Turbulence and Transport Studies

in the Edge Plasma of the HT-7 Tokamak

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Abstract. The edge fluctuations and transport in the HT-7 tokamak are investigated using a Langmuir probe in ohmic and IBW heating discharges. The normalized fluctuation levels are in the range of 35-50% and 10-25% for electron density and temperature respectively and have a non-Boltzmann relation in the SOL. In IBW heated plasma, the particle confinement is greatly improved, the poloidal velocity shear in the SOL is strongly modified, equivalent to an additional poloidal velocity in electron diamagnetic direction. A de-correlation in the fluctuations and suppression in turbulent transport by the effect of the poloidal shear are found to be a common mechanism. The electrostatic driven turbulent transport can account for a significant part of global particle loss in both ohmic and IBW heated plasmas.

1. Introduction

Turbulence driven transport has been found to play an important role in plasma confinement in the edge region of tokamaks. It is widely accepted that sheared radial electric field, hence sheared poloidal flow $\mathbf{E}_r \times \mathbf{B}$ plays a key role in confinement improvement as well as the global confinement property of plasmas [1]. Sheared $\mathbf{E}_r \times \mathbf{B}$ flows can influence the turbulence by shear decorrelation mechanisms and modify the turbulent induced transport.

Recently, particular attention is being paid to IBW due to its ability to generate sheared poloidal flow at the plasma layer where the ion cyclotron damping takes place. Theory shows that IBW is the most promising method to induce a poloidal flow [2, 3]. It has been demonstrated experimentally in the TFTR tokamak [4] and in non-fusion plasmas [5]. In the HT-7 tokamak, improved particle and energy confinement performance, as well as electron and ion heating, are achieved in IBW heated plasmas by proper selection of resonant location in the plasma [6], which is interesting for understanding the underlying physics.

Various experiments show that turbulent convection due to fluctuating $\mathbf{E}_\theta \times \mathbf{B}$ velocity is a major contribution to the observed anomalous radial transport [7, 8]. In this paper, we studied the fluctuation driven $\mathbf{E}_\theta \times \mathbf{B}$ particle transport in the edge plasma of the HT-7 tokamak using a Langmuir probe array in different conditions to examine the correlation between the global particle confinement and edge behavior including profiles and fluctuation.

2. Description of experiment

The experiments reported here were carried out in the HT-7 tokamak boundary plasmas. HT-7 is a medium sized super-conducting tokamak with circular limiter configuration. The main parameters of these plasmas are: R_0=122 cm, a=27.5 cm, 1.8 < B_T < 2.2 Tesla, 100 < I_P < 250 kA and pulse length of 0.5-1 second in typical ohmic discharges. It has a circular cross section and a poloidal limiter composed of molybdenum. RF waves up to 300kW can be launched into the plasma directly in IBW mode [6].

The data presented here are predominantly from a Langmuir probe array located at the top of the tokamak. The Langmuir array consists of a square array of four identical single Langmuir probes with 2mm separation between adjacent probes. They are located at the end of a stainless support tube which can be rapidly reciprocated for 5 cm in 50 ms. Two tips are operated in double Langmuir probe mode. Another two tips, aligned along the poloidal direction, are used to measure floating potentials. The fluctuation signals are digitized at 1 MHz. The fluctuating quantities are analyzed using standard spectral analysis technique [9].

3. Characteristics of turbulence of ohmic heated edge plasmas

The electron density and temperature profiles in the SOL are estimated from measurement of the fast reciprocating Langmuir probe. The radial profiles of $n_e(r)$ and $T_e(r)$ in the SOL are well expressed by radial decay lengths, which are 1.85 cm for λ_n and 3.1 cm for λ_T for ohmic heated plasma with I_P=140kA and $\bar{n}_e = 1.4\times10^{13}/\mathrm{cm}^3$. The edge electron temperature $T_e(a)$ and density $n_e(a)$ near the limiter are estimated to be 19eV and $1.8\times10^{12}/\mathrm{cm}^3$ respectively.

The radial profiles are obtained in shot by shot scanning in repeatable plasma discharges. The absolute fluctuations increase as the probe moves from the SOL to the plasma edge, as represented by ion saturation current fluctuation in fig. 1a. The normalized electron density fluctuation level (fig.1b) varies from 35% to 50% in the SOL. The normalized electron temperature fluctuation level shown in fig. 1c has a similar radial profile with a level of about 0.4 density fluctuation across the SOL. The normalized floating potential fluctuations (fig. 1d) are higher than the normalized density fluctuations, indicating that the fluctuations do not follow the Boltzmann relationship as observed in other tokamaks [10].

