile is weakly reversed. q_{min} is 0.9, which is around r/a = 0.3 ~ 0.4. There are two q=1 surfaces in this radius. The double sawteeth were observed by the soft X-ray diodes in the same radius that is shown in Figure 6. The soft-x diode at 9cm observed the double sawteeth. The diode at 6cm observed the same sawteeth and m=2 oscillations . This off-axis sawtooth behavior is related with double-tearing reconnection in a reversed magnetic shear plasma [8]-[9]. The high density and low toroidal magnetic field give the LH wave a weak absorption and multipass wave propagation regime. When a certain of fraction of the plasma current (50% to 15% for the line average density $1.0\times10^{13}cm^{-3}$ to $2.5\times10^{13}cm^{-3}$) is non-inductively sustained by the LH waves, a hollow current density profile is formed and the magnetic shear is reversed at the normalized plasma radius of 0.4. The off-axis electron heating is mainly contributed by LHH and the current density profile is modified by two LH waves. This off-axis hollow current profile and enhanced confinement improvement are attribute to a strong reduction of the electron thermal diffusivity in the reversed shear region.

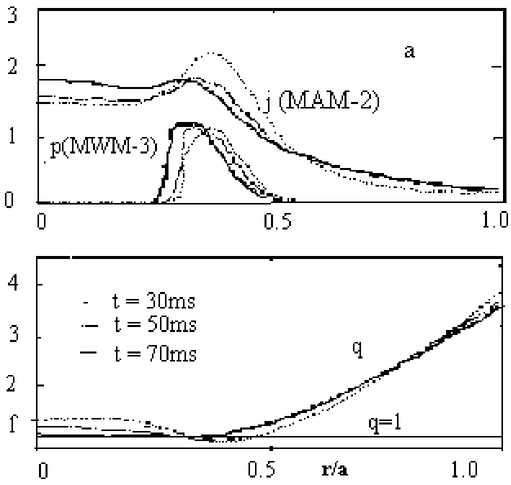

Fig. 5. Off-axis profiles at different times for the discharge of Fig. 2.

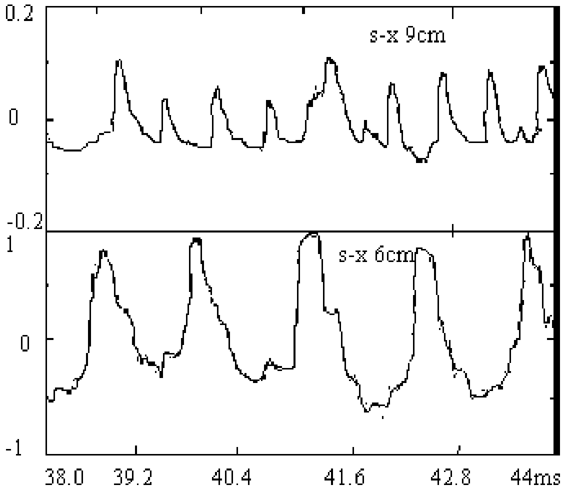

Fig. 6 Double sawtooth oscillations measured by soft X-ray diodes.

4 . Conclusion

The quasi-state-state H-mode with a density of 60% Greenwald density limit was routinely obtained by the injection of LHH and LHCD. Multipass absorption and off-axis LH power deposition were dominated and a weak reversed magnetic share was formed. The efforts are still need for the full wave current drive under steady-state high density condition. By combining ICRH, LHH and LHCD, higher current driven efficiency and lower loop voltage were obtained in the HT-6M tokamak. It may suggest that ICRH could provide one of the solution to meet this goal.

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