Modification of Boundary Plasma Behavior by Ion Bernstein Wave Heating on the HT-7 Tokamak

G.S. Xu 1), B.N. Wan 1), M. Song 1), B.L. Ling 1), C.F. Li 1), J. Li 1), HT-7 Team
1) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R. China
In cooperation with Fusion Research Center, the University of Texas at Austin, U.S.A.
e-mail contact of main author: gsxu@mail.ipp.ac.cn

Abstract. The boundary plasma behavior during Ion Bernstein Wave heating was investigated using Langmuir probe arrays on the HT-7 tokamak. A distinct weak turbulence regime was reproducibly observed in the 30 MHz IBW heated plasmas with RF power larger than 120 kW, which resulted in a particle confinement improvement of a factor of 2. The strong suppression and decorrelation effect of fluctuations resulted in the turbulent particle flux dropping by more than an order of magnitude in the plasma boundary region. An additional inward radial electric field and associated poloidal E×B flows were produced, which could account for the additional poloidal velocity in the electron diamagnetic direction at some radial locations of the boundary plasma. The electrostatic fluctuations were nearly completely decorrelated in the high frequency region and only low frequency fluctuations remained. The poloidal correlation was considerably reduced in the high poloidal wave number region and only the fluctuations with long poloidal wavelength remained. Three-wave nonlinear phase coupling between the whole frequency domain and the very low frequency region increased significantly in both the plasma edge and the SOL. Quite low frequency fluctuations (about 5 kHz) were generated, which dominated the boundary turbulence during IBW heating. Detailed analyses suggested that, when an IBW with a frequency of 30 MHz was launched into a plasma with the toroidal magnetic field between 1.75 T and 2.0 T, the ion cyclotron resonant layer of $5/2\Omega_D$ was located in the plasma edge region. The poloidal E×B sheared flows generated by IBW near this layer due to a ponderomotive interaction were found to be the mechanism underlying these phenomena.

1. Introduction

Bulk ion heating was the original motivation of the IBW heating scheme. More recently, theoretical and experimental results showed that IBW could produce sheared flows. Therefore, IBW could be used to suppress turbulence and improve transport. The IBW power available for the plasma ions can induce a ponderomotive E×B sheared flow [1-4] near the ion cyclotron harmonic resonant layer. This effect is provided by IBW more efficiently than by other waves, due to a peculiar feature of IBW, whose RF power flux is carried mainly by the kinetic contribution of the coherent motion of the particles in the wave field. The measure of the sheared flows during the IBW experiment on TFTR gave some support to this model [5]. IBW heating was also investigated in the HT-7 superconducting tokamak deuterium plasmas with an injection power of up to 320 kW. A quite low operating frequency of 24-30 MHz and a standard loop antenna located inside the vessel were utilized. However, a distinct weak turbulence regime was reproducibly observed in the 30 MHz IBW heated plasmas with RF power larger than 120 kW.

2. Description of the Experiments

HT-7 is a circular poloidal limiter superconducting tokamak [6] with major radius R_0 = 122 cm and minor radius a = 27 cm. These experiments were conducted in ohmic deuterium target plasmas with toroidal magnetic field B_ϕ = 1.75~2.0 T, plasma current $I_p \approx$ 140 kA, central chord-averaged electron density $n_e \approx 1.5\times10^{19}$ m^{-3}, and central electron temperature around $T_{e0} \approx$ 1 keV; the plasma discharge duration was typically 1 s. A quadruple T-antenna was used with a central feeder and short ends. The IBW antenna [7] was installed in the horizontal midplane on the low field side and oriented in the toroidal direction. The radii of the central conductor and the Faraday shielding were 32 and 28.5 cm respectively. The parallel refractive index of the launched wave power spectrum was about $N_\| \approx 7$. When an IBW with an RF frequency of 30 MHz is launched into a deuterium plasma with B_ϕ = 1.75~2.0 T, the hydrogen fundamental cyclotron resonant layer Ω_H (deuterium second cyclotron harmonic resonant layers $2\Omega_D$) is located in the plasma core. In this case, the $5/2\Omega_D$ resonant layer is located in the plasma edge region on the low field side. Non-linear ion cyclotron damping due to wave self-interaction could provide significant IBW power absorption at this resonant layer. One fast reciprocating Langmuir probe and one shot-by-shot scanning probe were both mounted on the top of the tokamak along the central line. The reciprocating probe can rapidly move 8 cm in 80 ms.

