Observation of spatiotemporal structures of temperature fluctuations by using of a statistical phase detection method in a linear magnetized plasma

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Abstract
In this paper, we evaluated electron temperature fluctuations by using a conditional sampling and a statistical phase detection method. These methods allow us to reconstruct probe \( I - V \) characteristics at each time delay; that is, we can extract electron temperature and ion saturation current fluctuations in high temporal resolution without complex electronic circuits. Our method was applied to two quasi-coherent fluctuations observed in a linear magnetized plasma device, PANTA. We observed spatiotemporal structures of electron temperature and ion saturation current fluctuations. The results revealed the amplitudes and phase relation between electron temperature and density fluctuations.

Keywords: temperature fluctuation, conditional sampling, transport, drift wave

(Some figures may appear in colour only in the online journal)

1. Introduction
Temperature fluctuations play essential roles in heat transport in magnetically confined plasma. It is theoretically expected that temperature gradient driven drift modes, such as the ITG and the ETG, drive heat flux and deteriorate energy confinement of nuclear fusion plasma [1]. The drift modes are usually saturated through non-linear processes and become turbulent and thus understanding of physics of the non-linear effects on the drift modes are especially important. In order to identify the ITG and the ETG modes and observe the non-linear processes of them, simultaneous measurement of multimodal fluctuations, e.g. temperature fluctuations, density fluctuations, flow fluctuations, at the same position is required. Generally, simultaneous measurement of multimodal fluctuations is difficult in fusion plasmas. On the other hand, observation of fluctuations is relatively easy in laboratory plasmas. Physics of the non-linear effects on the drift modes and drift-wave-driven transport is believed to be common between fusion plasma and laboratory plasma [2–4]. In a linear magnetized laboratory plasma of the PANTA, the nonlinearly saturated drift modes are observed and thus turbulence and
turbulence-driven transport study in the PANTA is significant to propel the thermal fusion research. In this study, we developed a method for double probe to measure fluctuations of electron temperature and density at the same position simultaneously and characterized the electron temperature fluctuation in the PANTA.

Some results of electron cyclotron emission (ECE) have been reported\(^5\), which is useful to evaluate the spatiotemporal structure of electron temperature fluctuations. However, ECE needs a large scale measuring device, and its signal to noise ratio is low. Thomson scattering measurement is very powerful to measure electron temperature in high spatial resolution, but its time resolution is too low to measure electron temperature fluctuations. In the scrape-off layer and basic plasma device, we can use electrostatic probes. Single and double probe method has a low temporal resolution because of regulations of sweeping frequency of bias voltage\(^6\). The triple probe method can measure electron temperature in high temporal resolution, assuming each tip of a triple probe is aligned at the same plasma potential. The assumption makes it difficult to measuring electron temperature fluctuation in small scale basic device. That’s why it is still challenging to measure electron temperature fluctuations.

Conditional sampling and averaging technique has been used to study temperature evolutions of coherent structures\(^7\). In tokamak experiments, these methods have been used for intermittent events with large amplitude\(^8\text{–}10\), such as blobs. To detect blobs, a spiky waveform with a large amplitude is determined as trigger events for the conditional technique based on normalized standard deviation. However, it is difficult to estimate that of non-spiky waveform i.e. in more general cases.

Recently, two coherent modes are observed in a linear device PANTA. In the experiment, there is a temperature gradient as well as a density gradient. When the temperature gradient exists, electron temperature can fluctuate. Then, to observe the electron temperature fluctuations associated with the two coherent modes, we applied the conditional sampling via a statistical phase detection method. The phase detection method allows us to apply conditional technique in general cases. In this paper, we report the results of our method and the spatiotemporal structure of the temperature and density fluctuations. The fluctuation levels and the phase relation between the density and temperature fluctuations are also evaluated.

Our method can be applied to various fusion device. If we apply it to laser Thomson scattering, we could evaluate electron density and temperature fluctuations at the same time and at the same position. One of the candidates to observe ion temperature fluctuation in fusion device is ultra-fast charge exchange recombination spectroscopy (CXRS)\(^11\). Applying our method to the ultra-fast CXRS will make it possible to observe non-linear ion temperature dynamics of ITG. Observation electron and ion temperature fluctuation will contribute to understand anomalous energy transport and to improve of plasma confinement.
2. Experimental setup and method

The experiments are carried out by linear magnetized plasma device, PANTA, of which vacuum vessel is 4000 mm in length and 450 mm in diameter. Argon plasma is produced by helicon wave with 6kW input power at 7MHz radio frequency. The typical plasma radius is about 50 mm. Argon neutral gas pressure is controlled at 0.5 Pa. An axial magnetic field of 0.13 T, is directed from the helicon source to the opposite side.

