Pellet Injection During RF Heating on the HT-7 Tokamak[1]

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Abstract. One of the main focuses of the plasma research on the HT-7 superconducting tokamak is the exploration of advanced steady-state operation. RF heating and pellet injection experiments are carried out. D and H pellet injection has been utilized successfully for extending the operational density and modification of plasma parameters. Effective heating has also been observed in the 1999 and 2000 experimental campaigns. Recently, experiments on HT-7 illustrate a good effect on the off-axis RF heating by H and D pellet injection. The heating effect is observed clearly, the reason for which may lie in the steep electron pressure gradient created by the pellet injection. Combined with the steep local η_e gradient, good off-axis heating could provide another condition for profile and local transport studies. In addition, shortly after the injection of the pellet, the coupling efficiency of the wave is enhanced and confinement is improved. In the paper, the experiments are introduced and discussed.

1. Introduction

With a peaking density profile realized by pellet injection, the shape of the auxiliary heating profile is important, in that heating of the densified core region is good for realizing the maximum potential of the peaking density profile. Centrally peaked heating of a centrally peaking electron density profile has been studied extensively on many tokamaks [1]. For most pellet injection experiments with auxiliary heating, the favorable plasma heating sources are more localized ones, such as NBI and ICRH. Energy and particle confinement can be improved significantly as in the ohmic heating case. On the HT-7 tokamak, experiments with combined pellet injection and RF heating have been performed since the campaigns in 1998, and heating of the densified core has been observed after pellet injection during RF heating in recent experiments. In Section 2 of this paper, pellet injection work on the HT-7 tokamak is introduced briefly, then the injection and diagnostic systems are presented. Section 3 gives the experimental arrangements, and results are discussed in Section 4.

2. The HT-7 Tokamak and its Pellet Injection System

HT-7 is a superconducting middle-size tokamak, with a major radius of 1.22 m and a minor radius of 0.26-0.28 m in the circular cross section. There are one stainless steel liner and two fixed and two movable stainless steel limiters, on the tip of which different materials have been tested, such as carbon and molybdenum [2]. A toroidal magnetic field (B_t) of 1.5-2.0 T is commonly maintained during the discharge. The HT-7 ohmic heating transformer with an iron core can provide a magnetic flux of 1.7 Vs at its maximum. Recently a feedback control system for the simultaneous control of plasma current, density and displacement was developed and put into daily operation. Typical plasma current ranges from 110 to 160 kA. The major research fields on HT-7 are steady-state operation, high-performance discharge, fuelling study, lower hybrid wave (LHW) current drive [3] and ion cycle range of frequency (ICRF) heating [4].

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The primary objectives of the fuelling study are to master the technology of pellet injection, enlarge the operation region, and in the long run, to control the profile and study the improving effect on plasma confinement. In 1997, a multi-shot, in-situ pellet injection system was constructed and used for single and multi-pellet injection experiments on the HT-6M and HT-7 tokamaks. For this injector, pellets with sizes of 0.6-1.5 millimeters in diameter and 0.8 to 5 millimeters in length have been obtained in the bench test. Pellets with a size of around 1.0 millimeter in diameter and 2 millimeters in length are chosen for central fueling on the HT-7 tokamak. The velocity of the pellet ranges from 0.7 to 1.4 km/s, and the scattering angle is kept within 5^{o}.

The main HT-7 diagnostics relevant to this study include: a vertical 5-channel FIR HCN laser interferometer system for density profile measurement [5], a multi-channel ECE diagnostic for electron temperature profile measurement [6], 2 multi-channel $H_{\alpha}(D_{\alpha})$ radiation arrays, a multi-channel soft X-ray array for intensity measurement, a neutral particle analyzer (NPA), and a 3-channel soft X-ray spectrum analyzer.