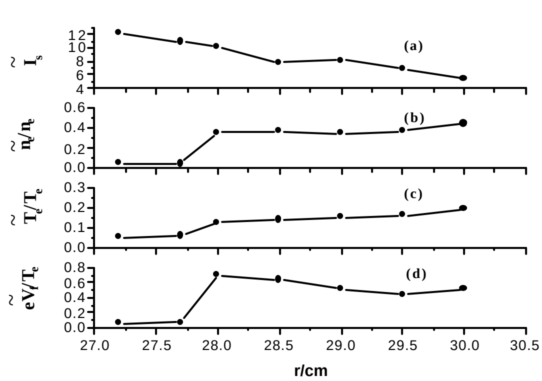

Fig. 1. Radial profiles of fluctuations for ohmic heated plasmas.

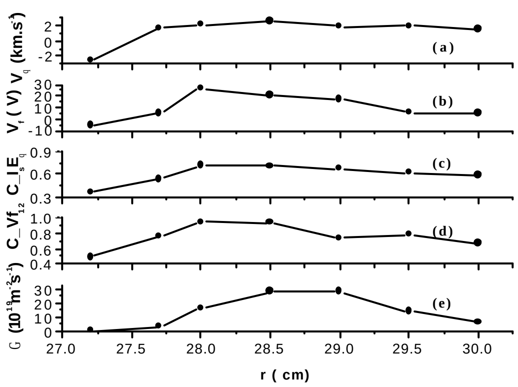

Fig.2. Radial profiles of V_q (a), V_f (b), coherence between I_S~E_q (c) and V_f~V_f (d) and G_r (e).

The time averaged cross correlation analysis of probe signals is shown in fig. 2. The poloidal phase velocity of floating potentials (fig. 2a) changes sign as the probe moves from the SOL across the limiter radius into the edge of the main plasma. The radial position of the velocity

shear layer is located at around the radius of the limiter. The propagation of the fluctuation is in the ion diamagnetic direction in the SOL region and the electron diamagnetic direction at the edge of the main plasma [11]. The floating potential changes its sign also at the same location as the velocity shear layer in fig. 2b. In this paper, we discuss the de-correlation effect of the poloidal velocity shear instead of the radial electric field because of the large uncertainty in $\mathbf{E_r(r)}$ derived from the differential of the plasma potential $V_P(r)$ to the radius.
Significant poloidal coherence between two floating voltages (fig. 2d) as well as between poloidal electric field and ion saturated current shown in fig. 2c have been observed. They decrease from r=28.5cm as the probe moves into the poloidal velocity shear layer. This has been explained by a de-correlation in the fluctuations by the effect of the velocity shear layer [12]. The time averaged turbulent particle flux (fig. 2e) is decreased in the velocity shear region, at least, partially due to the reduced correlation in fluctuations, although their absolute fluctuation levels do not decrease in the same region.

4. Turbulence and transport in IBW heated plasmas

Experiments using IBW as a heating mechanism have been performed on a variety of machines [13]. Of particular interest is the improvement in particle confinement and decreased fluctuations. In the HT-7 tokamak, IBW heating is carried out successfully to heat the plasma [6]. Significant particle confinement improvement has been observed in IBW heated plasmas with power greater than 120kW with Ip ~ 140kA, $n_e \sim 1.2\times10^{13}/cm^3$. In this paper, we discuss only the impact of the IBW induced poloidal flow on suppression of fluctuations in the edge plasmas and particle confinement without details in IBW physics.
To assure proper energy deposition near the edge plasma [2], an IBW with a frequency of 30MHz is launched into a plasma with B_T =1.95T. The resonant layer of $5/2\Omega_D$ is located at a radius of about 26cm. Fig. 3 shows a typical behavior in an IBW (at 280 ms) heated plasma discharge with P_{IBW} = 140kW. The central line averaged electron density (fig. 3b) increases, while H_α emission (fig. 3c) decreases after IBW power is applied. The fluctuation levels of ion saturation current as well as floating potentials (fig.3d) are suppressed significantly. MHD degrades the confinement and terminates the improved confinement.

