Radial Propagation of Electrostatic Turbulence in the HT-7 Tokamak

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Abstract. Radial propagation of electrostatic turbulence was measured using a triple Langmuir probe array and a pyramid Langmuir probe array in the plasma peripheral region (r/a = 0.6 ~ 1.1) of the HT-7 superconducting tokamak (R_0 = 1.22 m, a = 0.27 m, B_t = 2 T). In order to improve the accessibility of Langmuir probe, the experiments were conducted in low Te ohmic discharges. A technique based on Euclidean distance in envelope phase space was utilized to estimate the spreading velocity of fluctuation energy. And in the paper two-dimension turbulence structures were reconstructed in the k_θ, k_r space. It was found that the electrostatic turbulence propagated in the radial direction not only in the scrap-off layer but also in the confinement region. In the confinement region turbulence propagates outward with a relative small velocity V_r ~ 300 m/s compared with poloidal propagating velocity V_θ ~ −1.5 km/s. Radial average wavenumber is k_r ~ 3 rad/cm, which is much higher than the poloidal k_θ ~ −1 rad/cm. Radial correlation length is about 0.5 cm, which is about a half of the poloidal correlation length, implying eddy structures are elongated in the poloidal direction and correlation is stronger within magnetic surface than across the surface, possibly due to magnetic shear. The turbulence picture observed in our experiments seems to show that plasma turbulence in a tokamak generally manifest itself as wavelike structures mainly localized near its resonant surface, but the coupling mechanisms between flux surfaces can enable the radial propagation. These radial-propagation characteristics from the HT-7 tokamak support the turbulence theory proposed by Mattor and Diamond. They suggested that the radial propagation is a candidate mechanism responsible for driving the edge turbulence by fluctuations in the plasma core region. This scenario explains the higher fluctuation levels observed in the plasma edge as compared to the core.

1. Introduction

Turbulence spreading or radial transport of fluctuation energy from unstable region of a particular turbulence mode to stable region has recently been reemphasized within plasma transport research community, mainly stimulated by recent new findings in global gyrokinetic particle simulations of toroidal ion temperature gradient (ITG) turbulence,[1-4] indicating that turbulence can spread in the radial direction and result in nonlocal effects and Bohm-like transport scaling. Since most turbulence models are established basing on the assumption of local fluctuation and transport, the appearance of Bohm-like transport in an essentially gyro-Bohm model actually present a possible explanation for this long-time puzzle. The simulation results show a transition of turbulence ion transport scaling from the Bohm-like dependence for nowaday small devices to the gyro-Bohm scaling in future larger devices. This trend has significant implications, since an accurate description of size scaling of transport is critical fro design of fusion reactors. The presence of turbulence spreading will introduce a nonlocal dependence in the fluctuation levels, and under this assumption fluctuation level does not simply depend on local parameters, although the fluctuation characteristics are microscopic and the resulting transport is local. This new viewpoint will challenge the traditional mixing length based local transport picture and scaling. The initial simulation work has recently stimulated the development of several independent dynamical theories for turbulence spreading.[5-10] Many features of the simulation results have been reproduced in the theoretical models.

Turbulence spreading presents a possible nonlocal transport mechanism, and besides interpreting transport scaling it can be used to explain some nonlocal transport phenomena commonly observed in different devices, such as transport barrier back transitions and cold front radially fast propagation. In fact the study of turbulence spreading in magnetically confined fusion plasmas is not new. Radial wave propagation in other contexts has been considered by J. Schmidt and S. Yoshikawa in 1971. The first model based on toroidal mode coupling was proposed by X. Garbet in 1989, used to explain cold front propagation during pellet injection. The competition between torordal and nonlinear mode coupling was addressed by R.E. Waltz in 1990 and X. Garbet in 1992. The mode coupling theory in tokamak configuration was presented by X. Garbet in 1994.[11] A simple explanation of turbulence propagation in magnetized plasmas relies on mode coupling processed. In a toroidal plasma with magnetic shear each fluctuation component of a turbulence is expected to be localized near its resonant surface. If these components overlap and if there is a coupling between them, turbulence will propagate. Two sources of coupling exist in a tokamak: the toroidal geometry which couples two adjacent poloidal wavenumbers, and the nonlinear mode coupling which couples modes of a triad. One result of the coupling is the formation of some radial extended large-scale toroidal mode structures, as observed in ITG simulations [1-4], which can considerably enhance radial transport scale and generate Bohm-like transport scaling.