Radially movable 4-tip probe array is installed at z = 1375 mm from the plasma source [14], as shown in figure 1. Two of the 4-tip probe were used as a double probe. Double probe characteristics are written as

$$I_p = I_s \tanh \left( \frac{eV_p}{2T_e} \right),$$

(1)

where $I_p$ and $V_p$ are probe current and bias voltage, respectively. $I_s$ is ion saturation current which is proportional to electron density $n_e$. $e$ is elementary charge, and $T_e$ is electron temperature. We obtained $I_p - V_p$ curve in 1 MHz sampling. The sweeping frequency of bias voltage is 100 Hz. $I_s$ and $T_e$ were evaluated by fitting I-V characteristics to equation (1), after correction of the $I_p - V_p$ curve [15]. Radial profiles of $n_e$ and $T_e$ are shown in figure 2. The density gradient scale length $L_n = |\partial n_e/\partial r|^n_e |\partial I_s/I_s|^{-1}$ is about 1.1cm$^{-1}$. The ratio of density gradient length $L_n$ to temperature gradient length $L_T$ is $\eta_e = L_n/L_T \sim 0.56$.

An azimuthal 64ch probe array is installed at the plasma radius of $r = 40$ mm and at $z = 1875$ mm from the plasma source [16], as shown in figure 1. The 64ch probe array can measure azimuthally propagating density and potential fluctuations simultaneously. Figure 3 shows typical spatiotemporal structure of normalized ion saturation current $I_s/I_{sat}$ and 2-dimensional power spectrum density (PSD) decomposed into frequency and wave number. We observed quasi-coherent density (and floating potential) fluctuations with $m = 4$ and 9.6 kHz of frequency, and with $m = 1$, and 1.7 kHz of frequency, where $m$ is azimuthal mode number and the positive sign means rotating to the electron diamagnetic direction. Electron drift velocity is $V_e \approx 8.0 \times 10^2$, and drift frequency $f_s = V_e k_\theta / 2 \pi$ of the $m = 1$ mode and the $m = 4$ mode are 3.5 kHz and 14 kHz, respectively. Here, $k_\theta$ is azimuthal mode number. The ion gyroscale of $m = 1$ mode and the $m = 4$ mode are approximately 0.17 and 0.68, that is $k_\theta \rho_i < 1$, where $\rho_i$ is gyro-radius normalized by ion sound speed. The excited modes are not electron scale fluctuations but ion scale fluctuations.

In this study, we carried out conditional sampling to reconstruct temperature fluctuations. Unlike the blobs which have spiky waveforms, the two modes have sinusoidal-like waveforms. Therefore, a method to detect emergence timings of not only spiky but also sinusoidal-like waveforms is required. To determine the emergence timings of sinusoidal-like waveforms, we used statistical phase detection method, the template method [12, 13]. The template method determines the fluctuation emergence timings based on the peaks of cross-correlation between the original signal and the template waveform obtained through the iteration process. By the template method, we can evaluate time evolutions of electron temperature synchronized with sinusoidal-like density fluctuations.

The template method framework is briefly reviewed as follows. First, we determine an initial template $f_0(\tau) = \cos(2\pi \tau/T)$ ($-T/2 < \tau < T/2$), where $T$ is the fundamental period of target fluctuation. $f_0$ with $T \approx 10\mu s$ is shown in figure 4 (c) We note that we can not only choose sinusoidal wave but also sawtooth, triangle wave and so on, as the initial template. Next, we calculate the normalized cross-correlation function

$$C_j(t) = \frac{1}{\sigma_F(t)\sigma_{f_j}} \int_{-T/2}^{T/2} (F(t′′) - F(t)) \cdot (f_j(t′′) - f_j) \, dt′$$

(2)

where $j$ denotes number of iterations and $f_j$ is the $j$-th template. $F(t)$ is original time series signal which is $I_{sat}$ measured with 64ch probe in this study, as shown in figure 4. $F(t)$ and $\sigma_F(t)$ are average values and standard deviation of $F(t)$ from $t - T/2$ to $t + T/2$, $f_j$ and $\sigma_{f_j}$ are average value and standard deviation of $j$-th template $f_j$. The peaks of $C_0$ represent the emergence timings of $f_0$ in $F(t)$. Based on the peaks, we extract and average the data for each $T$ from $F(t)$, we obtained the 1st initial template $f_1$, (conditional averaging). The $j$-th template $f_j(\tau)$ are calculated as

