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2D turbulence structure observed by a fast framing camera system in linear magnetized device PANTA

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Abstract. Two dimensional turbulence observed in the linear magnetized device PANTA is studied using a visible high speed camera system. When the fluctuation component are decomposed with Fourier-Bessel expansion, complex density fluctuations are recognized as the superposition of the several mode having low mode number, e.g., m = 1, 2, and 3. The phase relations between waves indicate that they are non-linearly coupled.

1. Introduction

Mesoscale structures, such as the zonal flow and the streamer play important role in the drift-wave turbulence. The interaction of the mesoscale structure with the turbulence is a key to understand the structural formation of turbulence and the turbulence-driven transport in the magnetically confined plasmas. In a cylindrical magnetized device, the interaction of the streamer and the drift wave has been found [1]. In that study the spatial shape of the streamer-like structure were obtained by using the bi-spectrum analysis with a fixed probe array and a movable probe system. Statistical nature of the mesoscale structure can be studied by this method. However, if the dynamic wave-wave interaction can be observed directly, our understanding of the turbulence will be improved further. For this purpose, direct visualization of the turbulence with a high-speed camera system was performed. The analytical procedure and initial results are presented in this article.

2. Experimental Setup

A fast framing camera system observing the cylindrical plasma through an end port of the PANTA device is schematically shown in figure 1(A). If the perturbation is aligned to the magnetic field lines, two dimensional turbulent structures can be observed from this arrangement. It is noted that when we observed the plasma column perpendicularly, the mode structure is well aligned to the magnetic field lines. The parameters of the target plasma is the following; T_e ~ 3 eV, n_e ~ 1 × 10^{19} m^{-3}, T_i ~ 0.3 eV, B = 900 G, the neutral pressure P_n = 0.8 m Torr, the minor radius a ~ 6 cm and L = 4 m. Helicon source (7 MHz, 3 kW) is used to generate plasma. No filter was used for the camera. Since the electron temperature is several eV, line emission of Ar I is the dominant component of the visible image. Its intensity is sensitive to the local electron density fluctuations and local electron temperature fluctuations. A sample image is shown in figure 1(B). The plasma is surrounded by azimuthally aligned 64-pin Langmuir probe array. The contour plot with white lines shows the coherence between

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imaging data and the ion saturation current measure by a probe tip of 64 pin system. High-coherence region is well localized so that the local density / temperature perturbation can be estimated from the visible emission intensity. It is confirmed that the spatial / frequency spectra measured by ion saturation using the probe system is quite similar to that by 2D visible measurement described in detail in Section 3. It is thus reasonable we assume that the fluctuation of the light emission density fluctuations having low mode number. .

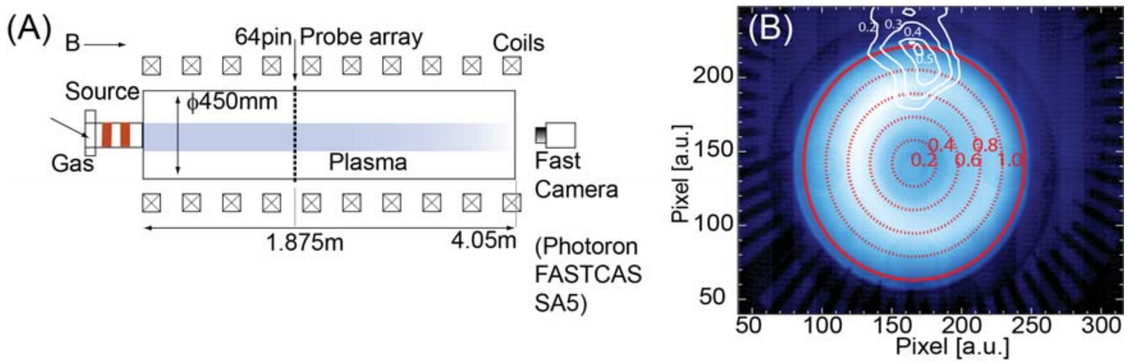

Figure 1. (A) Schematic drawing of the high-speed-camera measurement. (B) A typical emission profile (Blue-White gradation) and the contour of the correlation coefficient between the ion saturation current of a probe and the emission data are shown with the white lines. The region where the Fourier-Bessel decomposition is performed is shown by the red circles.