One important reason for resorting to turbulence spreading is that many observations of turbulent fluctuations in locally stable or damped regions of both simulations[12,13] and experiments[14]. Especially at plasma edge, experiments usually report fluctuation level increase near the edge, with $\tilde{n}/n$ ~30% or larger, but in the core region, where usually with $\tilde{n}/n$ ~1%. Although numerous instabilities have been explored theoretically and tested experimentally, none have yet been recovered both the universality and the high amplitude of observations. The source of the strong edge fluctuations remains a mystery.

Well known that the dissipative drift-wave instability can be stabilized by magnetic shear, so some toroidal effects are needed to provide a nonadiabatic electron response sufficient to drive the mode, dissipative trapped electron mode (DTEM) is one of the candidates, however in the region of low-temperature plasma edge high collision frequency will make the fluctuation level of DTEM turbulence drop towards the edge regions in contrast to the observed rise. The same case also happened to other typical core-region modes, such as ITG. Nonlinear effects may drive the drift-wave and self-sustain the turbulence, but seem to be not strong enough. The fact of lacking strong local instability at plasma edge contradicts the observations of the “universality” and high amplitude of edge fluctuations. One might argue that the drift resistive ballooning mode can be unstable at plasma edge and impurity or atom process such as ionization and recombination can also contribute additional unstable factors. It is true but edge fluctuation measurements always report that edge turbulence bear typical drift-wave characteristics, and some of which are very similar to those in the core region. So the possibility that edge turbulence may originate from the core still exists. In 1993 N. Mattor and P.H. Diamond proposed that the “beach scenario” can also be applied to the magnetized plasma. Both slab and toroidal theories of “drift wave propagation as a source of plasma edge turbulence” were presented in their papers.[15-17] And based on the wave reflection by shear flows at plasma edge they proposed a theory of edge-H-mode formation. In their toroidal model, waves can propagate over radial distance of order a^2/R, where a and R are the minor and major radii of the torus. This is wide enough that one expects a substantial portion of the modes in tokamak core region will overlap the edge region. In their slab model, when a wave propagates into a low density and temperature edge region, the normalized fluctuation level varies roughly as $\tilde{n}/n \sim n^{-1.5}$. Thus it appears that the observed levels of edge turbulence can be explained without the need to invoke specific edge instabilities. In addition they showed that a wave launched in the adiabatic core region can become nonadiabatic when propagating into a low density and temperature edge region, suggesting a possible explanation for the breakdown of the "Boltzmann relation", demonstrated by Langmuir-probe measurements in edge plasmas.