3. 30 MHz IBW Heating Experiments

Fig.1 shows a typical discharge with 30 MHz IBW heating (shot 44388). The RF power was about P_{IBW} = 160 kW, which was larger than the power threshold of 120 kW. After switching on the IBW at 350 ms, the central line averaged electron density slowly increased by a factor of 2 (Fig.1.b) without active gas puffing and increased particle recycling, as indicated by the drop in the Dα emission signal, see Fig.1.c. Accompanying the decrease of Dα emission, the fluctuation level of the floating potential, which was measured at the last closed flux surface (LCFS), was suppressed significantly, as shown in Fig.1.d. There was no evident increase of the impurity influx during IBW injection, as indicated by the Z_{eff} signal (Fig.1.e). This benefited from the effective wall conditioning of the ion cyclotron radio frequency (ICRF) boronization technique [8]. The increase of plasma density and temperature together caused the enhancement of radiation, as displayed by the central chord soft X radiation signal in Fig.1.f. The level of MHD instability (m = 2 ~ 4) increased a little, which can be seen from the Mirnov probe signal in Fig.1.g.

Fig.2 shows a comparison of the boundary profiles between the IBW heating phase (shot 45575 and 45576) and the only ohmic heating phase (shot 45577). The toroidal magnetic field was $B_\phi \approx$ 1.92 T, which made the $5/2\Omega_D$ layer located in the plasma edge of r $\approx$ 26±1 cm on the low field side, where an IBW is expected to induce sheared flows. In front of the IBW antenna the electron density increased, as shown in Fig.2.(a). The expected significant drop of density in front of the IBW antenna

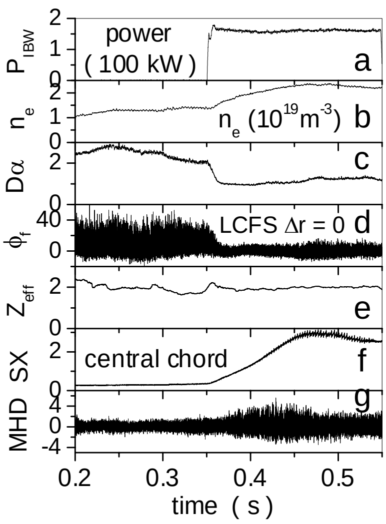

FIG.1. Time waveforms of (a) IBW power, (b) electron density, (c) Hα , (d) floating potential, (e) Z_{eff} ,(f) soft X-ray, (g) Mirnov.

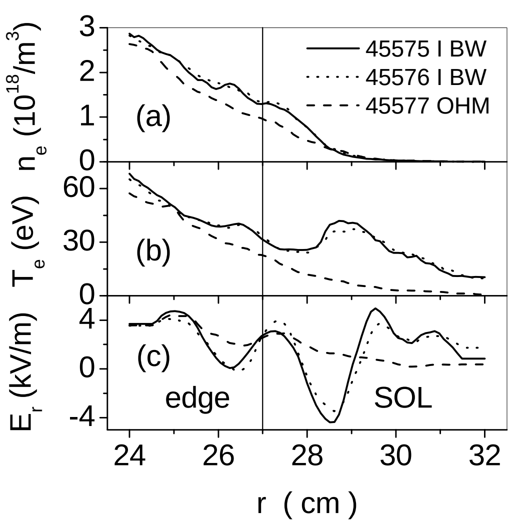

FIG.2. Profiles of the boundary (a) electron density, (b) electron temperature, and (c) radial electric field.

