Investigation of plasma performance in high l_i scenario in HT-7

Jikang Xie 1), Baonian Wan 1), Xianzu Gong 1), Yuejiang Shi 1), Biao Shen 1), Jinping Qing 1), Yinxian Jie 1), Zhenwei Wu 1) and Zhongyong Chen 1)

1) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

Contact of main author e-mail: bnwan@ipp.ac.cn

Abstract: Fast plasma current ramp down at a rate of –(0.5-1.2) MA/s have been used to create different high l_i target plasmas in HT-7. The LHW pulse was applied before or just before the plasma current is ramped down. The IBW heating was applied to further increase the plasma beta and improve the plasma confinement. With such a scenario, the steady state value of l_i>1.5 was obtained for a duration of several current diffusion times, which is nearly quasi steady state. The global electron heating was observed with the strongly peaked electron temperature profile. Highest central electron temperature up to 4.5 keV at line-averaged density of 1.6×10^{19} m^{-3} has been obtained. A stationary improved confinement has been observed in such high l_i plasma. No impurity accumulation was observed during the improved confinement phase. The global confinement time at lower P_{LHW} and density is lower than the ITER-89P scaling, but close to or higher than the ITER-89P scaling at higher P_{LHW} and density. The energy confinement time is increased to the level above the ITER-89P scaling when IBW was applied. The current profile effect on the global confinement has been investigated through changed of the plasma internal inductance, l_i. An increase of the energy confinement time with l_i in the range of 1.3-1.8 is observed at the constant line averaged electron density and the injected power.

1. Introduction

Advanced tokamak scenarios need simultaneous increase in the confinement enhancement and normalized beta in near steady state conditions. Various tokamak operational regimes have been studied including the H-mode, negative central reversed shear (NCS), high l_i and radiative I-modes (RI) [1]. The impact of the current profile in the high l_i and NCS regimes is motivated by a stabilizing effect from magnetic shear on both idea high n ballooning modes and electrostatic microinstabilities, which require high positive shear and low or negative shear over a substantial portion of the plasma [2]. It is observed that the energy confinement enhancement increases with l_i in various experiments [3-5]. The maximum achievable beta has been shown to increase also with l_i, which the maximum normalized beta β_N is close to $4l_i$ [6]. Although the high l_i scenario is attractive for the advanced tokamak conception, its compatibility with significant bootstrap current and the steady state requirements is still questionable.

High positive shear is obtained when plasma current profile is strongly peaked, which gives a high internal plasma inductance l_i, while NCS requires plasma currents primarily in the outer portion of the plasma with a low l_i. High l_i plasmas can be created by negative current ramp [4,5] by increasing plasma volume, by elongation ramp [7]. High l_i plasmas were created by negative current ramp in the present experiments. Tore-Supra has produced improved confinement in high l_i LHCD steady state plasmas by this method [5]. Fast plasma current ramp down have been used to create the high l_i target plasmas at a rate of –(0.5-1.2) MA/s in HT-7. The LHW pulse was applied before or just before the plasma current is ramped down. The IBW heating was applied to further increase the plasma beta and improve the plasma confinement. With such a scenario, the steady state value of l_i>1.5 was obtained for a duration of several current diffusion times, which is nearly quasi steady state.

2. Experiments

The high l_i plasmas have been created by fast plasma current ramp-down at a rate of –(0.5-1.2) MA/s in HT-7, which were sustained by applying LHCD before or just before the plasma current is ramped down. The information of the current profile indicated by the plasma internal inductance l_i and global energy confinement times were deduced both from magnetic and diamagnetic measurements. The measurements of the interferometer, Thomson scattering, neutral particle analyzer and SX-PHA provide the kinetic electron and ion energy. The plasma inductance l_i in the range of 1.3 and 1.8 was obtained at different current ramp rate and sustained by central LHCD with an equilibrium density and temperature profiles. Fig.1 shows such two typical discharges having steady-state l_i=1.5&1.7 at I_p ramp rate of –0.7 MA/s and –1 MA/s respectively, while the transient l_i can be as high as 2.5 during the ramping phase. In such discharges, the LHW pulse at $N_{||}^{peak}$=2.3 are applied just before the plasma is ramped down. Negative loop voltage was obtained during ramping down.