Experimental demonstration of the "beach scenario" is not sufficient up to the present, mainly due to the inherent difficulty in implementing radial multipoint local measurement of fluctuation quantities in high temperature fusion plasmas. Most early measurements of plasma turbulence show no radial propagation.[18] However, these conclusions are all based on local measurements, in toroidal geometry radial propagation is more subtle. N. Mattor [15-17] and T.S. Hahm [19] discussed the difficulties associated with the measurement of radial propagation. Early measurements also showed very short radial correlation length (in the order of 1 cm), which is generally considered not consist with the spreading picture. The initial evidence of nonzero $\bar{k}_r$ was from the Texas Experimental Tokamak (TEXT) [20] and some evidence for radial propagation in the scrape-off layer (SOL) were found in the Caltech tokamak [21]. Recently there has been renewed interest in this topic and there are a number of indirect and a few direct measurements. Huber *et al.* reported radial propagation using two lithium beams in the SOL of Tokamak Experiment for Technology Oriented Research (TEXTOR-94). Existence of intermittent structures or events in the SOL plasma with a finite radial propagation was also reported on DIII-D. Indirect evidence of radial propagation also came from DIII-D using laser imaging diagnostics reported by Coda *et al.* Similar results were also reported from the Wendelstein 7-AS (W7-AS) stellerator. Imaging of SOL in Alcator C-Mod and National Spherical Torus Experiment (NSTX) using a fast camera also revealed radial propagation. McKee *et al.* also reported asymmetric $S(k_r)$ in the SOL of DIII-D using beam emission spectroscopy diagnostics. There is a report on measurement using Langmuir probes in a small tokamak Keda Tokamak-5C (KT-5C) [22]. However, this tokamak has a discharge duration of only 2 ms with a current flat top in the range of 0.5–1.0 ms. More recently, similar Langmuir-probe measurements were conducted in the edge region of Saskatchewan Torus-Modified (STOR-M) tokamak,[23,24] with a longer discharge duration ~ 50 ms. In most of these experiments it was commonly found that turbulence propagates both inward and outward, and imbalance or asymmetry were frequently reported and leading to the radial transport of net turbulence energy.

In this paper we report a measurement of the radial propagation of plasma turbulence using elaborate Langmuir-probe structures in a steady-state medium-sized tokamak HT-7.[25] HT-7 is a superconducting tokamak with $R = 1.22$ m, $a = 0.3$ m, $B = 2$ T and discharge duration of several seconds. Probe structures are shown in Fig.1. These probe structures are symmetrical in the poloidal direction, so by using these structures the contribution from the poloidal direction can be eliminated, as we know plasma turbulence is propagating in the poloidal direction, so eliminating the poloidal contribution is important for the achievement of correct measurement of radial propagation.

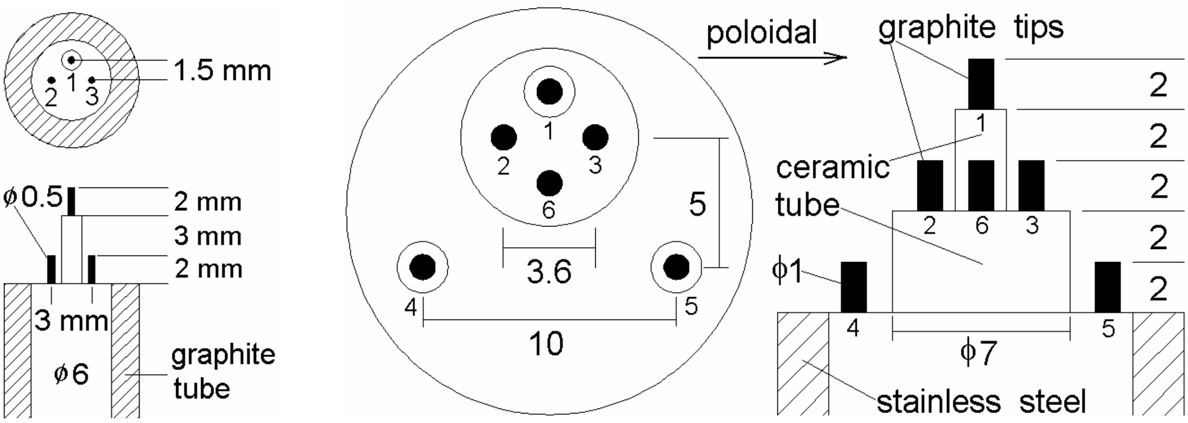

Figure.1 The sketch of a triple Langmuir probe array and the sketch of a pyramid Langmuir probe array.

