Two Distinct Regimes of Turbulence in HL-2A Tokamak Plasmas

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Abstract: In the present paper, two distinct regimes of turbulence are identified with Langmuir probe arrays in the edge plasma of the HuanLiuqi (HL)-2A tokamak plasma for the first time. The spatial and temporal characteristics of the low frequency fluctuations (LFFs) of 20-100 kHz are found in significant contrast with the high frequency ambient turbulence (HFAT) of 100 kHz or higher. In the LFF regime, the deviations from the regular linear dispersion relation of the HFAT turbulence towards long wavelength direction are observed. Both the poloidal and toroidal correlation lengths of the fluctuations in the former are measured one order of magnitude longer than those in the latter. The ratio of the temporal scales of the fluctuations in the LFF and HFAT regimes is estimated the same order as that for the spatial scales. The LFFs may coexist with and differentiate from the geodesic acoustic modes. The bispectrum analysis of the experimental data indicate that nonlinear three wave coupling between the LFF and HFAT turbulence is a possible creation mechanism for the former. Possible correlation of the experimental results with the theory and simulation predictions on quasimode is discussed.

Keyword: Quasimode, long range correlation, low frequency fluctuation, ambient turbulence

1. Introduction

Cross field transport in magneto-confined plasmas is primarily governed by non-linear turbulence processes, with multiple drives and suppression mechanisms, occurring on multiple spatial and temporal scales. The identification of turbulence characteristics in magneto-confined plasmas, in particular, in tokamak plasmas, has always one of the key topics under intensive investigation in recent decades. One of the major progresses made in this field is the observation of zonal flows (ZFs), including low frequency zonal flow (LFZF) [1,2] and geodesic acoustic mode (GAM) [3-5]. ZFs are self-generated coherent structures of large scales, resulting from secondary instabilities and regulating the turbulence, and intrinsic components of turbulent systems that, therefore, are zonal flow-turbulence systems in fact [2]. The turbulence is usually considered as a uniform segment of such system in most theoretical and experimental studies. Recently, however, theory and simulation indicate that the drift-wave turbulence in tokamak plasmas consists of high frequency ambient turbulence (HFAT), resulting from nonlinear development of drift instabilities such as electron/ion temperature gradient (E/ITG) modes, and quasimode, generated by nonlinear toroidal coupling of the former [6-8]. The quasimodes with frequencies between ZF and HFAT play an important role in determining saturation level of the HFAT and corresponding transport, especially, in the absence of zonal flows such as in ETG driven turbulence. In addition, the nonlinear wave coupling, leading to coherent structures besides ZFs and GAM, seems universal in drift wave turbulence [2, 9,10].

In the past, as mentioned above, turbulence was generally considered as uniform fluctuations of broad spectrum and difference between the lower and higher frequency components was seldom concerned in previous experiments [4,5,11]. In particular, detailed experimental studies on distinct characteristics and creation mechanisms for fluctuation in different frequency regimes, and on interactions between them are lacking.

