On the Observation of ETG-Scale Turbulence on HT-7 tokamak*

Tao Zhang, Yadong Li, Shiyao Lin, Xiang Gao, Junyu Zhao, Qiang Xu

Institute of Plasma Physics, Chinese Academy of Sciences, P.O.BOX 1126, Hefei, Anhui 230031, People's Republic of China

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ETG-scale turbulence can be measured by CO_2 collective scattering system on HT-7 tokamak. In ohmic plasma, electron density fluctuation was measured from 16 cm^{-1} to 38 cm^{-1}. These turbulence show low frequency features. At $\bar{n}$ =1.5×10^{19} m^{-3} (where $\bar{n}$ is the line average density), the k-spectrum satisfy a power law $S(k) \propto k^{-4}$. In order to have an idea about the turbulence evolution in one discharge, analyses are done for shot #100878 at two time slices in the current and density flat-top phase. It is found that at t =500 ms, an evident low frequency feature (f ~ 80 kHz) appears in the frequency spectrum of k=20 cm^{-1} fluctuation by contrast with that of t=300 ms. The difference can be attributed to the steeper electron temperature profile at t=500 ms. PDF analysis is conducted on the scattering signal. The result shows that the signal is random within the experimental precision.

Keywords: CO2 collective scattering, small scale turbulence, HT-7 tokamak

1. Introduction

It is believed that drift-wave turbulence is responsible for anomalous transport [1] in magnetic fusion device. Usually, the turbulence driven transport is mainly attributed to long wavelength modes at $k_\perp \rho_s \sim 0.2$, such as ITG (ion temperature gradient) mode. Here, $k_\perp$ is the perpendicular wave number and $\rho_s = C_s/\Omega_{ci}$, where $C_s = (T_e/m_i)^{1/2}$ is the ion sound speed and Ω_{ci} the ion Larmor frequency.

In advanced tokamak configurations with a reversed magnetic shear, an improved confinement with the internal transport barrier (ITB) has been found [2-4]. From transport data analyses [5, 6], it has been shown that the ion thermal diffusivity reduces to the neoclassical level in the ITB region. This can be attributed to the **E×B** flow shear suppression for micro-instabilities, especially for the ITG mode. However, the electron thermal diffusivity is often still anomaly. Recent gyrokinetic simulations have shown that smaller scale mode (e.g ETG with $k_\perp \rho_s > 1$) may be responsible for the electron thermal transport, at least partly [7-9]. Experiment results on TFTR [24] showed that the short scale turbulence may be responsible for the electron heat transport. So the measurement of the small scale turbulence is necessary and important.

Furthermore, as tokamak plasma turbulence is a multiple scale system, analyzing fluctuations on a wide range of scales can characterize the nonlinear interaction dynamics and the energy transfer process between different scales. Kolmogorov law [19] show that in 3D fluid turbulence the kinetic energy at the scale 1/k ($\int E(k)dk = 1/2\langle v^2 \rangle$) cascades as a power law $E(k) \sim k^{-5/3}$ in the inertial range. The situation is different for 2D turbulence because the existence of two conserved quantities, energy and enstrophy (integrated square of vorticity) make dual cascade take place. It can be assumed that at a given initial time energy is injected at a scale k_f. The nonlinear interaction will transfer energy to larger scales $k<k_f$, which is called inverse energy cascade, usually leading to the formation of large structure. The cascade process will result in a power law energy distribution $E(k) \sim k^{-5/3}$ at $k<k_f$. On the other hand the direct enstrophy cascade will transfer fluctuation energy to smaller scales $k>k_f$ until dissipation scale, leading to energy distribution $E(k) \sim k^{-3}$ at $k>k_f$. Due to strong magnetic field in tokamak, the turbulence is generally expected to follow the two dimensional picture.

In order to better understand the turbulence and anomalous transport, fluctuation measurements over a range in wavenumbers have been undertaken in a variety of fusion research devices. These efforts include broad wave number fluctuation measurement in DIII-D [10], far-infrared (FIR) scattering and Doppler backscattering in Tore Supra [11, 12], microwave scattering in NSTX [13] and enhanced upper-hybrid resonance backscattering in FT-2 [14]. On HT-7 tokamak, CO2 collective scattering system has been employed to measure density fluctuation over a broad wave number from medium k to high k

author's e-mail: zhangt@ipp.ac.c

[15].The diagnostics has been applied in different operational regime to understand the turbulence and transport on HT-7 tokamak. In the paper, we focus on some results in ohmic discharge.