2. Experimental setup

The experiments are conducted in the HT-7 superconducting tokamak, which has a circular cross-section and toroidal-limiter configuration. In fact we have carried out these experiments in HT-7 for three years, in different experimental campaign and with different limiter configuration. From the experience we accumulated in these experiments we find an important technique problem may strongly influence the measuring results regarding the radial propagation of plasma turbulence. The problem is that second electron emission from the probes will strongly influences the measurement. An electron cloud is possibly generated around the probes, leading to the reduction of plasma resistance between probes; so that the measured correlation and propagation relation change a lot. Usually this effect will increase the correlation and reduce the phase difference between fluctuations, so that in the case of strong second electron emission the probes can not measure any radial propagation. This problem becomes relative serious in a larger device, due to higher edge temperature. It is possible that in the previous experiments in other machines they also met the same problem. So, in order to improve the accessibility of Langmuir probe and achieve correct measurement this experiment is conducted in low-plasma-current ohmic discharges. Toroidal magnetic field B_t = 1.8 T, plasma current I_p = 80 kA, central-chord-averaged electron density n_e = 1.5×10^{19}m^{-3}, central electron temperature T_{e0} ~ 0.5 keV, central ion temperature T_{i0} ~ 0.3 keV and deuterium plasmas with typical duration of 1 second. The discharges are stable and reproducible.

In order to minimize the disturbance on the ambient plasma, all probe tips are used to measure floating potential $\phi_f = \phi_p - \alpha T_e$, where ϕ_p is the plasma potential, T_e is the electron temperature and α is a constant usually close to 2.5. In the theory of N. Mattor and P.H. Diamond [15-17], they predicted that radially propagating waves in a sheared torus are asymmetric about the toroidal midplane and the characteristics of radial propagation will be more easy to detect at the up and down than at the midplane of the machine. So in our experiment the probes are mounted on the top of the HT-7 machine. The data are simultaneously sampled at 2 MHz with 12-bit resolution using a multi-channel digitizer. All measurements are performed in the laboratory frame of reference. A typical discharge is shown in Fig. 2. The displayed waveforms are (a) plasma current, (b) central-chord-averaged electron density and (c) floating potential original signal. Flat top duration is from 200 ms to 800 ms.

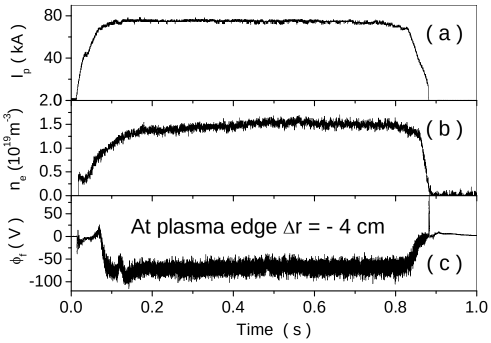

Fig 2. Typical discharge waveforms. (a) plasma current, (b) central-chord-averaged electron density, (c) a floating potential original signal measured at plasma edge $\Delta r = -4$ cm.

3. Experimental results

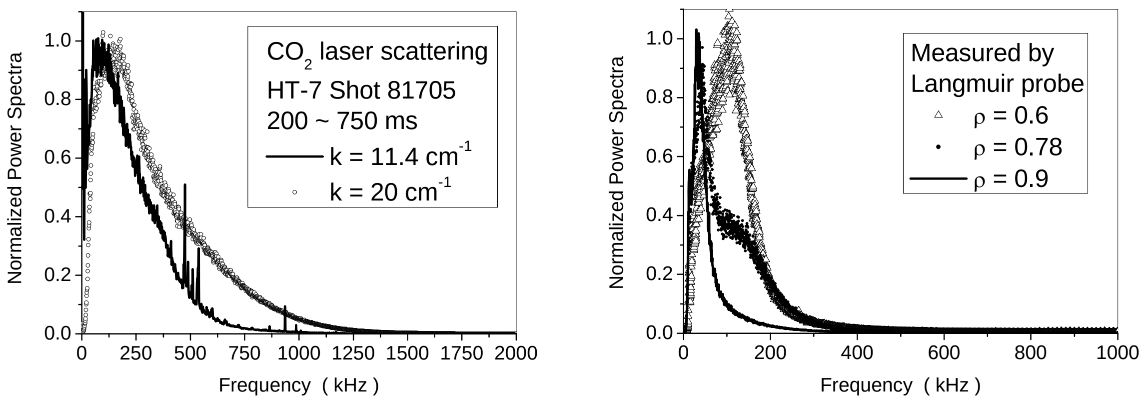

Fig.3 Left: Two typical spectra at $k_\perp$ = 11.4 and 20 cm^{-1} simultaneously measured by the CO_2 laser coherent scattering system on the HT-7 tokamak. Right: Typical turbulence spectra measured by Langmuir probe at three radial locations ρ = 0.6, 0.78 and 0.9.