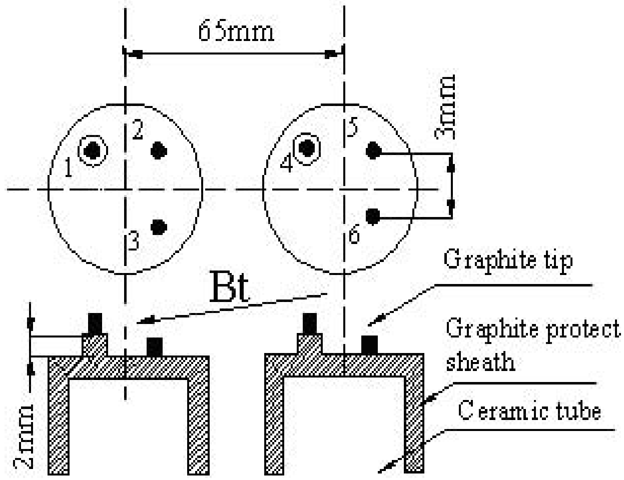

Fig.1 Layout and structure of the Langmuir probe arrays

The distinct characteristics of the low frequency fluctuations (LFF) of several tens kHz and the high frequency ambient turbulence (HFAT) of 100 kHz or higher are measured in the edge of the HuanLiuqi (HL)-2A tokamak plasmas by Langmuir probe arrays (LPs) with high spatial and temporal resolution.. Three dimensional wave number spectra and dispersion relations are investigated and compared between the LFF and HFAT. Significant differences revealing the existence of the two distinct regimes, are observed for the first time. In addition, the nonlinear coupling between the LFF and HFAT is analyzed with bispectrum technique. The main results are presented in this paper.

2. Experimental Set up

The structure and layout of the LPs employed in the present experiments are shown in Fig.1. Each LP array is composed of 3 probes possessing 2 and 3 mm separations in the radial and poloidal directions, respectively. Two of them, forming a magneto-force driven movable 6 probe set are placed at the outside middle plane with a separation of 65 mm in the toroidal direction. There is a third array of fast reciprocating 3 probes which measure the electron temperature and density profiles in the edge region. The length and diameter of each probe tip are 2 and 1.5 mm, respectively. Such experimental arrangement of the LPs with high spatial resolution allows us to measure the three dimensional wave vector spectra of the turbulence in the LFF and HFAT regimes.

The experiment was conducted in an ohmic heated hydrogen plasmas of circular cross section. The major and minor radii of the HL-2A tokamak are R = 1.65m and a = 0.4m [12], respectively. The parameters set specially for the experiments are the toroidal magnetic field B_t~1.4-2.4T, the plasma current I_p=120-300kA, the line averaged electron density $\overline{n}_e = 1 - 2.5 \times 10^{13} cm^{-3}$, the safety factor at the plasma boundary q_a = 3.5-5.3 and the discharge duration d_t =1-2s. The edge electron temperatures are calculated as T_e = 20-70eV from the LP signals. The LPs are located at r/a = 0.92-0.95.

The sampling rate of the LP signals is 1MHz corresponding to Nyquist frequency f_N = 500 kHz. 779 sets of 2^{10} data records were used and the frequency resolution is 0.98 kHz in the analysis unless otherwise stated.

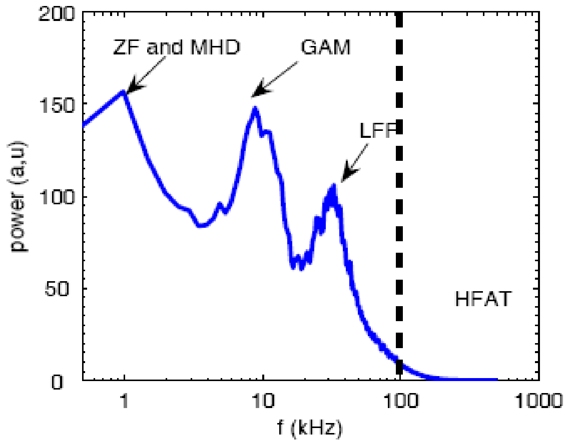

Fig.2. A representative auto-power spectrum of the floating potential fluctuation.

3. Experimental Results

A representative auto-power spectrum of the floating potential fluctuation ϕ_{f1}, with three peaks, is shown in Fig .2. where, the frequency resolution is 0.49 kHz. The first peak centered at frequency of about 1 kHz, corresponding to magnetohydrodynamic (MHD) modes and LFZF, will be discussed in a separate work. The toroidal symmetry of the second peak of GAM at frequency ~ 9 kHz and its interaction with ambient turbulence are discussed in detail in previous papers [4, 5]. The third peak centered at the frequency of ~ 35 kHz is the LFF and $\frac{\Delta f}{f} = 0.7$ which is the focus of this paper.

