Edge Electrostatic Fluctuation Characteristics in the Sino-United Spherical Tokamak *

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Edge plasma parameters, including electron temperature T_e, density n_e, plasma potential ϕ_p, radial electric field E_r and the corresponding fluctuations in the Sino-united spherical tokamak spherical tokamk have been systematically measured with Langmuir probe arrays. Wave-number spectrum analyses show that edge fluctuations have a radial propagation character of the drift wave turbulence, with a characteristic radial phase velocity $v_{phr} \sim 0.7\,\mathrm{km\cdot s^{-1}}$ in the scrape-off layer and $v_{phr} \sim 0.9$–$1.4\,\mathrm{km\cdot s^{-1}}$ in plasma edge.

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Recently, spherical tokamak (ST) configuration[1] has received considerable attention due to encouraging experimental results.[2−4] ST is a tokamak with low aspect ratio ($A \equiv R/a$ of typically less than 2, where R is the major radius and a is the minor radius). ST plasmas have some attractive properties compared to conventional large-aspect-ratio devices, such as high β_t (where β_t is the ratio of the plasma pressure to the toroidally magnetic pressure, experimentally, $\beta_t \sim 0.4$[5]), naturally large elongation ($\kappa \equiv b/a \sim 2$, where b is the vertical radius of the poloidal plasma cross-section) which means extreme reduction in ampere-turns and leads to substantial saving in the cost of the magnet system of a device, good confinement (H-mode and energy confinement exceeds conventional tokamak scaling),[2−4] and the possibility of the steady-state operation at modest magnetic field. All these experimentally identified advantages stimulate people to greater effort in the further research of the ST concept.

Plasma fluctuations are pervasive as a very possible cause of the cross-field anomalous transport in magnetically confined plasmas. The magnetic geometry of the ST may bring edge plasma fluctuations evident differences in the turbulence dynamics, compared to that of the conventional aspect ratio tokamak. Theoretically, stronger magnetic field shear and higher β value of the ST may result in more effective suppression of the long wavelength turbulence by both $\boldsymbol{E} \times \boldsymbol{B}$ flow shear,[5] and a larger ratio of the inboard (favorable field line curvature) versus the outboard (unfavorable field line curvature) magnetic field strength of the ST will be beneficial to the stabilization of electrostatic and electromagnetic high-n instabilities.[6] Therefore, it is crucially important to investigate experimentally the edge plasma fluctuation characteristics in STs.

In this Letter, we report the concurrent measurements of the edge plasma fluctuationss in the Sino-United Spherical Tokamak (SUNIST). The SUNIST at Tsinghua University of China is the first spherical tokamak in China with major radius 0.30 m, minor radius (defined by a set of fixed four-block poloidal limiter) 0.23 m, and designed elongation 1.6.[7] In the first phase of the construct of this program, The SUNIST achieved first ohmically-heated hydrogen plasma at the end of 2002 with 0.15 T of the toroidal field and 50 kA plasma current.

The primary diagnostics employed in this experiment are two sets of radially moveable Langmuir probe arrays, a four-tip probe array (array 1) and a three-tip array (array 2), toroidally separated 150°, located on the outer side of the equatorial plane of the device. Both are square arrays with side 2 mm and all tips are made of molybdenum wire 3 mm in length and 1 mm in diameter. Array 1 is operated as a triple probe[8] to obtain the time-averaged and fluctuating electron temperature (T_e, $\tilde{T}_e$), plasma density (n_e, $\tilde{n}_e$), and plasma potential (ϕ_p, $\tilde{\phi}_p$). A dc bias of 43–145 V is loaded between two tips located toroidaly to measure the ion saturation current (I_{si}, $\tilde{I}_{si}$). Array 2 is used to measure the floating potentials to provide simultaneous measure of the radial wave-number and the poloidal wave-number of the fluctuations, by which the radial and poloidal wave-number spectra can be calculated.[9] All probe tips are orientated off the magnetic field lines to avoid shadowing of probe tips from each other.