3. Experimental Arrangements

At the first stage, a hydrogen pellet was injected into an ohmic heating plasma to extend the operational region of HT-7. For a typical discharge, the central line averaged density $n_e(0)$ is raised by a half after one pellet injection, and the peaking of n_e commonly sustains for 50-100 ms before decaying to the pre-injection state [7]. It was observed that the fuelling efficiency, which was defined as the step increase of the plasma particle content divided by the number of particles in the pellet fired, was 70-80% for pellet injection [8]. In a low I_p ohmic discharge, H pellet injection successfully extends the operation region beyond the Greenwald limit.

Though pellet injection can extend the operational density greatly, it decreases the electron temperature at the same time. During the pellet injection experiments, a plasma with peaking of the electron density profile and a hollow electron temperature profile was obtained. Therefore, effective heating is urgently needed for further study on HT-7. With the mastery of both hydrogen and deuterium pellet injection technology, the focus of the experiments was turned to pellet injection into auxiliary heating plasmas for the exploration of a high-performance discharge. In recent experimental campaigns, RF heating combined with pellet injection was studied on HT-7. The RF frequency was 24-30 MHz and the maximum power applied was 300 kW. The toroidal field was regulated to locate different heating layers in the plasma. During RF heating, H or D pellets were shot into the plasma. Heating of the densified core was observed.

4. Results and Discussion

In recent experiments in the HT-7 campaign, RF heating was first applied to the plasma, and a deuterium pellet was shot when the RF heated plasma reached a stable stage. It was observed that the plasma parameters were obviously enhanced by pellet injection during RF heating. Figure 1 gives the electron pressure ($n_e \cdot T_e$) profile evolution of a typical shot. After pellet injection, the electron pressure in the plasma center increases by about 30% just 3ms later. The value keeps on increasing until 40 ms later, and the pressure at about a/3 outside the axis surpasses that in the plasma core, reaching about 2 times that of the pre-injection state. About 100 ms after pellet injection, the profile recovers to the pre-injection state and the electron pressure decreases to a lower value. The enhancement should be attributed to two factors, the increasing of the density and the effective RF heating.

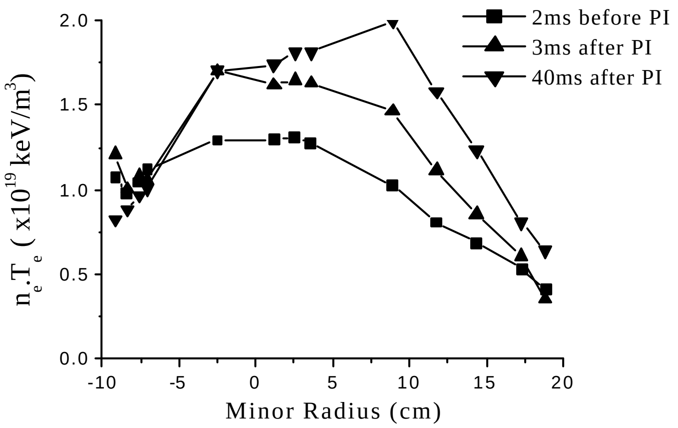

FIG. 1. Plasma parameter profile evolution of a discharge with pellet injection during RF heating (Shot 33094, I_p=140 kA, B_t=1.7 Tesla, P_{IBW}=180 kW).

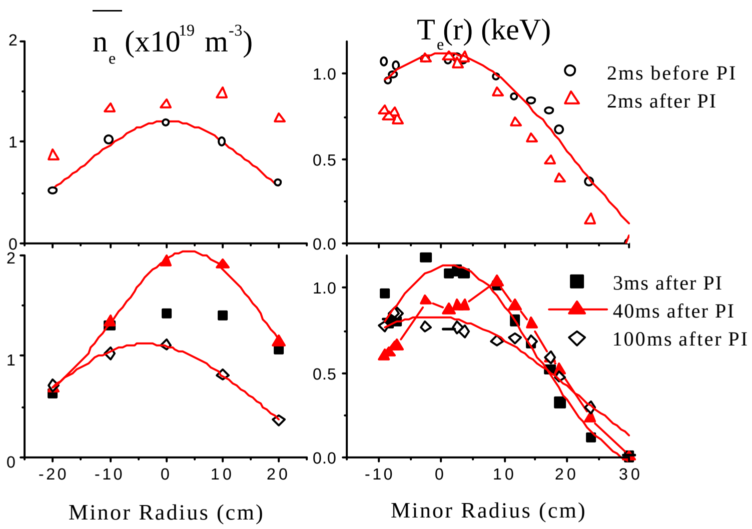

FIG. 2. Electron density and temperature profile of FIG. 1.