In such an operation scenario with the same I_p ramping rate, the steady state l_i with LHW is higher than the one obtained in ohmic ramping down case as shown in Fig.2d. The central electron temperature (Fig.2e) and soft-x ray emission (Fig.2f) in the central view line increase considerably with the LHW power, while they decrease without LHW after the I_p ramping down. The density and temperature reach an equilibrium profile about 200ms after the plasma is ramped from higher current down to the lower plateau. Such equilibrium with the constant l_i can be sustained for several current diffusion times, which limited mainly by LHW pulse. Bulk electron heating was observed in the whole plasma volume, leading to an increase of the volume averaged temperature $\langle T_e \rangle$ (Fig.3a) The electron temperature profile was strongly peaked, while density profile was less varied during the steady-state l_i phase shown in Fig.3c by $n_e(0)$ and Fig.3d by $n_e(0)/\langle n_e \rangle$. In this phase, the electron temperature profile was peaked at ρ~0.2-0.3, with a peaking factor, $T_e(0)/\langle T_e \rangle$, of between four and five, which is indicated by Fig.3b. A weak ion temperature increase of 0.2 keV was observed. Time evolution of the main parameters of a corresponding current ramp ohmic discharge are also given by dashed lines in Fig.2 and Fig.3, as comparison to the similar discharges with LHW.

No MHD activity was detected in the stationary phase, and small sawteeth only existed during the ramp down phase (see Fig.2f). The small sawteeth activity if it existed in the target plasma can be killed after the current ramp down. The suppression of sawteeth or MHD activity may be linked to the relaxation of the local current density at the center of the plasma. The central current density, j(0), continues to decrease with l_i for several hundred ms after the transient phase. At the same time, the bulk electron temperature increases and becomes peaked, which may cause the LHW driven current more or less off-axis. As a result of these two effects, the current density and the magnetic shear decrease at the center of the plasma.

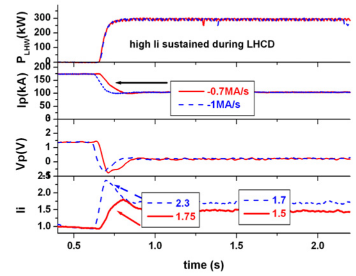

Fig.1 Steady state high l_i plasma created by the current ramp down at different rates and sustained by lower hybrid wave.

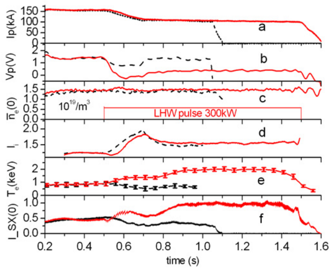

Fig.2 Time evolution of the main parameters of a typical current ramp discharge. Solid and dashed curves correspond to a LHCD and an ohmic discharge.

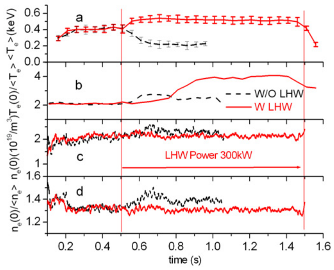

Fig.3 Time evolution of the electron temperature and density profiles indicated by the volume averaged T_e, peaking factor, central n_e and its peaking factor.

Probably it leads to formation of negative or weak positive magnetic shear close to the plasma center when the steady state current profile is reached. A similar phenomenon is observed in Tore-Supra [5]. This local behavior of the current density profile may account for the suppression of sawteeth or MHD activity and confinement improvement.