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The experiments are carried out in ohmically-heated hydrogen plasma discharges with the toroidal magnetic field $B_\phi = 0.13\,\mathrm{T}$, the plasma current $I_p = 30\,\mathrm{kA}$ and a loop voltage of 5 V. Normally the plasma discharge durations are 5–6 ms with a flat-top phase of 2 ms. A variety of radial profiles of edge parameters are obtained by shot-to-shot measurements. At each radial position 10–15 shots identical discharges are conducted to compute statistic averages. All the data are taken in the flat-top phase of the plasma current and digitized at 2 MHz with 12-bit resolution using a multichanned digitizer.

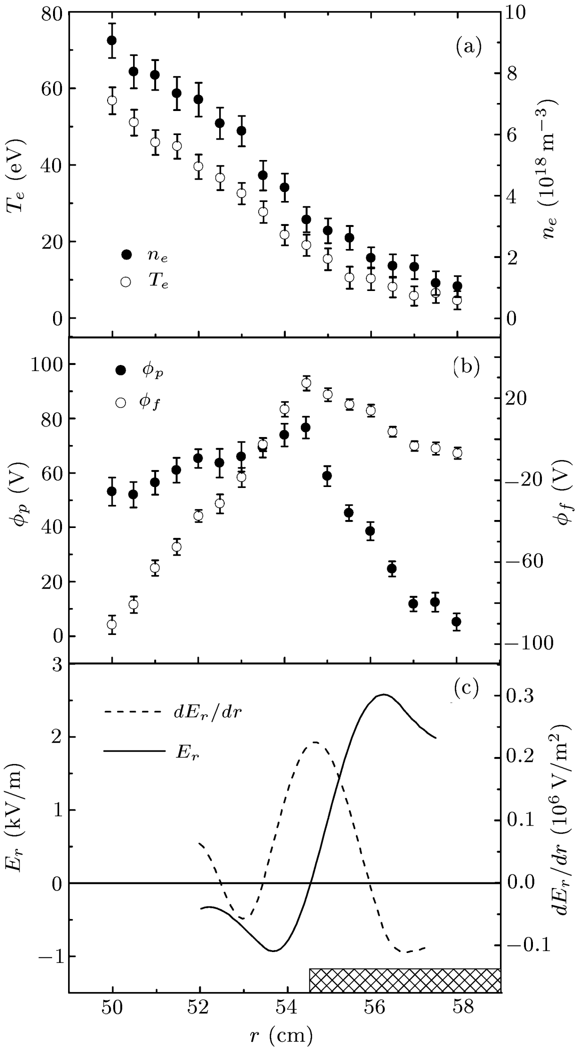

Fig. 1. Radial profiles of equilibrium: (a) T_e and n_e, (b) ϕ_f and ϕ_p, (c) E_r and dE_r/dr. The error bars are the statistical errors of the ensemble average. The shadow region represents the radial location of the limiter.

The electron density and plasma potential ϕ_p are determined by the measured I_{si}, ϕ_f and T_e with Stangeby's model:[10] $n_e = \alpha I_{si} T_e^{-1/2}$, $\phi_p = \phi_f + \mu T_e$, where α is the constant coefficient depended on the geometry size of tips, and μ is the sheath potential drop coefficient (taken to be 3 in our experiments).

The radial profiles of equilibrium T_e, n_e, ϕ_f and ϕ_p are shown in Figs. 1(a) and 1(b), respectively. The horizontal coordinate is the major radius and the shadow region stands for the radial location of the limiter. In the figure and hereafter, the error bars denote the statistical errors of the ensemble average. It can be seen from Fig. 1(a) that in the scrape-off layer (SOL, $r > r_{\mathrm{limiter}}$), $T_e \sim 10\,\mathrm{eV}$ and $n_e \sim 2\times 10^{18}\,\mathrm{m}^{-3}$, and the profiles are relatively flat. However, in the plasma confinement region ($r < r_{\mathrm{limiter}}$), the profiles of T_e and n_e are steep. The edge temperature and density are in the range $T_e = 10$–$60\,\mathrm{eV}$ and 0.5×10^{18}–$8.0\times 10^{18}\,\mathrm{m}^{-3}$, respectively, similar to the results obtained in other STs.[11,12] The profiles of ϕ_f and ϕ_p are shown in Fig. 1(b). With the seventh-polynomial fit of the ϕ_p profile, the radial profiles of the radial electric field $E_r = -(d\phi_p/dr)$ and thereby its radial gradient dE_r/dr can be inferred as shown in Fig. 1(c). We can see that the ϕ_p and dE_r/dr profiles are peaked at $r = 54.5\,\mathrm{cm}$, in the vicinity of the radial location of the limiter, where E_r changes its direction from inward in the plasma edge to outward in SOL. Thus in the radial range of probably 1 cm, a naturally formed poloidal $E_r \times B_\phi$ velocity shear layer (VSL) is formed. The VSL has been observed on many tokamaks.[13–15] We also notice that the variance of discharge parameters only affects the magnitudes of both E_r and dE_r/dr but does not change the radial location of the maximal shear of dE_r/dr.

