Investigation of the Synergy of IBW and LHCD for Integrated High Performance Operation in the HT-7 Tokamak

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Abstract. Control of the current density profile has been realized with off-axis current drive by the LHW and its synergetic effect with the IBW in the HT-7 tokamak. The IBW is explored as a means of improving current drive efficiency, creating a well-localized fast electron current channel and extending the high performance volume in LHCD plasmas. High performance via formation of an ITB-like profile in electron temperature, which was strongly correlated with the location of the LHW driven fast electron current, was achieved in the IBW and LHCD synergetic discharges through moving the IBW resonant layer to maximize the plasma performance and to avoid MHD activity. A variety of high performance discharges, indicated by β_N*H_{89} = 1–4, was produced for several tens of energy confinement times. This operation mode utilizing the synergetic effect of IBW and LHCD provides a new way to obtain steady-state operation in an advanced tokamak scenario.

1. Introduction

Steady-state operation of a tokamak plasma is one of the basic requirements for fusion reactors. On the other hand, high performance, as in an advanced tokamak operation scenario, is needed for the economic use of fusion reactors [1]. Investigations carried out in the HT-7 tokamak are contributing to these fusion reactor relevant issues and the underlying physics. The main purpose is to explore high performance plasma operation under steady-state conditions [2]. Control of the current density and electron pressure profiles becomes a crucial issue in advanced tokamak operation, where such control is needed for improving confinement, stabilizing instabilities and exploring high bootstrap current under high poloidal β [1].

Off-axis LHCD is a powerful tool for current density control to achieve an advanced tokamak scenario, such as the LHEP mode in Tore-Supra [3]. Significant improvement of confinement was obtained by optimizing tokamak operation with a strong off-axis LHCD mode in HT-7 [4]. Performance with H_{89} around 2 was obtained. β_N was still low since high I_p, B_t was needed to obtain higher T_e for off-axis power deposition of the LHW, and lower electron density was required for LHW accessibility. Additional heating and more reliable profile control are needed to improve the current drive efficiency and to increase the plasma β for obtaining high performance discharges under a steady-state condition. Experimental studies show that the IBW has good features for heating electrons both locally and globally via electron Landau damping (ELD), and for controlling the electron pressure profile [5, 6]. Significant ELD is essential for the electrostatic waves utilized in the scheme of IBW slow wave launch, which can aid the localization of the non-inductive current generated in the

LHCD regime [7, 8]. This mechanism was first observed in the PBX-M tokamak [9]. Operation modes to show how the two waves work together in modifying the current density profile and in enhancing LHCD plasma performance are investigated in this paper.

2. Experimental Investigation of Synergy between LHW and IBW

The IBW antenna is a quadruple T-shape with central feeding and short ends and is oriented along the toroidal direction. The peak of the parallel spectrum is at around 8 for a frequency of 30 MHz, and the low $n_{||}$ portion is weak, which is favorable for electron heating via ELD. A vertical hard X ray (HXR) pulse height analyzer (PHA) array is used as a main tool in the present investigation [10]. It provides information on the spatial and velocity distribution of the electrons accelerated via ELD by LHW. To obtain HXR profiles, Abel inversion was performed.

In typical HT-7 discharges with $I_p \sim 150$ kA, B_t=2 T and $\bar{n}_e(0) \sim 1.5\times10^{19}/m^3$, $T_e(0)$ is around 1 keV. The LHCD was typically concentrated near the center of the plasma with $N_{||}^{peak}$ = 2.3 according to a 2-D Fokker–Planck (FP) code simulation [4]. Figure 1 (dashed lines) shows a typical LHCD discharge. The HXR was increased immediately after the LHW was applied. The HXR in the central viewing line was larger than that in the half minor radius viewing line. This implies a centrally peaked HXR profile, which supports the simulation. In the first approximation, the HXR can directly reflect the power deposition and driven current density. The HXR profile is shown in Fig. 2 by the open circles. Such a centrally driven operation mode normally has a higher current drive efficiency, but its performance is not high because the effective volume of high confinement plasma is small. An increase of the high confinement volume is necessary to enhance the plasma performance. The features of the global and local heating by IBW could be explored for this purpose.

In the case of an IBW of f = 30 MHz and B_t = 2 T, the elementary D^+ resonant layer is located at the plasma center. The global electron heating and density peaking were observed in the IBW heated plasma [5, 6]. Similar behavior has been observed when the IBW was applied to an LHW driven plasma. Typical results are shown in Fig. 1 by the solid lines. The density was increased and its profile was peaked, as shown by the increased $\bar{n}_e(0)/\bar{n}_e(10)$ ratio. $T_e(0)$ was increased considerably compared with the target plasma. The HXR intensities were increased significantly in the IBW + LHW plasma, which means more fast electrons were driven. The increment of the HXR at half minor radius was more prominent than at the central viewing line, implying a broadened HXR profile, shown in Fig. 2 by the solid circles.