2. Experimental Setup

The HT-7 superconducting tokamak [16] is a medium size fusion research device. It has a major radius of R = 1.22 m, minor radius of a = 0.27 m in the circular cross-section. There are two layers of thick copper shells, and between them are located 24 superconducting coils which can create and maintain a toroidal magnetic field (B_T) of up to 2.5 T. The HT-7 tokamak with the limiter configuration is normally operated under the basic parameters: I_P = 100 ~ 250 kA, the toroidal magnetic field B_T = 2 T, the central line-averaged plasma density $\overline{n}_e$ = (1 ~ 6) $\times 10^{19}$ m^{-3}, central electron temperature T_e = 0.5 ~ 3.0 keV and central ion temperature T_i = 0.2 ~ 1.5 keV. electron density were feedback controlled during discharges.

Density fluctuation has been measured by a CO_2 collective scattering system on HT-7 tokamak. The diagnostic is based on coherent forward collective Thomson scattering [17]. This scattering process should obey the energy and momentum conservation, i.e. $\omega = \omega_s - \omega_i$ and $\mathbf{k} = \mathbf{k}_s - \mathbf{k}_i$, where ($\omega_i$, $\mathbf{k}_i$) are frequency and wave vector for injected CO_2 laser respectively, (ω_s, $\mathbf{k}_s$) for scattering light and (ω, $\mathbf{k}$) for the density fluctuation wave. Generally, the momentum conservation can be written as Bragg relation, $k=2k_i\sin(\theta/2)$, where θ is the scattering angle. The diagnostics is homodyne detection currently. The signal received on the detector $i_k(t)$ is proportional to the spatial Fourier transform of density fluctuations at the scale corresponding to the scattering wave-vector $\vec{k}$, i.e.

$$i_k(t) \propto \int \tilde{n}(\vec{r},t) u(\vec{r}_\perp) e^{i\vec{k}\bullet\vec{r}} d\vec{r}$$

Usually, three independent channels with different scattering angles are used simultaneously to monitor density fluctuation as shown in Fig. 1. The radiation source is a continuous-wave CO_2 laser with an output power of 12 W at wavelength λ = 10.6 μm. Three beam splitters (BS1, BS2 and BS3 in Fig. 1) are used to produce three 'local oscillator' beams (LO1, LO2 and LO3 in Fig. 1) and a main probe beam. A movable mirror M1 is adopted to adjust the angle between the main and LO beams. Since the chord is central, the observed fluctuation wave-vector $\vec{k}$ is in the poloidal direction, i.e. k_θ. Currently, the system can measure density fluctuation with wave number k_θ ranging from 10 cm^{-1} to 40 cm^{-1}. The wave number resolution $\triangle k$ is about 2 cm^{-1}. Because the scattering angle θ is typically less than 1°, the measurement is non-local. The work on Tore Supra [18] has shown that the spatial resolution can be improved

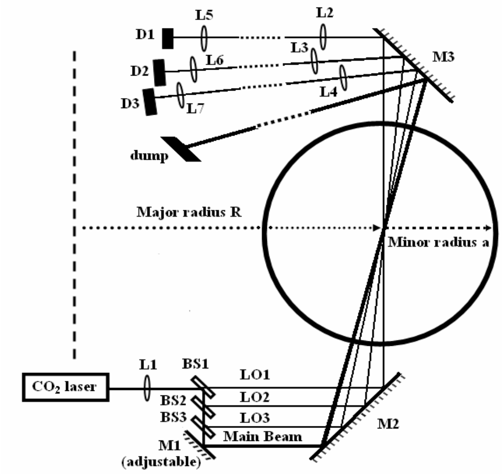

Fig. 1 Schematic diagram of CO_2 collective scattering system on Hefei tokamak-7 (HT-7).BS1, BS2 and BS3 are beam splitters; LO1, LO2 and LO3 are 'local oscillator' beams; L1~ L7 are lenses; M1, M2 and M3 are mirrors and is adjustable; D1, D2 and D3 are detectors.

for forward scattering by use of the assumption that the fluctuation wave number should be nearly perpendicular with the magnetic field, $\mathbf{k}\cdot\mathbf{B}\approx 0$.