Figures 2(a) and 2(b) shows the radial profiles of the relative fluctuation levels $\tilde{n}_e/n_e$, $\tilde{T}_e/T_e$ and $e\tilde{\phi}_p/kT_e$ and the absolute rms fluctuation magnitude $\tilde{n}_e$, $\tilde{T}_e$ and $\tilde{\phi}_p$. We can see that at all the measured radii, i.e., both the SOL and the plasma edge, $\tilde{n}_e/n_e \sim (2-3)\tilde{T}_e/T_e$ exists. This result is similar to the observations in other tokamaks,[16–18] indicating that the turbulence in the SUNIST edge is mainly not caused by the impurity radiation-driven mechanism.[19] We also notice that for the radial positions $r \geq 52\,\mathrm{cm}$, $\tilde{n}_e/n_e \neq e\tilde{\phi}_p/kT_e$ exits. This departure from the simple Boltzmann relationship in plasma edge region is a common feature and has been observed on many other tokamaks.[20] However, at the radial positions $r \leq 52\,\mathrm{cm}$, $\tilde{n}_e/n_e$ and $e\tilde{\phi}_p/kT_e$ become comparable and have nearly the same size within the experimental errors. That is to say, the Boltzmann relationship is roughly obeyed in these radial positions. According to the theoretical predictions of drift wave propagation present by Mattor and Diamond[21] that the edge turbulence is come from the adiabatic core region where the Boltzmann relationship, $\tilde{n}_e/n_e \approx e\tilde{\phi}_p/kT_e$, is satisfied. Therefore, the region of $r = 52\,\mathrm{cm}$ may be reasonably judged as the region close to the plasma core. This result is also similar to the observations in other tokamaks.[17]

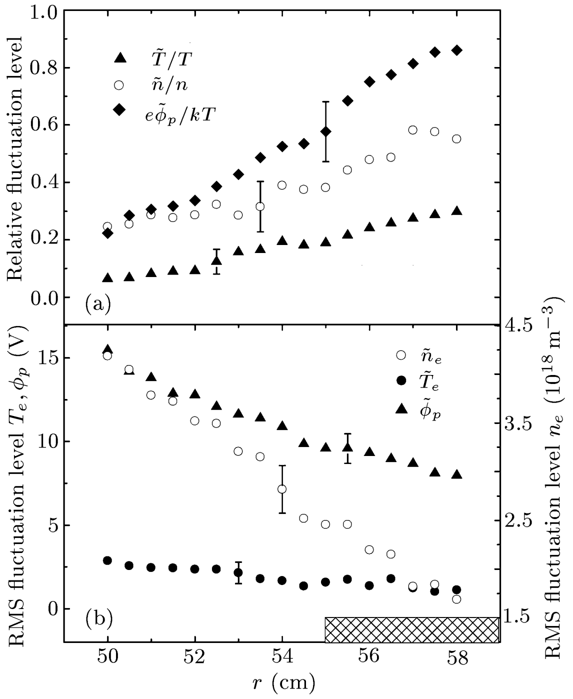

Fig. 2. Radial profiles of (a) relative fluctuation levels $\tilde{n}_e/n_e$, $\tilde{T}_e/T_e$ and $e\tilde{\phi}_p/kT_e$; and (b) the absolute rms fluctuations $\tilde{n}_e$, $\tilde{T}_e$ and $\tilde{\phi}_p$.