caused by the ponderomotive force was not found. As a consequence, the coupling between antenna and edge plasma was fairly good. The mode conversion from an electron plasma wave to an IBW is expected to occur at the cold LH resonance layer. In our experiments, it was located in the SOL of r ≈ 29 cm. The local deposition of RF power at this layer markedly modified the electron temperature profile in the SOL, as shown in Fig.2.(b). The electron temperature increased in the boundary region, especially close to the mode conversion layer. Significant change also took place on the profile of plasma potential, and consequently on the profile of radial electric field, as displayed in Fig.2.(c). An additional inward (negative) Er was generated in both the plasma edge and the SOL. The structure of two clear Er wells and the obvious increase of Er shear can be seen in this figure. A comparison between the profiles of the turbulence-shearing rate $\omega_{E\times B}$ [9] and the ambient turbulence decorrelation rate $\Delta\omega_D$ is shown in Fig.3. In the only ohmic phase (shot 45577), $\Delta\omega_D$ was larger than $\omega_{E\times B}$ in most of the boundary region, while in the IBW phase (shot 45575 and 45576) $\omega_{E\times B}$ exceeded $\Delta\omega_D$, especially in the SOL. This strong shear decorrelation effect produced a distinct weak turbulence regime in the boundary plasma.

The electrostatic fluctuation induced Reynolds stress tenser was measured by a triple probe array, see Ref.[10]. Interestingly, the launching of IBW strongly modified the properties of boundary turbulence. Three-wave nonlinear phase coupling increased significantly in both the plasma edge and the SOL, see Fig.4, where the time evolution of total cross bi-coherence between the electrostatic Reynolds stress and the floating potential fluctuations is shown. The coupling was between the whole frequency domain and the very low frequency region. Bi-coherence analysis indicated that very low frequency fluctuations (about 5 kHz) were generated, which dominated the boundary turbulence during IBW heating.

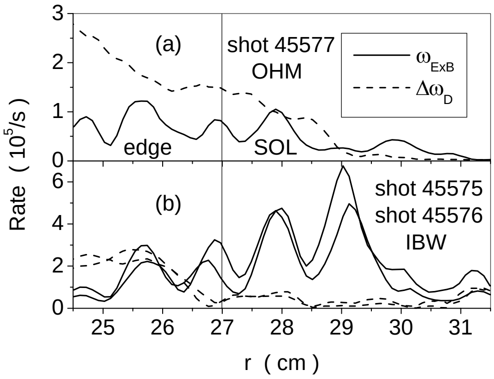

FIG.3. Profiles of the turbulence-shearing rate $\omega_{E\times B}$ and the turbulence decorrelation rate $\Delta\omega_D$ in (a) ohmic and (b) IBW phase.

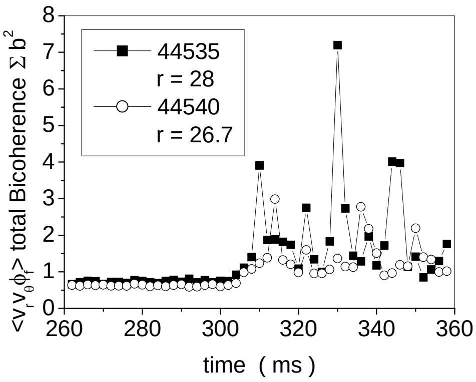

FIG.4. The time evolution of the total cross bi-coherence between electrostatic Reynolds stress and floating potential fluctuations.

In the SOL, the averaged poloidal phase velocity of turbulence turned from the ion diamagnetic direction to the electron diamagnetic direction after IBW switched on, as shown in Fig.5.(a). The additional inward Er and associated poloidal E×B flows can account for the additional poloidal velocity in the electron diamagnetic direction. The poloidal correlation length of turbulence decreased significantly in most of the boundary region (Fig.5.(b)), which demonstrated the shear decorrelation effect. Fig.5.(c) shows the statistical averaged frequency of turbulence. In the IBW phase the power of turbulence was concentrated on the low frequency region in the whole boundary plasma. The decrease of turbulence frequency was partially due to the strong suppression and decorrelation of fluctuations in the high frequency region.