Shown in Fig.3. (a) are the poloidal and radial coherency spectra of the floating potential fluctuations ϕ_{f5} and ϕ_{f6} with poloidal separation of 3mm (the heavy solid line), and ϕ_{f4} and ϕ_{f5} with radial separation of 2mm (the light solid line), respectively. The correlation of HFAT over the poloidal distance $d_\theta = 3mm$ is clearly demonstrated. On the other hand, the coherency of 0.93 in the LFF regime (shadowed region in Fig.3.) indicates that poloidal correlation of LFF is significantly higher than that of the HFAT. The average coherencies of the HFAT in the poloidal and radial directions are estimated to be 0.51 and 0.44, respectively, while they are 0.87 and 0.86 in the LFF regime (the shadowed region in Fig.3), indicating that both the poloidal and radial correlations of the LFF are significantly higher those of the HFAT. The corresponding wave vector spectra are presented in Fig.3.(b). Here, the poloidal wave vector spectra of the HFAT show apparent linear dispersion relation, from which deviation towards smaller wave vector direction occurs in the LFF regime. The latter means that the group velocities of the LFF are higher than that of the HFAT. The estimated poloidal mode number is of m ~ 15-95 in the former regime. The average poloidal wave vector of the LFF is calculated as 0.57cm^{-1} by $\bar{k}_\theta = \sum_{f,k} k_\theta S(k_\theta, f) / \sum_{f,k} S(k_\theta, f)$ [13]. The corresponding average poloidal mode number is $\overline{m} = \bar{k}_\theta r = 22$, where r is the radial position of the probe.

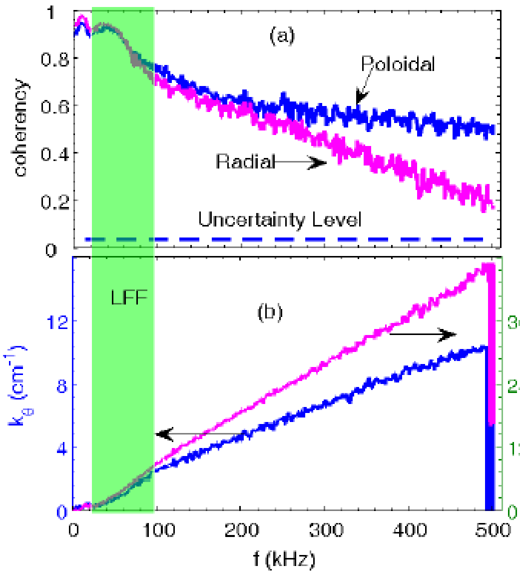

Fig. 3. (a) Coherency spectra of ϕ_{f5} and ϕ_{f6} (the heavy solid line, d_θ = 3mm), and of ϕ_{f4} and $\phi_{\phi_{f5}}$ (the light solid line, $d_r = 2mm$), (b) corresponding wave vector spectra.

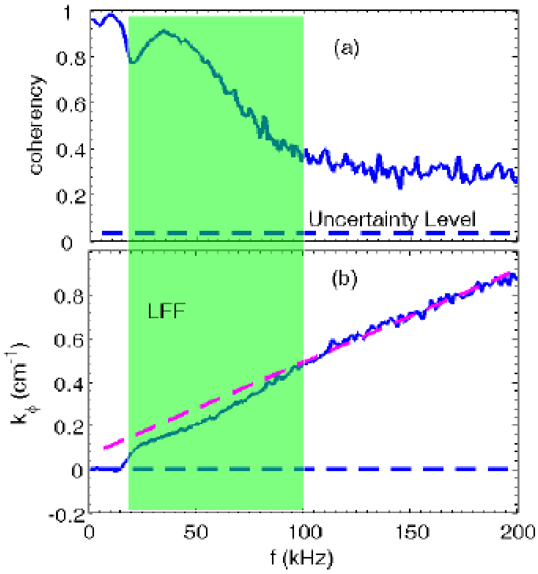

Fig.4. (a) Toroidal coherency spectra d_t = 65mm, (b) corresponding wave vector spectra.