We analysed the radial propagating characters of fluctuations with the standard two-point cross-correlation technique.[9] Figures 3(a) and 3(b) shows some evidence for radial propagation of the floating potential fluctuations. In the figures, the positive wavenumber corresponds to the propagation in radially outward direction. Figure 3(a) is the radial wavenumber spectrum $S(k_r)$ at the $r = 50$ cm. The spectrum has both positive and negative k_r components but the positive case is greater. The asymmetry of $S(k_r)$ means a net radial outward propagation of the electrostatic fluctuations. We observed such a spectral characteristic at all the measured radii, and the similar results are obtained. The radial profiles of the spectral-averaged redial wavenumbers $\bar{k}_r$ and the radially propagating phase velocity v_{phr} are shown in Fig. 3(b). It is clear that at all the radial positions, $\bar{k}_r > 0$. In the plasma edge region, we can obtain $\bar{k}_r < 1\,\mathrm{cm}^{-1}$ and it changes slightly with radial positions; but in SOL, $\bar{k}_r > 1\,\mathrm{cm}^{-1}$ and it increases with the probes moving radially outwards. In contrast, v_{phr} remains approximately constant ($v_{phr} \sim 0.7\,\mathrm{km{\cdot}s^{-1}}$) in SOL but raises with inward radial positions ($v_{phr} \sim 0.9$–$1.4\,\mathrm{km{\cdot}s^{-1}}$). Such features of the radial velocity of the turbulence resemble the results of the radial moving velocity of the "blob" structures measured by the gas puff imaging technique in NSTX.[16] It may be a signature of the self-organized structures motion in the SUNIST edge. These results support the predictions of the radial drift wave propagation theory, i.e., edge turbulence may originate from core fluctuations and may propagate to the edge.

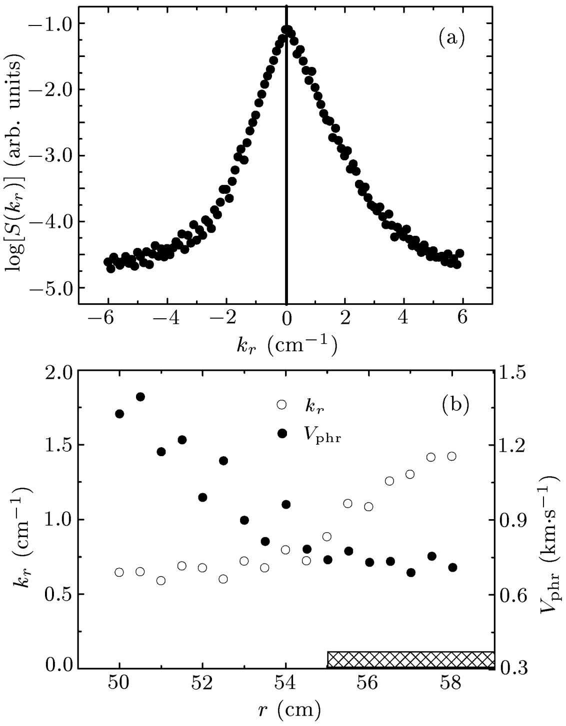

Fig. 3. (a) Radial wavenumber spectrum $S(k_r)$, (b) radial profiles of the radial spectral-averaged wavenumber $\bar{k}_r$ and radial phase velocity v_{phr}. Positive k_r represents the radially outward direction.

In conclusion, we have carried out systematic measurements for edge plasma parameters, including electron temperature T_e, electron density n_e, plasma potential ϕ_p, radial electric field E_r and their corresponding fluctuations in the SUNIST spherical tokamk with Langmuir probe arrays. The characteristics of the edge electrostatic fluctuations are experimentally investigated. The results show that edge fluctuations have a radial propagation character of the drift wave turbulence, with a characteristic radial phase velocity $v_{phr} \sim 0.7\,\mathrm{km{\cdot}s^{-1}}$ in SOL and 0.9–$1.4\,\mathrm{km{\cdot}s^{-1}}$ in plasma edge, suggesting that the edge turbulence may originate from the core, as is predicted theoretically.

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