3. Analysis and Initial Results

Fluctuating component of the visible emission *g(r, θ)* is decomposed to orthogonal components by the Fourier-Bessel expansion method [2] as,

$$\mathrm{g}(\mathrm{r},\theta) = \sum_{m=0}^{m_{max}} \sum_{l=0}^{l_{max}} \left(a_m^l \cos(m\,\theta) + b_m^l \sin(m\theta)\right) J_m\ \left(\lambda_m^{l+1} r\right) \tag{1}$$

where λ_m^l is the *l*-th zero point of the *m* th order Bessel function $J_m(z)$.

Decomposition is performed where emission light is strong. The boundary is shown by the red *r*=1.0 circle in figure 1(B). Since the Fourier-Bessel series are orthogonal, it is quite easy to obtain the coefficients a_m^l and b_m^l. Error in the decomposition is estimated to less than 5% when $m_{max} = 4$ and $l_{max} = 10$ are assumed. If we combine coefficients a_m^l and b_m^l to complex coefficient $z_m^l = a_m^l + i\, b_m^l$, z_m^l represents the magnitude of mode with phase information. Complex amplitude at a minor radius *r* with a mode number *m* can be written from the integral as,

$$z(t,r,m) = \sum_{l=0}^{l_{max}} z_m^l J_m\left(\lambda_m^{l+1} r\right) \tag{2}$$

Using the Fourier transform $\mathrm{Z}(\omega,\mathrm{r},\mathrm{m}) = \int_{-\infty}^{\infty} z(t,r,m) e^{-i\omega t} dt$, rotary spectrum *S(ω, m)* [3] can be defined as $S(\omega, m) = \langle Z^* Z \rangle$.

Rotary spectrum with *m* =1, 2 and 3 are shown in figure 2. There are many sharp peaks, labelled by f_1, f_2, ⋯, in broad spectra. It is noted that the *m* = 2 and *m* = 3 components are not strong in the core region. Those spectra in the edge region (e.g., $\rho = 0.8$) are quite similar to the spectra estimated with the multi-pin probe array data [1].

Figure 3 shows time evolutions of the emission pattern. Though the changes of the raw image are quite complicated, the dominant movement is the rotation of the m = 1 mode in the electron diamagnetic drift direction with f = f_2 and f_3, shown by the red curve in figure 3(A). Interaction with the other component, e.g., (m = *1, f* =f_1) which rotates in ion diamagnetic drift direction, shown by the blue dotted curve in figure 3(A), disturbs the constant rotation of the modes.

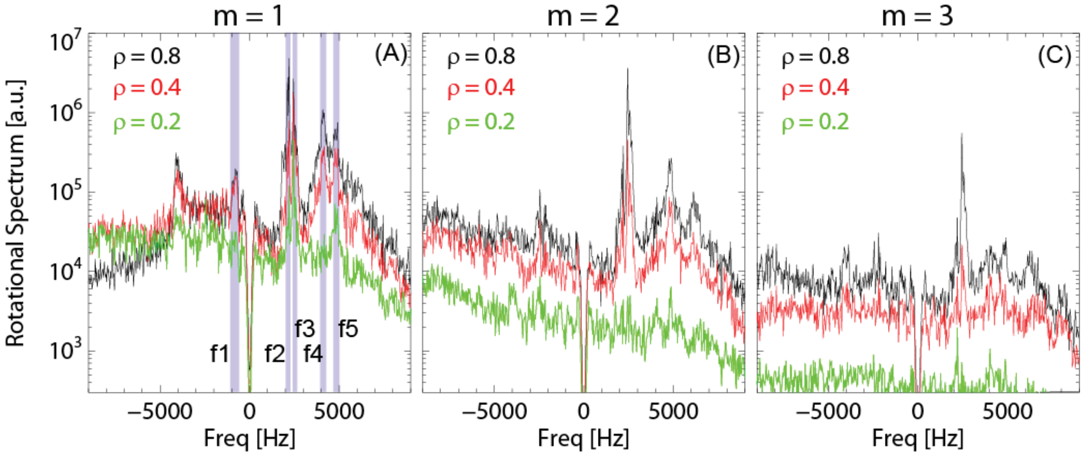

Figure 2. (A) Rotary spectra of fluctuations with the m=1(A), 2(B) and 3(C) are shown.