The poloidal wave number of the HFAT is estimated to be ~ 2.5-10cm^{-1}. The spectral width of poloidal wave vectors is $\Delta k_\theta = 1.99cm^{-1}$ and the poloidal phase velocity is estimated as

$$V_{ph\theta} = \sum_{(k,f)} \frac{2\pi f}{k_\theta} S(k_\theta, f) = 3x10^3 m/s$$

for the LFF. Both the LFF and HFAT propagate in the electron diamagnetic drift direction. The electron diamagnetic drift velocity of HFAT $v_{*e} = T_e / eBL_n$ is calculated to be $0.6x10^3 m/s$, where L_n is the scale length of the density gradient. The mean shear flow velocity is $\frac{\overline{E}_r}{B} = 2x10^3 m/s$.

The radial coherency is greater than 0.6 in the LFF regime, indicating strong correlation in this direction. The HFAT also show considerable coherency of >0.2 over the whole spectra due to the short radial distance $d_r = 2mm$. In addtion, the radial wave vector spectrum of the HFAT also shows a regular linear dispersion relation similar to that in the poloidal direction. Again, apparent deviation towards smaller wave vector direction occurs in the LFF regime. The wave number $\overline{k}_r$ is estimated as 2.6cm^{-1} in the LFF regime much smaller than that in the

HFAT regime where $k_r = 10 - 48cm^{-1}$. The radial spectral width of LFF is calculated as $\Delta k_r = 3.8cm^{-1}$. Both the LFF and HFAT propagate outward in the radial direction.

The toroidal coherency spectra of ϕ_{f1} and ϕ_{f4} are shown in Fig.4.(a). The maxmium toroidal coherency of 0.91 indicates strong correlation of the LFF over the toroidal separation of $d_t = 65mm$. Although the HFAT is also correlated over the distance, but the coherency is much lower in the frequency region of 100-200 kHz and even less than 0.2 in higher frequency region. The corresponding wave number spectrum is presented in Fig.4.(b). As shown here, the toroidal wave number spectrum of the HFAT exhibits a standard linear dispersion relation, indicated by the dashed line, while deviation from it towards smaller wave number direction is apparent in the LFF regime. The toroidal mode number of ~13-80 are estimated for the LFFs. The average toroidal wave number is calculated as $\bar{k}_\varphi = 0.14cm^{-1}$, corresponding to average toroidal mode number $\bar{n} = \bar{k}_\varphi R = 23$. Where, R is the major radius of the HL-2A tokamak.

In order to check the robustness of the distinct characteristics of the LFF and HFAT mentioned above, the poloidal wave number spectra are given in Fig.5 for three sets of typical discharge parameter. Here, the discharge parameters are toroidal magnetic field B_t = 2.4, 2.2 and1.4T, plasma current I_p=300, 200 and 180kA, and line average electron density $\bar{N}_e$ = 2.5, 1 and $2.5\times10^{13}cm^{-3}$. The three sets are denoted by notations A, B and C, respectively. The corresponding $S(k_\theta, f)$ spectra of them are also given in Fig.6. The averaged poloidal wave numbers of $\bar{k}_\theta$ =2.2, 1.2 and 0.76cm^{-1}, respectively, are calculated in the LFF regime. Although the wave vector spectra are different for the three discharges, the two-regime feature of the spectrum and thus of

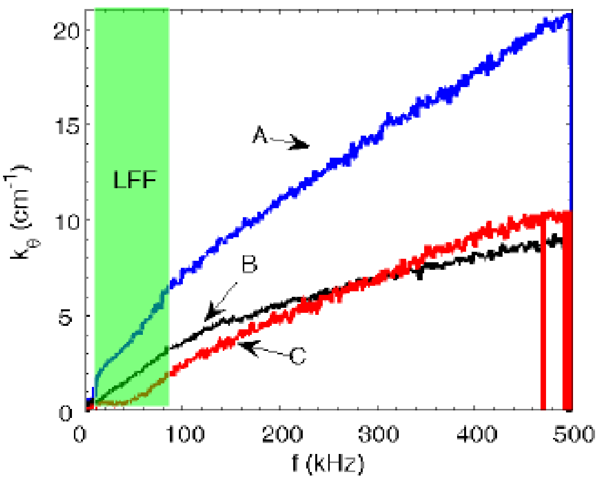

Fig.5. Poloidal wave vector spectra for the three typical discharge parameters. A. B_t=2.4T, I_p=300kA, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}, B. B_t=2.2T, I_p=200kA, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}, and C. B_t=1.4T, I_p=180kA, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}.