In HT-7 we have a CO_2 laser coherent scattering system, simultaneously monitoring three wavenumber in the plasma core region. The measured wavenumber range covers $k_\perp$ = 10 ~ 30 rad/cm. Edge Langmuir probe can cover the wavenumber range of $k_\perp$ = 0.1 ~ 10 rad/cm. Fig.3 shows two typical spectra at $k_\perp$ = 11.4 and 20 cm^{-1}. Fig.3 clearly indicates that short-wavelength fluctuation components have broader frequency spectrum. This observation is consistent with the recent experimental results from DIII-D tokamak.[26] Calculation indicates the dominant spectral frequency is close to the local electron diamagnetic frequency $\omega_e^* = -\frac{k_\theta T_e}{eBn}\frac{dn}{dr}$. In the HT-7 tokamak, since there is no high-power neutral beam injection, usually the machine is operated in the regime of Te > Ti. In most cases the ion temperature gradient threshold of ITG instability can not be reached, but calculation indicates the DTEM is unstable in the plasma core region with such plasma parameters. For comparison, Fig.3 also shows turbulence spectra measure by Langmuir probe at plasma edge. (Low-frequency MHD perturbations have been removed by using a digital filter). Obviously, edge and core fluctuations have very similar spectral shape, except that the spectra from edge region exhibit much lower frequency and more narrow frequency band. One reason is that the fluctuation components measured by probe are in relative smaller wavenumber range. Another reason is the lower temperature in the edge region. Calculation also indicates the dominant spectral frequency is in the vicinity of the local electron diamagnetic frequency. So fluctuation measurements on HT-7 strongly support drift-wave-type instability both in the plasma core region and edge region, and there are many similarities on turbulence features between these two regions.