The HXR peak was shifted from 0.2a to around 0.35a. This implies a broadening of the fast electron current channel created via IBW injection. The fraction of the fast electron current in the central region was dramatically reduced owing to the strong absorption of LHW

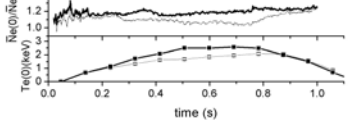

FIG. 1. Shot 45735, LHCD, and 45740, LHCD + IBW, (30 MHz) discharges.

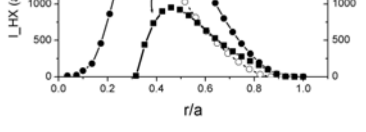

FIG. 2. HXR profiles as in Fig. 1, ΔI_{HX} = HRX (45740–45735).

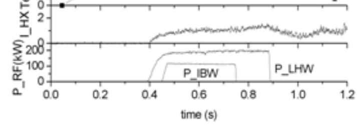

FIG. 3. Shot 46348, LHCD + IBW (27 MHz) discharge.

power in the outer region. This was partially due to the effect of the global IBW electron heating, which increases the LHCD efficiency in the outer region. Integration of the HXR of Fig. 2 in the poloidal cross-section shows that the global intensity in the LHW + IBW plasma is greater than that in the LHW plasma. This implies an increase of the global LHCD efficiency in the IBW-heated plasma in spite of increased electron density. The rising of the global electron temperature can partially account for this off-axis LHW power absorption at around 0.35a for higher $T_e(0) \sim 2$ keV according to a 2-D FP code simulation.

Recently, a numerical code was developed to simulate the IBW + LHW local synergy and to model the behavior of both waves in the PBX-M and FTU plasmas [7, 8]. The simulated results showed that the IBW $n_{\|}(x)$ oscillates along the trajectory as the ray approaches the plasma center. The IBW can quasi-linearly modify the electron distribution function and enhance damping of the LHW on the tail of this quasi-linearly modified distribution function at a maximum of $n_{\|}(x)$ and the resonant layer. The HXR radial profile in an IBW heated plasma was peaked at around 0.4a, as shown in Fig. 2. ΔI_{HX} indicates an off-axis increase of the fast electron population, which represents the region of interaction between the LHW and the IBW. The solution of the WKBJ ray-tracing equations shows the oscillating property of the IBW $n_{\|}(x)$ with plasma and wave parameters the same as shown in Fig. 1 [11]. The IBW $n_{\|}(x)$ reaches its first maximum at around r ~ 0.5a, which is nearly the radial location of ΔI_{HX} at around r ~ 0.45a. The correlation between the radial profile of ΔI_{HX} and the peak position of the first $n_{\|}(x)$ maximum implies that the incoming LHWs could damp on this tail, producing an increase of the LHCD efficiency, which results in the generation of a spatially localized current channel.

IBWs of 27 MHz were chosen to perform a systematic scan in the plasma and wave parameter space. Off-axis heating and broadening of density by IBWs of 27 MHz have been observed in the plasma around the resonant layer [6]. It is potentially possible to enhance the LHCD plasma performance through extension of the high performance volume via LHW and IBW synergy. Figure 3 shows such an LHCD discharge with IBW injection at a toroidal field strength of 2 T and plasma current of 200 kA. The corresponding ion cyclotron resonant layer is located at 0.5a. $\bar{n}_e(0)$ and $T_e(0)$ were increased when IBW was applied. The electron density profile was broadened, as shown by a decrease of $\bar{n}_e(0)/\bar{n}_e(0.37a)$ during IBW. The T_e profiles (Fig. 4) were increased in the whole plasma region and have a large gradient at around 0.45a, which is close to the resonant layer. The volume of higher n_e and T_e was considerably extended during the IBW phase compared with the LHW target plasma. The profiles of the corresponding electron pressure are shown in Fig. 5. As a result of the above, the performance was significantly enhanced. The HXR profiles from a reference LHCD plasma and a combined LHCD and IBW heated plasma are shown in Fig. 6. The peak position

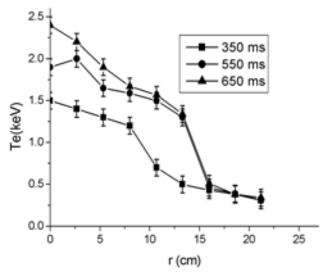

FIG. 4. T_e profiles for shot 46348.

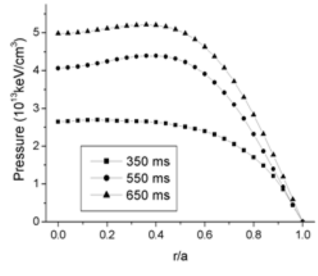

FIG. 5. Electron pressure profiles for shot 46348.