\[I_{64ch} \quad \text{probe array at } r = 40 \, \text{mm. Positive } \theta \text{ direction corresponds to the electron diamagnetic direction. (c)Power spectrum density of ion saturation current fluctuation.} \]
where $N$ is number of ensembles and $i$ denotes the peaks of $C_{j-1}$. Using $f_1$ in the above process, we obtain the second template $f_2$. We iterate the above process until the template. Then, the base pattern of target fluctuations is determined by a trial and error manner. Figure 4 (c) shows each template $f_j$ of the three iterations. Finally, we obtain the converged template as the base pattern and cross correlation $C_j$, whose peaks used for conditional sampling or conditional averaging of other measurements. Time difference between the peaks can be considered as an emergence period. Figure 6 shows histogram of the emergence period, and indicates the emergence period are fluctuated.

For reconstructing temperature fluctuation, we perform double probe measurement and 64ch probe simultaneously, as shown in figure 1. Then, we apply the template method to $I_{is}$ measured by one of 64ch probe. $C_j$ obtained by the template method are shown in figure 5 (a). Figure 5 (b) and (c) show the time series of $I_p$ and $V_p$ measured by double probe. Based on the peaks of $C_j$, we conditionally sampled $V_p$ and $I_p$ at each time delay. We reconstructed I-V characteristics from the resampled $I_p$ and $V_p$. Figure 7 (a) shows the I-V curve for one voltage sweeping at $r = 30$ mm where the $m = 4$ mode is most strongly excited. Figures 7 (b)–(d) show the results of the conditionally sampled I-V curve obtained from data for many voltage sweepings. The slightly different I-V curves are separated from the original I-V curve.

3. Results

Temporal evolutions of $\tilde{T}_e/T_e$ and $\tilde{n}_e/n_e$ obtained by fitting the $I-V$ curve at each $\tau$ are shown in figure 8. Here, $\tilde{n}_e/n_e$ was evaluated as $\tilde{n}_e/n_e \approx \tilde{I}_e/I_{is} - 0.5 \times \tilde{T}_e/T_e$. We succeeded to observe electron temperature fluctuations of the $m = 4$ mode. Conditional averaging is also applied to ion saturation current measurement with the same trigger obtained by the template method [13]. A comparison of the normalized waveforms.
obtained from conditional sampling and averaging is shown in figure 9. The waveforms obtained by conditional sampling agree with the waveform obtained by conditional averaging in the range of errorbars.

Figure 10 shows power spectrum density (PSD) of $\tilde{n}_e/\bar{n}_e$ and $\tilde{T}_e/\bar{T}_e$. For comparison, $I_s/I_0$ obtained by one of the 64ch probes as a reference signal is also plotted. The PSD of conditional sampled $\tilde{n}_e/\bar{n}_e$ indicate that only the $m = 4$ mode and its synchronized components are extracted without noise, as different from reference $I_s/I_0$. Both $\tilde{n}_e/\bar{n}_e$ and $\tilde{T}_e/\bar{T}_e$ at the $m = 4$ have higher harmonics of the fundamental mode. The fundamental mode and the second harmonic of $\tilde{n}_e/\bar{n}_e$ are larger than that of $\tilde{T}_e/\bar{T}_e$ while the third and the subsequent harmonics of $\tilde{n}_e/\bar{n}_e$ are smaller than that of $\tilde{T}_e/\bar{T}_e$. This can be caused by differences in non-linear coupling or dissipative processes. The phase difference between $\tilde{n}_e/\bar{n}_e$ and $\tilde{T}_e/\bar{T}_e$ are evaluated as about $\pi/10$ rad by cross-phase analysis. Because phase difference exists, the $m = 4$ mode can induce electron heat flux.

The $m = 4$ mode is excited at the same condition in PANTA at high reproducibility. Double probe measurement was performed at radially different positions ($r = 10–60$ mm) in a shot by shot manner. The spatiotemporal structure of $\tilde{T}_e/\bar{T}$ and $\tilde{n}_e/\bar{n}_e$ were estimated by conditional sampling via the template method, where we used the same probe for detecting the emergence timings of the $m = 4$ mode. Figures 11 (a) and (b) show the spatiotemporal evolutions of $\tilde{T}_e/\bar{T}_e$ and $\tilde{n}_e/\bar{n}_e$. Each fluctuation is radially localized around $r = 30$ mm.