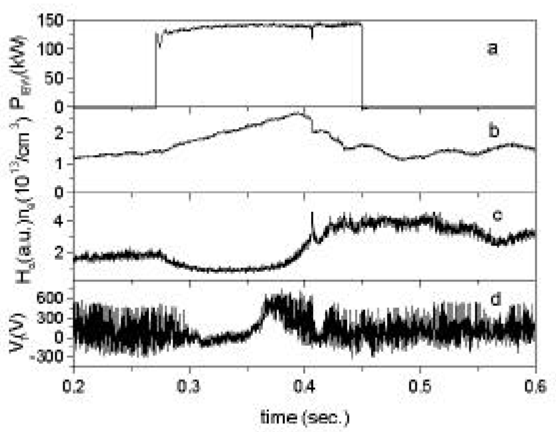

Fig.3. Typical discharges with IBW.

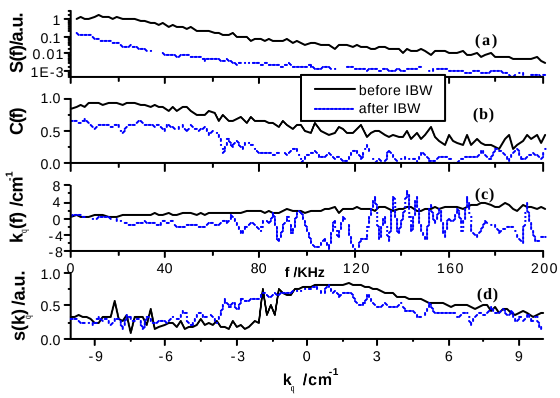

Fig. 4. Spectra of fluctuations for ohmic (solid) and IBW heated plasmas (dotted).

As the IBW is applied, the floating potential fluctuation level in the whole frequency range shown in fig. 4a is strongly suppressed, as well as the levels all of other fluctuations. The full curves in fig. 4 are the reference for the target plasma and dashed curves for IBW heated plasma. The normalized fluctuation $s(k_\theta)$ in the resolved wave-number plot in fig. 4d is shifted towards the electron diamagnetic direction. It is also clearly seen in $k_\theta(f)$ shown in fig. 4c. This fact implies that the direction of the equivalent radial electric field produced by the IBW is negative in the SOL, which modifies the global radial electric field in the SOL considerably. A similar result was also observed in the TFTR tokamak [4] and the Thorello device [5], where the direction of E_r produced by the IBW is inwards inside the resonant layer and outwards outside or in the vicinity of the resonant layer. The coherence between the two floating potentials is significantly reduced as shown in fig. 4b.

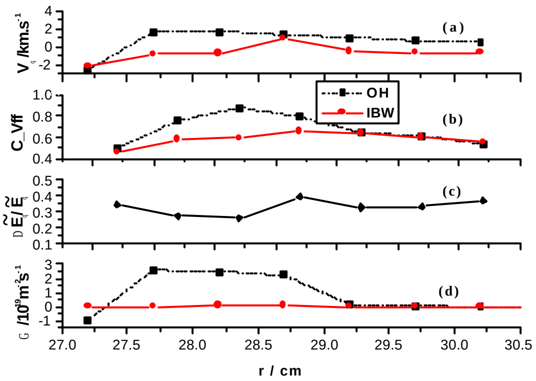

Fig.5. Radial profiles of V_q (a), coherence (b), relative E_q fluctuation and G_r (d) for ohmic (dashed) and IBW heated (solid) plasmas.

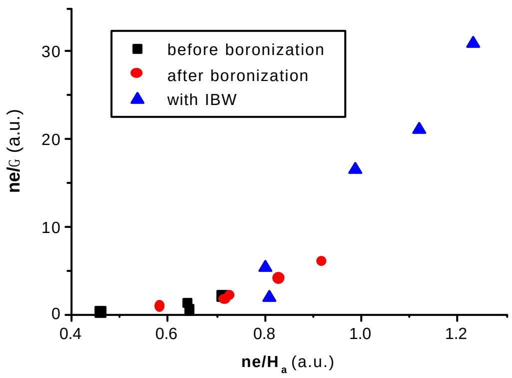

Fig.6. Correlation of particle loss measured with H_a and Langmuir probes for discharges under different conditions.

As a consequence of the modified radial electric field produced by the IBW, the radial profiles of the poloidal velocity and wavenumber are significantly changed as shown in fig. 5a. The location of the velocity shear layer is shifted inwards. In the velocity shear layer, the coherence (fig. 5b) and relative fluctuation level of E_θ (fig. 5c) are decreased considerably, which results in a significant reduction of the turbulent particle flux shown in fig. 5d. The reduced turbulent particle flux in IBW heated plasma causes the improvement in the particle confinement.