In order to measure a wide range of wave number turbulence in the same condition, a series of identical discharges were conducted. The discharge gas was deuterium for ohmic heating. The parameters were as follows: toroidal magnetic field, B_T = 1.84 T; plasma current, I_P = 140 kA; central line average density, $\overline{n}$ = 1.5×10^{19} m^{-3}; central electron temperature, T_e, about 0.8 keV. The measured turbulence ranged from k=16 cm^{-1} to 36 cm^{-1}, the normalized wave number $k\rho_s$ = 2 ~ 6. In the experiment, the scattering always take place in the poloidal plane. According to the idea in [18] and a simple calculation, the main contribution to scattering signal comes from the confinement zone (ρ = 0.3 ~ 0.6, where ρ is normalized minor radius) of the tokamak.

3. Experimental results and discussions

Shown in Fig.2 (a) is the k (wave number) – f (frequency) spectrum of the turbulence. A typical frequency spectrum (k=24 cm^{-1}) is shown in Fig.2 (b). The lower frequencies (f <20 kHz) include noise of the detector and the effects of acoustic vibrations on the optical system have been filtered from the signal. The peak frequency is about 120 kHz. In the frequency range from f = 120 kHz to 1000 kHz, the turbulence energy satisfies a power law $S(f) \propto f^{-1.2}$, while for f >1000 kHz the energy fall off faster with frequency in a power law

$S(f) \propto f^{-4.2}$. The spectrum which follows power law remarkably well in a large range of frequencies implies self-similarity. These results show low frequency turbulences (compared to the ion cyclotron frequency f_{ci}, which is about 14 MHz in the experiment.).

The k-spectrum shown in Fig.2 (c) indicates the density fluctuation energy $S(k) = |\delta n/n|^2$ has a power law

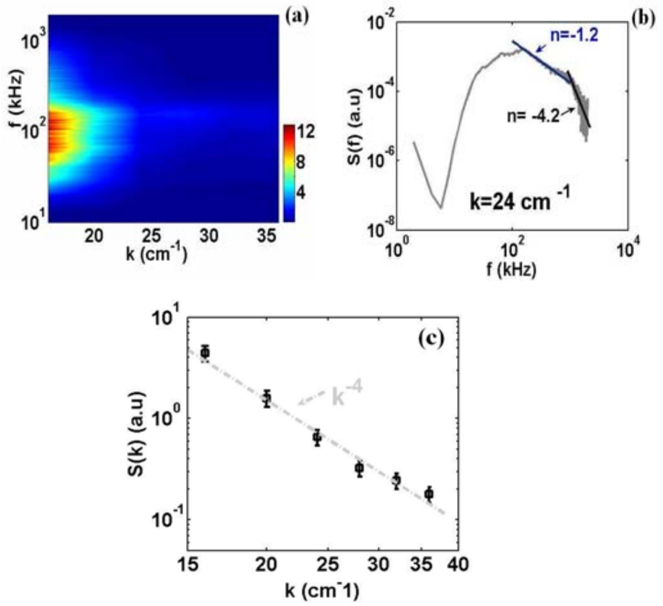

Fig.2 Characteristics of fluctuation in ohmic plasma (a) k-f spectrum (b) frequency spectrum of k =24 cm^{-1} turbulence (c) the k-spectrum.

distribution in k space, $S(k) \sim k^{-4}$. The k-spectrum of drift wave turbulence can be deduced from Hasegawa-Mima equation [20, 21]. The unidirectional energy spectrum $W(K)=(1+K^2)|\delta\varphi|^2$ satisfies $W(K)\sim K^{-4}$ in high K range as shown in [21] which is in accordance with the Kraichnan's inertial range spectrum, where K is the normalized wavenumber $K=k\rho_s$ and $\delta\varphi$ is the normalized fluctuating potential. It should be noted that in our experiment the measured physic quantity is density fluctuation. If electron satisfy Boltzmann distribution, i.e. $\delta n/n\sim \delta\varphi$ (adiabatic electron), then $|\delta n/n|^2 \sim K^{-4}/(1+K^2)$. Due to in our experiment, K>1 leads to $|\delta n/n|^2 \sim K^{-6} \sim k^{-6}$. This is not consistent with our experiment result with $S(k)= |\delta n/n|^2 \sim k^{-4}$.The experiment results on Tore Supra [23, 11，18] indicate $S(k) \sim k^{-3.5\pm0.5}$. Our result can also be compared with them. And these results can be compared with recent gyro-kinetic simulation [22].