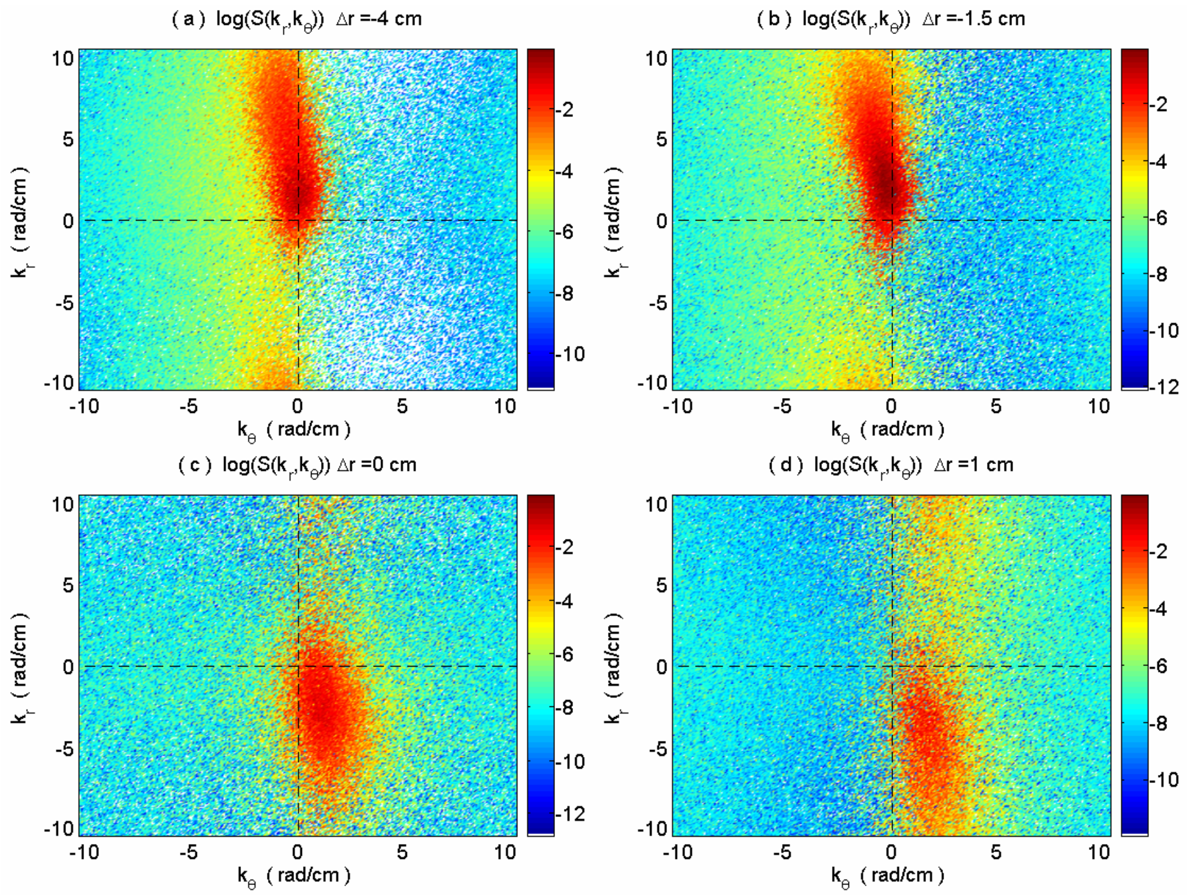

Figure.4 The (k_r,k_θ) double wavenumber spectra of electrostatic turbulence measured by a triple probe array at 4 radial locations: (a) Δr = –4 cm, (b) Δr = –1.5 cm, (c) Δr = 0 cm, (d) Δr = 1 cm. (a = 27 cm)

The standard two point correlation technique was used to analyze the radial propagation characteristics of the electrostatic potential fluctuations. It was found that the electrostatic turbulence propagated in the radial direction not only in the SOL but also in the confinement region. Figure.4 shows the (k_r,k_θ) double wavenumber spectra of electrostatic turbulence measured by a triple probe array at 4 different radial locations. In this figure, the spectra are peaked at small k_θ and finite k_r region, which means the electrostatic turbulence is dominated by long-poloidal-wavelength components. In the confinement region turbulence propagates outward with a relative small phase velocity V_r ~ 300 m/s, compared with poloidal propagating velocity V_θ ~ –1.5 km/s (negative indicates electron diamagnetic direction). Radial average wavenumber is k_r ~ 3 rad/cm, which is a little higher than the poloidal k_θ ~ –1 rad/cm. This means that the plasma turbulence is dominated by short radial wavelength fluctuating components. Radial correlation length is about 0.5 cm, which is about a half of the poloidal correlation length ~ 1 cm. This implies that turbulence eddy structures are elongated in the poloidal direction and correlation is stronger within magnetic surface than across the surface. The turbulence structure picture reflected here is a little different from those observed in ITG turbulence simulation, where one always see radial extended long wavelength structures if zonal flows are not strong enough to destroy these structures. Indeed the parameter range in our experiments seems to be below the ITG instability threshold. Another possible reason for the poloidally elongated structures at plasma edge is the magnetic shear. On the other hand, the naturally occurring poloidal velocity shear layer is not wider than 3 cm in these discharges, so at the location of 4 cm inside LCFS flow shear is small, can not be a reason. These radial propagation characteristics reported here are a little different from those observed in small tokamaks [22,23] and purely toroidal devices [24], but seem to be consistent with the early experimental observations in the TEXT tokamak [20].