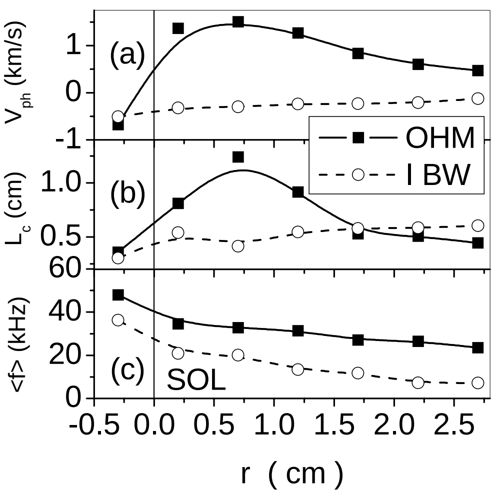

FIG.5. The profiles of
(a) averaged poloidal phase velocity,
(b) poloidal correlation length,
(c) statistical averaged frequency.

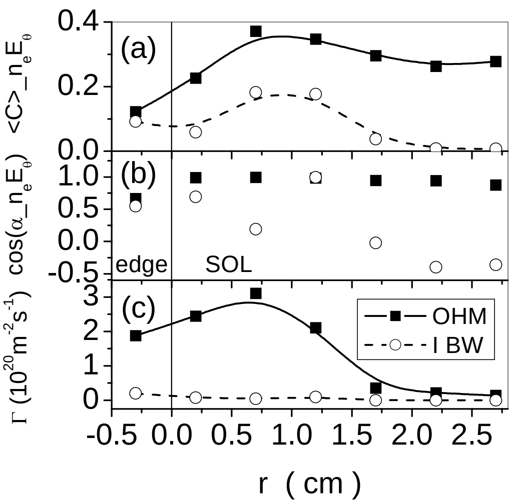

FIG.6. (a) Averaged correlation coefficient and (b) cosine of the phase difference between the electron density fluctuations and the poloidal electric field fluctuations, (c) turbulent particle flux.

Fig.6.(a) shows the averaged correlation coefficient between the electron density fluctuations δn_e and the poloidal electric field fluctuations δE_θ. A large reduction of the correlation in the SOL presents good evidence for the decorrelation effect of the sheared flows induced by IBW. Fig.6.(b) shows the cosine of the phase difference between δn_e and δE_θ. In the only ohmic heating phase, δn_e and δE_θ were approximately in-phase in the SOL, while in the IBW heating phase their relative phase was randomized. The absolute fluctuation levels of δn_e and δE_θ were both suppressed. As a result, in the whole boundary region, the turbulent particle flux was reduced more than an order of magnitude, as shown in Fig.6.(c). The intensive suppression of turbulent particle flux in the IBW heated plasmas resulted in the improvement of particle confinement.

4. Summary and Conclusions

The boundary plasma behavior during IBW heating was investigated using Langmuir probe arrays on the HT-7 tokamak. A distinct weak turbulence regime was reproducibly observed in the 30 MHz IBW heated plasmas with RF power larger than 120 kW, which resulted in a particle confinement improvement of a factor of 2. The strong suppression and decorrelation effect of fluctuations resulted in the turbulent particle flux dropping by more than an order of magnitude in the plasma boundary region. An additional inward radial electric field and associated poloidal E×B flows were produced, which could account for the additional poloidal velocity in the electron diamagnetic direction at some radial locations of the boundary plasma. Three-wave nonlinear phase coupling between the whole frequency domain and the very low frequency region increased significantly in both the plasma edge and the scrape-off layer. Quite low frequency fluctuations (about 5 kHz) were generated, which dominated the boundary turbulence during IBW heating. In the 30 MHz IBW experiment, the $5/2\Omega_D$ ion cyclotron resonant layer was located in the plasma edge region. The poloidal E×B sheared flows generated by IBW near this layer due to a ponderomotive interaction were found to be the mechanism underlying these phenomena.

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