One of the main hypotheses in the Kolmogorov-Kraichnan theory is the randomness of the fluctuation. The random character will lead to the Gaussian distributions of events. Therefore, comparing the probability distribution function (PDF) of the fluctuation to Gaussian distribution can measure how random the signal is. The deviation from Gaussian distribution can be attributed to the intermittency [19]. In our experiment, the PDF of fluctuation at all wavenumbers from k=16 cm^{-1} to k=36 cm^{-1} can be Gaussian distribution. Shown in Fig.3 (a) are the common logarithm of PDF ($\log_{10}$(PDF)) for normalized signals of k=16 cm^{-1} and k=36 cm^{-1} fluctuation. The two plots can be fitted by quadratic function well. In order to better understand the result, some statistic quantities usually are used for comparison, such as skewness and flatness, i.e, third and fourth order normalized moment. They are defined by

$$S = \frac{\langle X^3 \rangle}{\langle X^2 \rangle^{3/2}}, \qquad F = \frac{\langle X^4 \rangle}{\langle X^2 \rangle^2}$$

The first quantity skewness S measures the asymmetry of the PDF, and the second quantity flatness F measure the tail's weight with respect to the core of the PDF. For Gaussian distribution, they are 0 and 3 respectively. The two quantities are calculated for all the measured fluctuations in our experiment. The results are shown in Fig.3 (b) and Fig.3 (c) respectively. Within experiment precision the values of skewness are zero and those of flatness are three for fluctuations at all the analyzing scales, which are consistent with the values from Gaussian distribution. These results suggest that the signal is random at all analyzing scales.

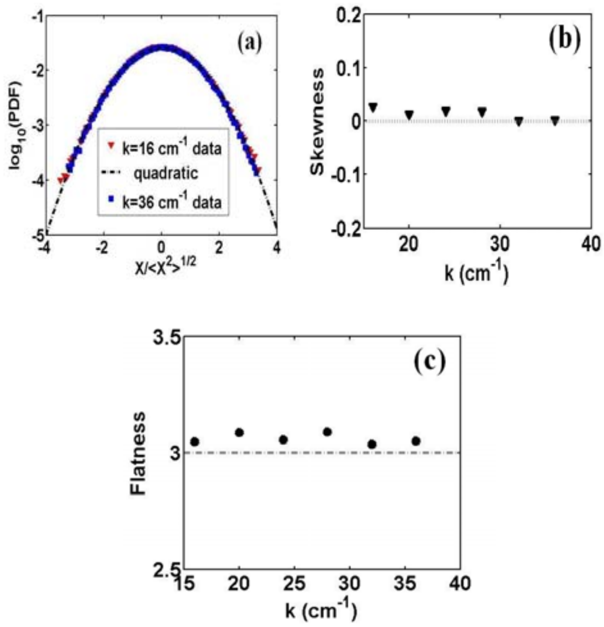

Fig. 3 (a) $\log_{10}$(PDF) for normalized scattering signal of k=16 cm^{-1} and k=36 cm^{-1} fluctuation, fitted by quadratic function (b)The skewness factors are zero for fluctuation of all analyzing scales, (c)The flatness factor are nearly three for all the fluctuation.

In order to have an idea about the turbulence evolution in one discharge, analyses are done for shot

#100878 at two time slices (t=300 ~ 320ms and t=500 ms~520 ms) in the current and density flat-top phase. The discharge parameter is showed in Fig.4 (a). It is found that at t =500 ms, an evident low frequency feature (f ~ 80 kHz) appears in the frequency spectrum of k=20 cm^{-1} fluctuation by contrast with that at t=300 ms as shown in Fig.4 (b). And the fluctuation amplitude increases about

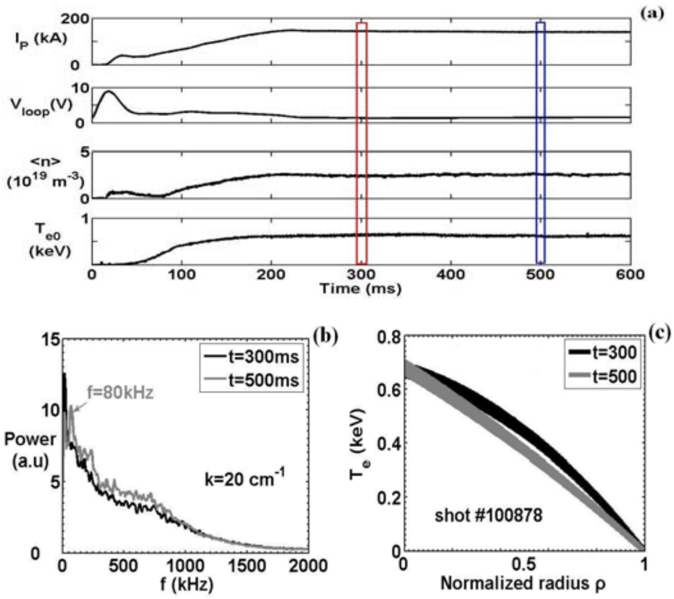

Fig.4 (a) discharge parameter of shot #100878 (b) the frequency spectrum of k=20 cm^{-1}(c) Electron temperature profile from ECE .