Across the separatrix, the turbulence propagation directions reverse not only poloidally but also radially. In the SOL, turbulence poloidally propagates in the ion diamagnetic direction and radially propagates inward. The poloidal direction reversion is due to E×B drift, i.e. plasma potential profile. The radial propagation direction in the SOL in our experiments is not always inward; we find it depends on the limiter configuration. When the device is operated with toroidal belt limiter and relative short connection length, turbulence propagates inward, and when operated with poloidal limiter and relative long connection length, turbulence propagates outward, just like the case in the confinement region. The connection length plays an important role in the radial propagation of turbulence in the SOL region. Turbulence mode at the plasma edge has very long wavelength along magnetic field, in the SOL, when the connection length is shorter than the parallel wavelength, the turbulence mode structure can be significantly modified. This presents a possible explanation for the observed limiter configuration dependence. In the shearing layer (close to the LCFS location), the poloidal correlation length is reduced and become close to the radial correlation length, which means large-scale turbulence eddy are suppressed in the shearing layer, as indicated in Fig.4(c).

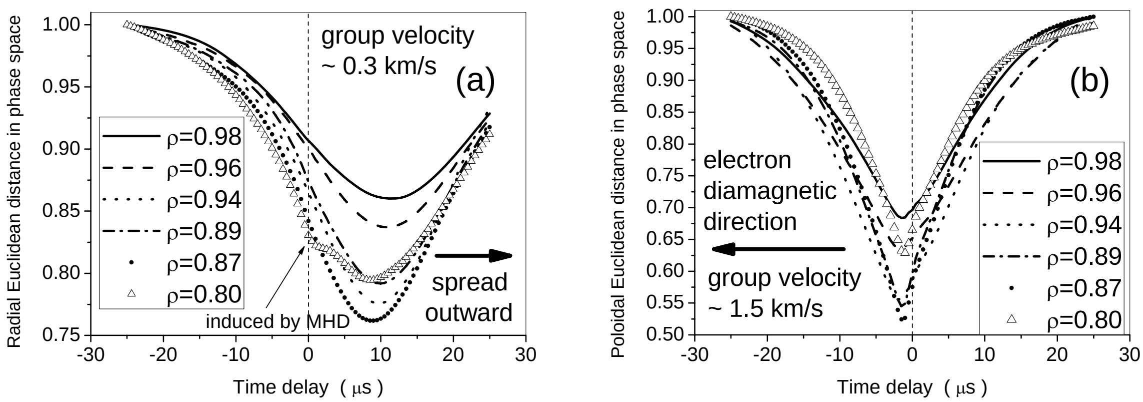

Fig.5 (a) Euclidean distance in envelope phase space between two radially spaced fluctuating signals; (b) Euclidean distance in envelope phase space between two poloidally spaced fluctuating signals. The Euclidean distance is plotted as a function as time delay. Different curves are from different radial positions.

We have developed a technique to evaluate group velocity based on the nonlinear correlation technique. First, the amplitude of analytical signal is used to describe the envelope of fluctuating signal, i.e. $\left|\phi^{analytic}(t)\right| = \left|\phi(t)+i\phi^{H}(t)\right|$, where $\phi^{H}(t)=\textbf{Hilbert}\{\phi(t)\}$ is the Hilbert transform of the fluctuating signal. Then, the group delay is estimated by calculating the Euclidean distance in envelope phase space. The principle of this technique can also be understood as calculating the information-transfer delay time between two spatial positions. The experimental results are presented in Fig.5. Fig.5(a) indicates turbulence energy spreading 3 mm in the radial direction will take about 10 μs. It implies a group velocity about V_r^g ~ 300 m/s. Fig.5(b) shows turbulence propagate poloidally in the electron diamagnetic direction with a group velocity very close to its phase velocity $V_\theta^g \sim -1.5$ km/s.

4. Summary

It is found that in HT-7 tokamak plasma, turbulent energy is spreading outward with a group velocity close to 300 m/s in these experiments. These radial-propagation characteristics from the HT-7 tokamak support the turbulence theory proposed by Mattor and Diamond.[15-17] They suggested that the radial propagation is a candidate mechanism responsible for driving the edge turbulence by fluctuations in the plasma core region. This scenario explains the higher fluctuation levels observed in the plasma edge as compared to the core.

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