Figure 2 gives the electron density and temperature profile evolution for the same shot. The evolution of T_e corresponds to that of n_e quite well. For an off-axis penetration on HT-7, n_e increases broadly, while T_e drops on the whole and shows a peaked profile for a very short time. However, beginning about 3ms after the pellet injection, improved particle confinement makes the n_e profile peak greatly, and off-axis heating near the pellet deposition depth is obtained at the same time. In shot 33094, 40 ms after pellet injection, T_e around a/3 rises by more than 15% over that of the transient state shortly after pellet injection, and is higher than the pre-injection state. Electron temperature in this region even surpasses that of the plasma center by about 20%. Such a condition could be maintained for tens of milliseconds before recovering to the pre-injection state. The modification of the plasma parameter profile brought by pellet might play an important role for the enhancement of the off-axis heating.

For pellet injection experiments with low RF heating, a favourable influence on the coupling of RF heating was observed after pellet injection. In shot 21854, about 50 kW of IBW with a frequency of 27 MHz was applied, during which a pellet was injected at about 180 ms. From top to bottom, figure 3 illustrates such diagnostic signals as horizontal position of the plasma, central line averaged electron density, power of reflective RF wave, intensity of H_α signal, input power RF wave, and plasma current.

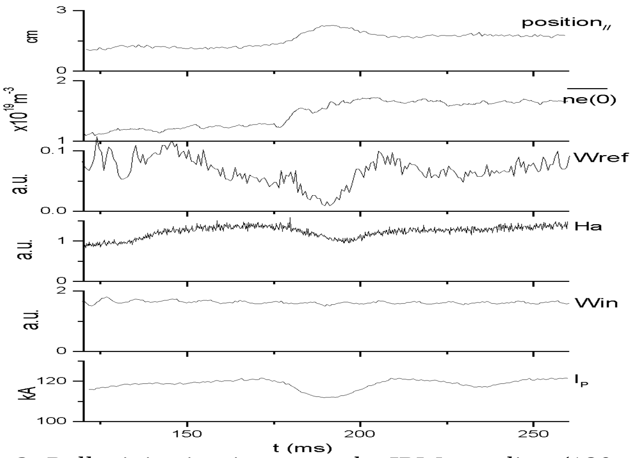

FIG. 3. Pellet injection improves the IBW coupling (180 ms).
(Shot 21854, I_p=120 kA, B_t=1.5 Tesla).

No dramatic heating effect was observed, and the reason might be that the ratio of the IBW heating was too small (only about 25% of the ohmic heating power). However, it can be seen that, corresponding to the pellet injection, the reflective power of the RF heating decreases to about 20% of the pre-injection state on the condition that there is no change of the input power. During the good coupling, the central line averaged density rises, and the intensity of the H_α signal drops at the same time, which implies that a better confinement of the plasma is obtained. Since after the loss of this better confinement the electron density remains higher than that during the pre-pellet-injection period, the modification of the plasma profile by pellet injection may be a valuable factor for confinement improvement.

5. Conclusion

It is found in HT-7 pellet injection experiments that pellet injection has a favorable impact on the off-axis RF heating. Therefore, another experimental condition is obtainable for profile and local transport studies by varying the density and temperature profiles via pellet injection and RF heating. It is suggested that there exists a favorable relationship between RF heating and plasma parameter profile. In addition, it is possible to improve the coupling of the RF wave and plasma confinement by pellet injection during the application of the RF wave. The electron density gradient might be the key point for this harmony. The relationship will be studied intensively in the future.

Acknowledgements

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