15% from t=300 ms to t=500 ms. The correspond electron temperature profiles at the two slices are plotted at Fig.4 (c) (The density profiles are nearly the same between the two slices, not plotted). From the plots, it is known that the temperature profile is steeper at t=500 ms for $\rho < 0.5$. For example, the value of L_{Te} (=$|T_e/dT_e/dr|$) at ρ=0.4 for t =300 ms discharge is about ~ a (minor radius, 0.27 m), while for t =500 ms discharge that is about ~ 0.65a. Then the value of R/L_{Te} is about 4.5 for the former and 6.9 for the latter. The steeper temperature profile may explained the appearance of a low frequency turbulence feature and the increased fluctuation amplitude at t=500ms. The results show that in tokamak plasma, instability can be driven by the free energy from the parameter inhomogeneity.

4. Summary

On HT-7 tokamak, small scale turbulence can be measured by use of the CO_2 collective scattering diagnostics. In the paper, some results in ohmic plasma are shown. The turbulence energy is mainly in low frequency and low k domain. The k- spctrum satisfy a power law with S (k) ~ k^{-4}, which is consistent with the simulation result. The PDF analysis of the scattering signal suggests the signal random character. The analysis of the shot#100878 show that the appearance of a low frequency turbulence feature in spectrum at t=500 ms compared with that at t=300 ms can be attributed to the steeper temperature profile at t= 500ms.

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References

[1] W. Horton, Rev. Mod. Phys. **71**,735 (1999).
[2] F. M. Levinton *et al.*, Phys. Rev. Lett. **75**, 4417 (1995).
[3] E. J. Strait *et al*., Phys.Rev.Lett. **75**, 4421 (1995).
[4] T. Fujita *et al*., Phys.Rev.Lett. **77**, 2377 (1997).
[5] C. M. Greenfield *et al*., Phys. Plasmas **4**, 1596 (1997).
[6] H. Shirai and the JT-60U Team, Phys. Plasmas **5**, 1712 (1998).
[7] W. Dorland, F. Jenko, M. Kotschenreuther and B. N. Rogers, Phys. Rev. Lett **85**, 5579 (2000).
[8] W.M.Nevins, *et al*., Phys.Plasmas **13**,122306 (2006).
[9] T. Görler and F. Jenko, Phys. Rev. Lett **100**,185002 (2008).
[10] T. L. Rhodes, *et al*., Plasma Phys. Control. Fusion **49,** B183 (2007).
[11] P. Hennequin, *et al*., Plasma Phys. Control. Fusion **46**, B121 (2004).
[12] P. Hennequin, *et al*., Nucl.Fusion **46**, S771 (2006).
[13] D. R. Smith, *et al*., Rev. Sci. Instrum. **75**, 3840 (2004).
[14] E. Z. Gusakov, *et al*., Plasma Phys. Control. Fusion **48**, B443 (2006).
[15] Yadong Li, Jiangang Li and Jianshan Mao Plasma Sci. Technol. **6**, 2526 (2004).
[16] X. Gao,*et al*., Phys. Plasmas **7**, 2933 (2000).
[17] R. E. Slusher and C. M. Surko, Phys. Fluids **23**, 472 (1980).
[18] P. Devynck *et al*., Plasma Phys. Control. Fusion **35**, 63 (1993).
[19] U. Frisch *Turbulence: the legacy of Kolmogorov* (Cambridge: Cambridge University Press 1996).
[20] A. Hasegawa and K. Mima Phys. Fluids **21,** 87 (1978).
[21] A. Hasegawa *et al*., Phys. Fluids **22**, 2122 (1979).
[22] S. V. Henriksson, *et al*., Phys. Plasmas **13,**072303 (2006).
[23] G. Antar *et al.*, Plasma Phys. Control. Fusion **40**, 947 (1998).
[24] K. L. Wong *et al*., Phys.Lett. A **276**, 5-6,281 (2000).