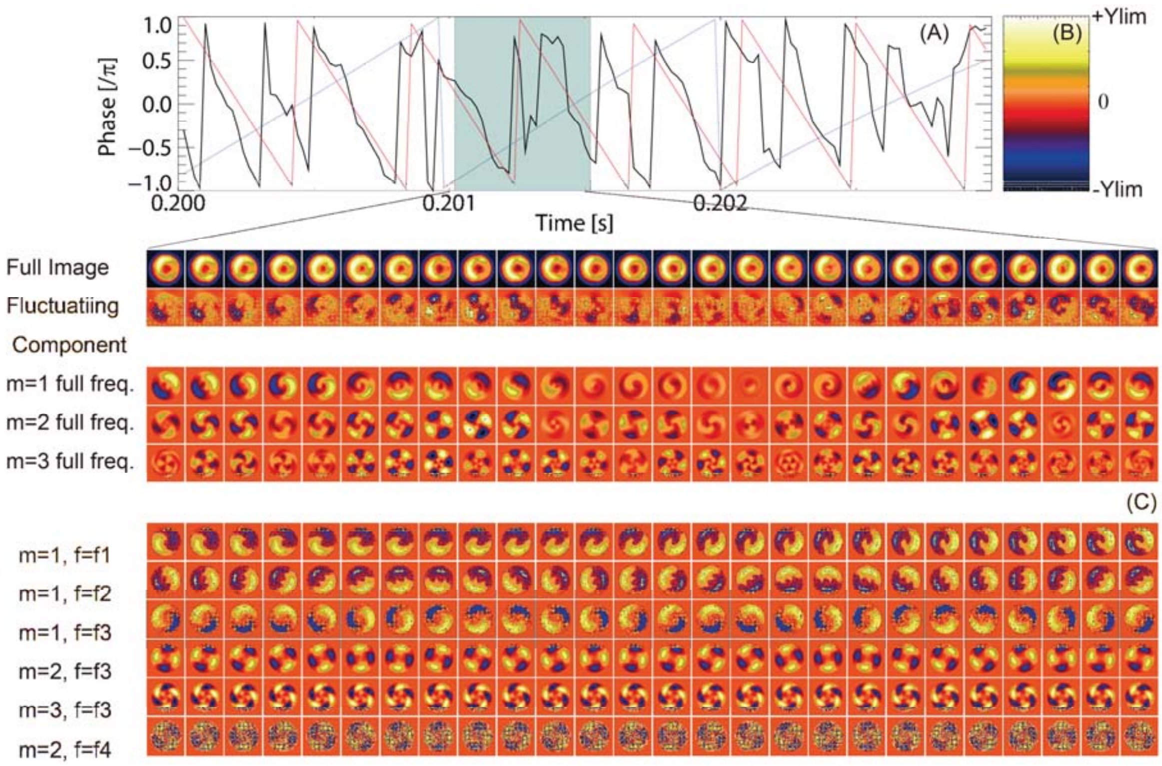

Figure 3. Time evolution of the rotation angle of the fluctuation is shown (A). Phase of total m=1 component, component with m = 1 and f= f_2, and component with m = 1 and f = f_1 is drawn by red b line, black line and blue dotted line, respectively. The color bar for the 2D images is shown in (B).

Sequential images of the emissions are shown in (C). Here, [+Ylim, -Ylim] = [22500, 0] (Full image), [0.18, -0.18] (Fluctuating components), [0.09, -0.09](m=1, full frequency), [0.09, -0.09](m=2, full freq.), [0.05, -0.05] (m = 3, full freq.). The image with frequency filter (6 bottom rows) is drawn with auto-scale in order to emphasize the spatial structure.