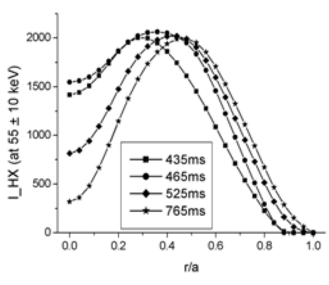

FIG. 6. HXR profiles for shot 46348

was at 0.2a in the LHCD plasma and shifted to around 0.5a in the two-wave case. This is coincident with the position of the localized IBW heating, implying that the incoming LHWs can damp on the tail of the modified electron distribution function due to IBW injection and create localized current channels.

IBWs with a frequency of 27 MHz can heat electrons globally if the resonant layer is put close to the plasma center. The $n_{||}(x)$ of the IBW oscillates along the wave trajectory. Global heating of electrons is the result of the IBW absorption at several locations, where the $n_{||}(x)$ maxima are located. The first maximum of $n_{||}(x)$ is located at around r = 0.5a with a toroidal field strength of 1.8 T. As discussed above, the LHW can interact strongly with the IBW owing to the modification of the electron distribution function. Localized current channels and a large electron pressure gradient could be created. This feature can be utilized for external control of current density and electron pressure profiles, and hence for integrated high performance.

3. Integrated Performance

The operation of IBW and LHCD synergetic discharges in HT-7 was optimized through moving the IBW resonant layer by changing B_t and selecting proper plasma parameters. This strategy was chosen to maximize the plasma performance and to avoid MHD activity. A variety of high performance discharges, indicated by the normalized product β_N*H_{89} = 1–4, were produced for a duration of several tens of energy confinement times. Figure 7 shows one such optimized discharge. The plasma performance indicated by β_N*H_{89} > 3 and H_{93} > 1 was achieved for >$50\tau_E$. The plasma current was 130 kA and the toroidal field strength was 1.85 T in this shot. The resonant layer of the IBW with a frequency of 27 MHz was at ~3 cm, very close to the plasma center. The first maximum of $n_{||}$ was located at around 15 cm (0.55a). $T_e(0)$ was significantly increased during LHCD and IBW heating, while $\overline{n}_e(0)$ was increased slightly. The profiles of electron temperature and density were gradually broadened in the plasma core region up to about half the minor radius. The results are shown in Fig. 8 for 0.5, 1 and 1.5 s. An ITB-like profile in both T_e and n_e was formed at around 1 s. At this time, a clear enhancement of the plasma performance was initiated. The profiles of LHW driven fast electron current density evolved and reached a stable state at about 1 s, as shown in Fig. 9. The position of the maximum fast electron current channel at 1.4 s was at nearly the same radius, where the electron temperature and density profiles had the largest gradients. This clear correlation between the location of the first maximum $n_{||}$ and HXR profiles confirms the role of the localized fast electron current density and the created plasma profiles in the plasma performance.

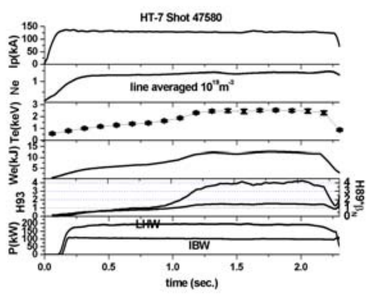

FIG. 7. Shot 47580, an LHW + IBW high performance discharge.

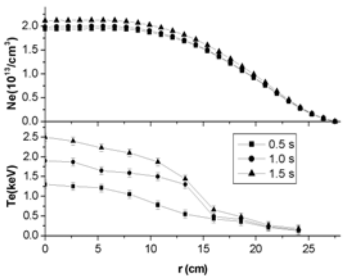

FIG. 8. T_e and n_e profiles for shot 47580.

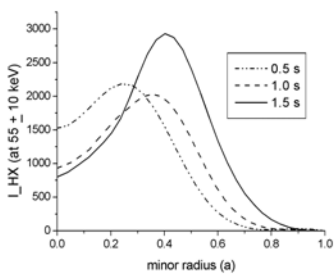

FIG. 9. HXR profiles for shot 47580.

4. Summary and Conclusion

In this paper, experimental investigation on HT-7 confirms that a local synergetic interaction between the LHW and the IBW can create a well-localized non-inductive current channel. Therefore, it can potentially become a powerful tool for controlling the current density profile. The properties of IBWs in controlling T_e and n_e profiles can be integrated into LHCD plasmas not only to improve the current drive efficiency but also to change the electron pressure profile. This feature is particularly important because the volume of high performance plasma could be significantly extended by proper selection of the plasma and wave parameter space. A large volume of high performance plasma, as well as active control of localized current density and pressure profiles, are required for an advanced tokamak scenario. LHWs, IBWs and their synergetic interaction can at least partially match these requirements. The operation mode utilizing the synergetic effect of IBW and LHCD on HT-7 provides a new way to obtain steady-state operation in an advanced tokamak scenario. The operation of IBW and LHCD synergetic discharges was optimized through moving the IBW resonant layer to maximize the plasma performance and to avoid MHD activity. A variety of high performance discharges via formation of an ITB, indicated by β_N*H_{89} = 1–4, were produced for several tens of energy confinement times.

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