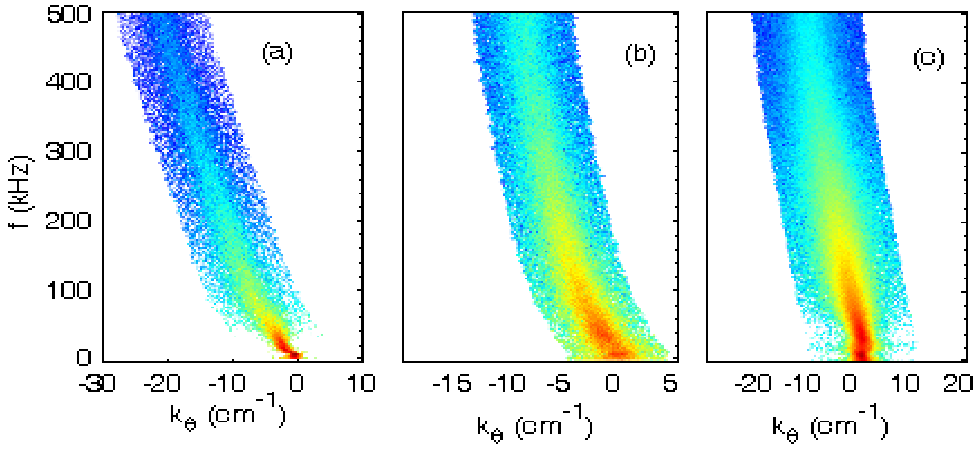

Fig.6. $S(k_\theta, f)$ spectra for the three typical discharge parameters. A. B_t=2.4T, I_p=300kA, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}, B. B_t=2.2T, I_p=200kA, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}, and C. B_t=1.4T, I_p=180kA, $\bar{n}_e = 2.5\times10^{13}$ cm^{-3}.

the turbulence seems universal and reproducible.

The phase shift between the LFF and the envelopes of the HFAT is around π, indicating possible regulating effects of the former on the latter as shown in [5].

4. Discussion and Summary

The theory and simulation of ETG turbulence predict that the quasimode of intermediate frequencies can be generated by nonlinear toroidal coupling of linearly unstable fluctuations [6, 7]. The frequency and wave number of the former are one order of magnitude lower than that of the latter. In addition, the quasimode has long wavelengths along magnetic field lines and is the major saturation mechanism of the fluctuations in the absence of ZFs. Similar results have also be found in ITG turbulence simulation, where zonal flows play an important role in the saturation processes [8]. It is not difficult to find out that the LFFs identified above have some similarities with the quasimodes. However, detailed comparison is beyond the scope of this paper and will be the subject of future work.

In summary, two distinct regimes of turbulence, LFF and HFAT, are identified with Langmuir probe arrays in the edge plasma of the HL-2A tokamak plasma for the first time. The spatial and temporal characteristics of them are demonstrated to be significantly different. The deviations of the dispersion relations in the two regimes are apparent. Both the poloidal and toroidal correlation lengths of the fluctuations in the LFF regime are one order of magnitude longer than those in the HFAT regime. The ratio of the temporal scales of the LFF and HFAT is the same order as that for the spatial scales. The LFF may coexist with and differentiate from the GAMs. The bispectrum analysis of the experimental data indicates that nonlinear three wave coupling between the LFF and HFAT turbulence is a plausible generation mechanism for the former. Possible correlation of the LFF with the theory and simulation predictions on quasimode is discussed. The results of the present work in combination with the theory and simulation may bring new concept for the compositions of turbulence systems.

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