Wave-wave interaction of the each component is then investigated to study the non-linear nature of the turbulence. Among the possible wave-wave coupling pair, interaction of mode A ($m = 1$ and $f = f_2$) and mode B ($m = 2$ and $f = f_4$, ($\sim 2 \times f_2$,)) is quite obvious. The phase of the Mode B, ϕ_B and the two times of the phase of A, 2 ϕ_A are shown in figure 4(A).

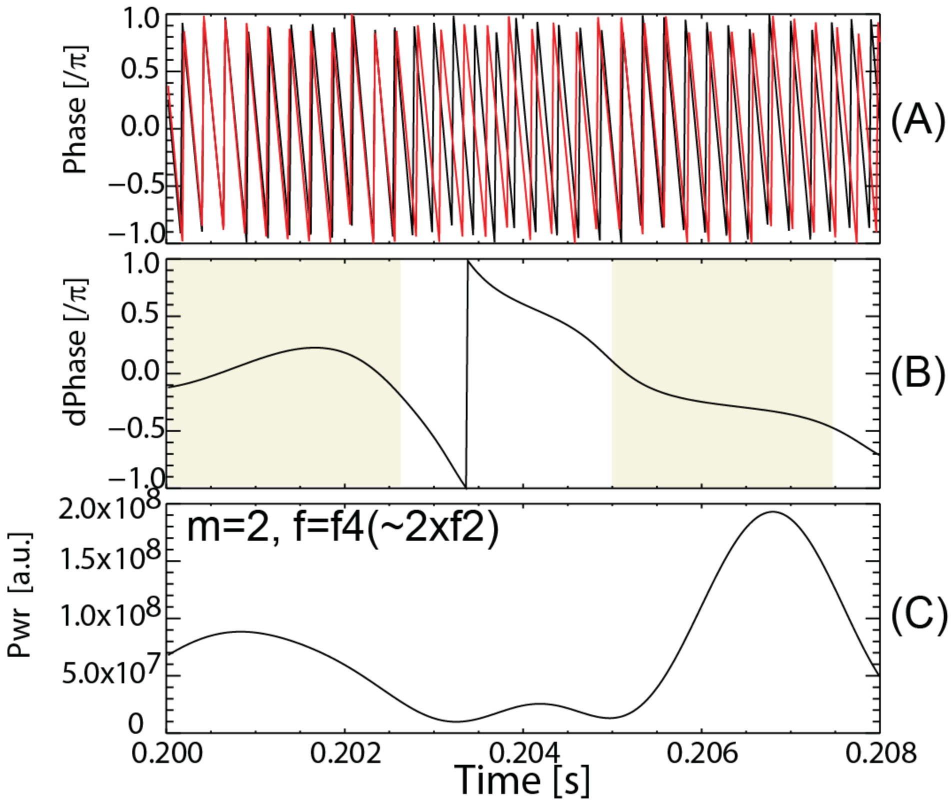

Figure 4. Time evolution of two times of the phase of the Mode A ($m = 1$ and $f = f_2$) ϕ_A (black line)) and the phase of the Mode B ($m = 1$ and $f = f_2$) (red line)) are shown in (A). The difference of the two phases is shown in (B). The amplitude of the Mode B is shown in (C).

There is a time period where the two phases are locked between each other (Shaded region of figure 4(B)). That is the reason finite bi-coherence between mode A and mode B is observed. The amplitude of the mode B is larger when the two phases are locked (figure 4(C)). It is possible that the mode B is produced from the mode coupling of the mode A. Many peaks in the rotary spectra might be caused by this kind of wave-wave coupling of the fundamental mode. It is noted that from the time evolution of the phase difference (figure 4(B)), there is a period where the two waves are unlocked, as well. Therefore, the wave-wave coupling process is found to be not simple steady process but a kind of intermittent process.

In summary, Fourier-Bessel expansion method is shown to be an effective tool to analyse two dimensional turbulences observed in the linear device. Non-linear coupling of the waves are clearly observed. It is found that coupling process is not constant in time and intermittently activated.

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