Efficient electron heating by IBW was observed through optimization of the operation scenarios in HT-7 [8]. The IBW is applied during the LHW pulse to further increase the plasma temperature and beta. It is also found that application of IBW can improve the plasma confinement. Typical discharge is shown in Fig.4 for the current ramp down experiment with combination of LHW and IBW. The central electron temperature up to 4.5 keV at line-averaged density of 1.6×10^{19} m^{-3} (Fig.4c) has been obtained by applying the 400 kW LHW at $N_{||}$=2.3 and 100 kW IBW at 27 MHz just before the current is ramped down from 160 kA to a 100 kA plateau at a rate of –0.8MA/s. The ion temperature in such discharge was 1.5 keV during steady state. The fraction of the non-inductive current was about 80% of the total plasma current in the steady state. The electron temperature profile is strongly peaked at ρ~0.2 as shown in Fig.5. A large gradient is formed at ρ~0.2, which may imply an improvement of the core plasma confinement. A stationary improved confinement has been observed in such high l_i plasma indicated by the increased H_{89} factor shown in Fig.4e. No impurity accumulation was observed during the improved confinement phase.

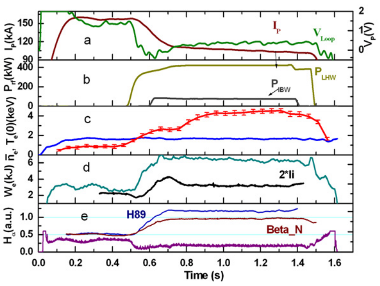

Fig.4 Time evolution of the main parameters of a typical current ramp discharge with LHW and IBW.

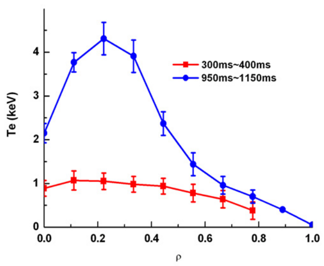

Fig.5 The electron temperature profiles at two times for the same shot in Fig.4

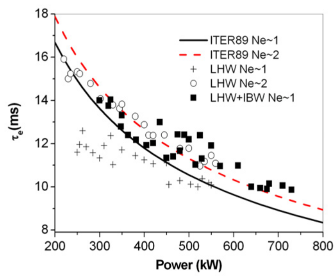

Fig.6 The energy confinement time against total injected power from the discharges with the same current ramp rate.

3.Confinements

The current ramp experiments have been carried out at the central line averaged densities of between 1.0×10^{19} and 3.0×10^{19} m^{-3}. The total injected power of P_{LHW} and P_{IBW} was ranged from 250 kW to 800 kW. The storage energy increases nearly linearly with the total injected power at constant density and current ramp rate. Figure 6 shows the plots of the energy confinement time against the injected total power at the line averaged densities around 1.0×10^{19} and 2.0×10^{19} m^{-3}, toroidal magnetic field strength of 2 T and current ramping from 180 kA to about 100 kA with a rate of 0.7 MA/s. In the case of only with the LHW pulse, the global energy confinement time with lower P_{LHW} and electron density is lower than the prediction from the ITER-89P scaling. But it is close to or higher than the ITER-89P scaling at higher P_{LHW} and density. The effects on LHW power and density could be explained assuming that the absorbed LHW power increases with electron density and LHW with higher power can improve the particle confinement more efficiently. Indeed, the particle confinement improvement was observed at the higher injected LHW power with slightly increased and peaked electron density.

The energy confinement time is increased to the level above the ITER-89P scaling when IBW was applied. The solid squares in Fig.6 were obtained from those discharges with IBW power of 80-200 kW at 27 MHz and the central line averaged density of 1.0×10^{19} m^{-3}. It is found that the IBW heating can significantly increase the plasma beta and improve the confinement of the plasmas at the same total injection power if part of LHW power was replaced by IBW. Both electrons and ions were significantly heated in this operational scenario, which leads to a considerable increase of the volume-averaged temperature, $\langle T_e \rangle$. The $\langle T_e \rangle$ shown in Fig.7 is increased by a factor of 3 for the shot indicated by Fig.4, which is higher than the one obtained only with LHW of the same total injection power. The peaking factor of the electron temperature is increased by a factor of 2, which is close to the one obtained in LHW pulse only. This effect could be attributed partially to the synergy of LHW and IBW and partially to the particle confinement by the IBW heating. The synergetic effect can improve the power deposition both for LHW and IBW [9]. The particle confinement improvement by applying IBW was observed by the drop of the Ha emission as indicated in Fig.4e and slightly broadened density profile (Fig.7d) and constant central density (Fig.7c).