Assuming the fluctuations at every radial positions rotate as rigid-body, we can draw the cross-section images as shown in figures 11 (c) and (d). The cross-section images demonstrate that $\tilde{T}_e/\bar{T}_e$ and $\tilde{n}_e/\bar{n}_e$ have distorted waveforms, that is, the fluctuation pattern twisted. Wavefront distortion is related to non-linear coupling. They have finite radial wave number $k_r$ which are roughly estimated as $20$ m$^{-1}$.

Our method are also applied to the $m = 1$ mode coexisting with the $m = 4$ mode. We note that double probe data obtained from 5 discharges at each position are conditionally sampled to evaluate the $m = 1$ waveform, and the number of the conditionally I-V pairs is about 2500 at each $\tau$. Figures 12 (a) and (d) show reconstructed the spatiotemporal structure of the $m = 1$ mode. Not only the $m = 1$ mode but also the $m = 4$ mode are extracted. The time evolutions at $r = 30$ mm is shown in figure 13. When the $m = 4$ mode is not synchronized with
the $m = 1$ mode, the $m = 4$ component should disappear. These results indicate $m = 1$ is non-linearly coupled with the $m = 4$ mode and agree with bicoherence analysis [13]. $T_e/T_s$ contains more harmonics components than $\tilde{n}_e/\bar{n}_e$. For more clear understanding, we show low-pass-filtered patterns (< 9 kHz) in figures 14(a) and (b) to eliminate higher harmonics components. $\tilde{T}_e/T_e$ has different pattern than $\tilde{n}_e/\bar{n}_e$. $\tilde{\bar{n}}_s/\bar{n}_e$ is radially spread, on the other hands, $\tilde{T}_e/T_s$ has a node at $r = 25$ mm.

Figure 10. Power spectrum density of normalized electron temperature (red line) and density (blue line) obtained by each conditionally sampled waveform. Yellow line is the power spectrum density of ion saturation current used as a reference.

Figure 11. Spatiotemporal structures of normalized electron temperature fluctuation (a) and density fluctuation (b) at the $m = 4$ mode and its higher harmonics. (c) and (d) are the reconstructed cross-section images of them.

Assuming they rotate in the electron diamagnetic direction as rigid-body and $m = 1$ structure, we also evaluated cross-section image as shown in figures 14 (c) and (d). A node of $\tilde{T}_e/T_s$ is clearly visible. The pattern of $\tilde{n}_e/\bar{n}_e$ is similar to solitary wave pattern observed in LMD-U [17]. Radial wave number $k_r$ of $\tilde{n}_e/\bar{n}_e$ and $\tilde{T}_e/T_s$ are about 30 m$^{-1}$. The phase difference at $r = 20$ mm is about $\pi/5$ rad.

Figure 12. Spatiotemporal evolutions of normalized electron temperature fluctuation (a) and density fluctuation (b) at the $m = 1$ mode and its higher harmonics.

Figure 13. Radial wave number $k_r$ of $\tilde{n}_e/\bar{n}_e$ and $\tilde{T}_e/T_s$.

4. Discussion

In Fourier analysis, the time resolution $\Delta f$ and the frequency resolution $\Delta f$ are limited as $\Delta f \cdot \Delta f = 1$. In our method, however, the time resolution is about a period of target fluctuation and the frequency resolution is about reciprocal of Nyquist frequency. Broad peaks in Fourier spectrum appear when amplitude or period of the wave-like structure vary in time and such broad peaks are frequently observed. Fourier analysis cannot distinguish them but our method can trace such temporal variation of the emergence period of the wave-like structure. Figure 6 shows histogram of emergence period of the $m = 4$ mode. Here emergence period is evaluated by $t_i - t_f$ where $C(t_i)$ has a local maximum. The histogram shows that the emergence period varies in time. When the fluctuation of the emergence period is derived spontaneously and randomly, the histogram will become the normal distribution. However, the histogram seems to be asymmetry, i.e. merely skewed into the longer period region. Bicoherence analysis indicates presence of the non-linear couplings between $m = 4$ mode and others [13]. These couplings are considered to be caused by wave-wave coupling and/or amplitude modulation by background flow fluctuations and may distort the histogram externally. Clarification a connection between emergence period histogram and non-linear processes is left in future work.