5. Turbulent particle transport versus global particle confinement time

The measured fluctuation driven particle flux is 2.5×10^{19} $m^{-2}s^{-1}$ for typical ohmic discharges at r=27.5cm. Assuming poloidal symmetry and the dominance of turbulent particle flux in transport, this implies an effective perpendicular diffusion coefficient of $D_{eff} = L_n\Gamma/n_e$ = 2.3 m^2/s, where L_n=1.85cm, T_e=21eV and $n_e = 2\times10^{18}$ m^{-3}. Applying a simple SOL model [14] to the measured values at r = 27.5 cm, the perpendicular diffusion coefficient and total particle flux at the edge are $D_{SOL} = c_sL_n^2/2L_c \sim 1.6$ m^2/s and $\Gamma_{SOL} = nD_{SOL}/L_n \sim 1.7\times10^{20}$ $m^{-2}s^{-1}$ respectively. There is a good agreement between the directly measured turbulent particle flux and the estimated total particle flux despite the simplicity of the SOL model, which ignores the local source of the plasma. These measurements indicate that fluctuation driven transport plays an important role in particle confinement in the edge plasma of the HT-7 tokamak. Both

D_{SOL} and D_{eff} are larger than the Bohm diffusion coefficient of $D_{Bohm} = T_e/16B \sim 0.7m^2/s$.
A strong correlation between the turbulent particle flux and optically measured particle confinement time was found in all discharges presented here. Fig. 6 shows the value of $\bar{n}_e / \Gamma$, which is equivalent to a particle confinement time, as a function of the global particle confinement time measured from the H_α emission. A clear linear relationship between the two measurements shows evident correlation of the turbulent particle flux and the global particle loss. This observation strongly suggests a critical role of the electrostatic fluctuation driven mechanism in the particle transport at the edge of the plasma in the HT-7 tokamak.

6. Summary and Conclusions

The edge fluctuations and transport in the HT-7 tokamak are investigated using a Langmuir probe in different discharges. The normalized fluctuation levels are 35%-50% for electron density, 15%-25% for electron temperature in the SOL. The fluctuations are non-Boltzman ($e\tilde{\phi}/T_e > \tilde{p}/p$) and have $e\tilde{\phi}/T_e > \tilde{n}_e/n_e > \tilde{T}_e/T_e$ in the SOL.

A velocity shear exists in the plasma edge and locates at around the radius of the limiter. IBW induces additional sheared poloidal flow, which is equivalent to a positive radial electric field, and shifts the poloidal velocity shear layer outwards in the SOL. The fluctuation levels and coherence, and as a consequence the turbulent particle flux, are significantly suppressed by the IBW. The minimum of the coherence and the turbulent particle flux are observed within the maximum shear layer in both the ohmic heated and the IBW heated plasmas. The reduction of the coherence levels can be explained by the decorrelation effect of the sheared poloidal flow.
The electrostatic fluctuation driven mechanism in the plasma edge plays a crucial role in determining the confinement in particle transport. The turbulent particle flux can account for the global particle confinement time well both for ohmic heated and IBW heated plasmas.

References

[1]. Burrell K H, Phys. Plasmas **4** (1997) 1499.
[2]. Craddock G G, Diamond P H, Ono M and Biglari H, Phys. Plasma **1** (1994) 1944.
[3]. Berry L A, Jaeger E F and Batchelor D B, Phys. Rev. Lett. **82** (1999) 1871, 3.
[4]. Leblanc B P, Bell R E, Bernabei S, et al, Phys. Rev. Lett. **82** (1999) 331.
[5]. Riccardi C, Bevilacqua C, Mozzi D, et al, Plasma Phys. Control. Fusion **41** (1999) 209.
[6]. Li J, Wan B N and Mao J S, Plasma Phys. Control. Fusion **42** (2000) 135.
[7]. Hidalgo C, Plasma Phys. Control. Fusion **37** (1995) A53.
[8]. Endler M, J. Nuclear Mater. **266-269** (1999) 84.
[9]. Beall J M, Kim Y C and Powers E J, J. Appl. Phys. **43** (1982) 3993.
[10]. Diebold D, Nershkowitz N, Pew J et al., J. Nuclear Mater. **196-198** (1992) 789.
[11]. Wooton A J, Carreras B A, Matsumoto H et al., Phys. Fluids **B2** (1990) 2879.
[12]. Hidalgo C, Harris J H, Uckan T et al Nuclear Fusion **35** (1995) 1307.
[13]. Ono M, Phys. Fluids **B5** (1993) 241 and references therein.
[14]. Stangeby P C, McCracken G M, Nuclear Fusion **30** (1990) 1225 and references therein.