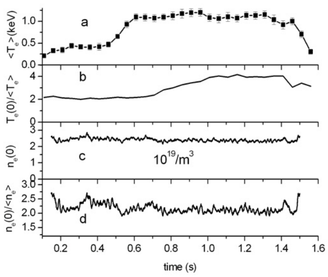

Fig. 7 Time evolutions of the electron temperature and density profiles indicated by the volume averaged T_e, peaking factor, central n_e and its peaking factor.

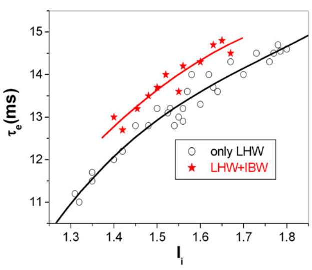

Fig.8 The energy confinement time against l_i from the discharges with the same current total injection power.

The current profile effect on the global confinement has been investigated through changed of the plasma internal inductance, l_i. This was realized at different current ramp rate. An increase of the energy confinement time with l_i in the range of 1.3-1.8 is observed at the constant line averaged electron density of 1.5×10^{19} and the total injected power of 450 kW. Figure 8 shows the results. It is shown that the IBW heating can improve the plasma confinement at the same total injection power if part of LHW power was replaced by IBW. In the present experiments, the achievable maximum normalized beta is still much lower than the beta limit. The effect of the maximum normalized on the plasma inductance l_i is not yet proved due to the limitation of available injection power. This will be investigated in further experiments.

4.Summary

Present experiments show that the high l_i plasma can be created by fast current ramp down and the steady state high l_i with an equilibrium temperature and density can be sustained by the lower hybrid wave for several current diffusion times. The global electron heating was observed with strong peaked profile, while the electron density profile is less affected by the current ramp down and LHW. This leads an increase of the volume averaged electron temperature and storage energy. No MHD activity was detected in the stationary high l_i phase. The plasma temperature and beta is considerably increased when IBW is applied during the LHW pulse. A stationary core improved confinement has been observed in such high l_i plasma, which indicated by a large gradient in the electron temperature profile. The plasma confinement is improved by IBW at the same total injection power if part of the LHW power is replaced by the IBW power, which leads the energy confinement beyond the ITER-89P scaling. The global energy confinement time decreases with the plasma inductance at the same other plasma parameters and the total injection power.

Acknowledgment

This work was supported by the National Natural Science Foundation of China under Grant No. 10235010.

[1] T.S.Taylor, Plasma Phys. Control. Fusion **39** (1997) B47-73.
[2] R.E.Waltz, G. D. Kerbel, J. Milovich and G. W. Hammett, Phys. Plasmas **2** (1995) 2408.
[3] E.J.Strait, Phys. Plasmas **1** (1994) 1415
[4] Y. Kamada, et al., Nucl. Fusion **34** (1994) 1605.
[5] G.T.Hoang, C.Gil, E.Joffrin, et al., Nucl. Fusion **34** (1994) 75.
[6] K.H.Burrell, Nucl. Fusion **43** (2003) 1555.
[7] L.L.Lao et al., Phys. Rev. Lett. 70 (1993) 3435.
[8]. Baonian Wan, Yanping Zhao, Jiangang Li, et al., Phys. Plasmas **10** (2003) 3703.
[9]. Baonian Wan et al., Nucl. Fusion **44** (2004) 400.