Fluctuation amplitudes provide useful information for identifying instabilities. Figure 15 shows radial profiles of amplitudes of $\tilde{T}_e/T_s$ and $\tilde{n}_e/\bar{n}_e$ at the $m = 4$ and $m = 1$ modes. The amplitudes of fluctuations are evaluated as root mean square value. At all measurement positions, the $\tilde{T}_e/T_s$ are lower than that of $\tilde{n}_e/\bar{n}_e$. The ratio of the normalized fluctuation levels between $\tilde{T}_e/T_s$ and $\tilde{n}_e/\bar{n}_e$ are about $T_e/T_s \approx 0.45$. Drift type instabilities are driven by density or temperature...
In the experimental condition of $\eta_e \sim 0.56$, the electron temperature gradient (ETG) mode is linearly stable but the density gradient driven drift wave (DW) can be unstable. The spatial scale of the DW is ion scale, i.e. $k_i \rho_i < 1$ and $m_e$ is low but finite, the DW can fluctuate electron temperature. For the $m = 4$ mode, we calculate $k_|| \sim 4$ rad/m, $\chi_|| \approx 1.0 \times 10^4$ m$^2$/s, $\omega_e = k_0 V_s \approx 8 \times 10^4$ rad/s$^{-1}$ by using $T_e = 2.0$ eV and $n_e = 0.5 \times 10^{19}$ m$^{-3}$. Then the ratio of the normalized fluctuation levels is $\tilde{T}_e/\tilde{n}_e \sim \chi_||/k_0 \sim 0.3$, which is the same order of magnitude with observed value. Therefore, the $m = 4$ mode could be a drift mode.

While the $m = 4$ mode is localized radially, the $m = 1$ mode broadens. The fullwidth at half maximum of the amplitude profile is 15 mm and 30 mm for the $m = 4$ and the $m = 1$ modes. Regarding to the $m = 1$ mode, a node structure appears in $\bar{T}_e$ at $r \sim 25$ mm but does not $\bar{n}_e/\bar{n}_e$. The result seems to be related to fine structures of $\bar{T}_e$ profile. As shown in figure 2, there is a fine $\bar{T}_e$ structure (flat or small bump) around $r \sim 25$ mm. When $\bar{T}_e$ is written as $\bar{T}_e = \nabla T_e \zeta$ where $\zeta$ is fluctuation of radial displacement of plasma, the $\bar{T}_e$ can be 0 through $\nabla T_e \sim 0$. On the other hands, $\bar{n}_e$ profile does not have such a fine structure. The node structure in floating potential fluctuation has been observed as reviewed in Ref [18]. The floating potential fluctuation includes information of electron temperature fluctuation component and thus this suggests presence of the node structure in temperature fluctuation.

To evaluate fluctuation driven energy transport, we have to measure density, temperature, and space potential fluctuations at the same position and at the same time. Regarding plasma potential $V_s$, the model equation is written as

$$\tilde{V}_s = \tilde{V}'_s + \frac{\alpha}{e} \tilde{T}_e,$$  

(4)

here,

$$\alpha = \ln\left(\exp\left(\frac{1}{2}\right)\sqrt{\frac{m_i}{2\pi m_e}}\right) \approx 5.2,$$  

(5)

$m_e$ and $m_i$ are electron and Argon ion mass, respectively. Usually, in basic plasma experiments, it is believed that electron temperature fluctuation can be negligible and thus, $\tilde{V}_s \approx \tilde{V}_e$. In the experiment case, however, the amplitude of $\tilde{T}_e$ of the
\( m = 4 \) mode is about 0.2 eV at \( r = 30 \text{ mm} \), while that of \( V_f \) is a few volts. Therefore, space potential fluctuation is difficult to measure by using floating potential because of \( \alpha \tilde{T}_e \sim V_f \). That is, an evaluation of fluctuation driven heat transport is still a challenging problem. Direct space potential measurement using emissive probe and advance uses for emissive probe are reviewed [19] and a possibility of the space potential measurement using ion sensitive probe [20] is also reported. We will perform both methods in the future.

5. Summary

We proposed new methods to evaluate electron temperature fluctuations. Using the template method, which is the statistical method to detect emergence timings of fluctuation, we applied conditional sampling to double probe current and voltage. We succeeded to observe electron temperature and density fluctuations by the conditionally sampled I-V curves. Our method revealed the spatiotemporal structure of electron temperature and density fluctuations of the features of two quasi-coherent modes, the \( m = 4 \) mode and the \( m = 1 \) mode (1) the phase differences between \( \tilde{T}_e \) and density fluctuations \( \tilde{n}_e \) exist, (2) the ratio of normalized amplitudes of \( \tilde{T}_e / \overline{T}_e \) and \( \tilde{n}_e / \overline{n}_e \) are about 45\% for the \( m = 4 \) mode, (3) the \( m = 4 \) mode is radially localized, (4) the \( m = 1 \) mode is relatively spread structure and has nodes in \( \tilde{T}_e \). Applying the template method for fusion plasma diagnostics allows observing ion and electron temperature fluctuation induced by such as MHD fluctuations and ITG.

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