Streamer Structures in Experiment and Modeling[*)]

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Validation of modeling in meso-scale structure formation is undergoing by using multi-channel probe measurements and advanced analyzing techniques such as bispectrum. Study of meso-scale structures including streamers is important for understanding anomalous transports in magnetized plasmas. A streamer structure and its mediator mode were observed in the Large Mirror Device-Upgrade linear plasma. The mediator mode nonlinearly coupled with many other drift wave modes and generated a streamer structure by phase locking. The radial biphase profiles indicating the phase locking showed the radial elongation of the streamer structure. Modes having similar characteristics to the mediator were also found in a theoretical work based on the Hasegawa-Mima model and a numerical simulation code.

Keywords: linear plasma, turbulence, nonlinear coupling, streamer, bispectrum, validation of modeling

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1. Introduction

For understanding anomalous transports in magnetized plasmas, study of drift wave turbulence has been an important subject. Theories and simulations have predicted that the nonlinear couplings between the drift waves can generate meso-scale structures, such as zonal flows and streamers, which should have a strong influence on the anomalous transports [1]. Zonal flow is a radially localized, poloidally elongated structure that suppresses radial transport. In contrast, streamer is a poloidally localized, radially elongated structure that enhances radial transport [2–5]. The streamer structure lives longer than the characteristic turbulence correlation time and is a global meso-scale structure generated by nonlinear phase locking of several drift wave modes. The study of nonlinear processes, such as turbulent Reynolds stress, which induces meso-scale structures, is essential for understanding transports of magnetized plasmas.

Theoretically, one example showed that envelope solitary vortices placing in the direction of the drift wave propagation, accompanied by a slow mode, were derived by a nonlinear Shrödinger equation based on the Hasegawa-Mima model [3]. The Numerical Linear Device (NLD) simulation code clearly presented the generation of the streamer structure and clarified that the collision frequency between ions and neutrals plays an important role for the selection rule of generating meso-scale structures including streamers [6,7]. Experimentally, zonal flows have been well studied, for example, zonal flow was first observed by a heavy ion beam probe in the Compact Helical System [8–12]. On the other hand, only few signatures of streamers have been found in toroidal plasmas so far [13,14]. Although, in the Large Mirror Device-Upgrade (LMD-U), a streamer structure was first observed in a linear magnetized plasma [15]. This observation was accomplished by using several multi-channel Langmuir probe measurements and bispectral analysis that investigates nonlinear coupling and phase locking between instability modes. In this way, validation of modeling in meso-scale structure formation is progressing by using multi-channel large-storage measurements and advanced analyzing tools. In addition, since the comparison between simulation and experiment has become more important, a turbulence diagnostic simulator project has been developed [16].

2. Theoretical Work

Meso-scale structures have been well studied in theoretical works. When the plasma is bounded in a y direction and drifts in an x direction, envelope solitary vortices placing in the x direction (fast mode) and a pair of large scale vortices (slow mode) are derived from the

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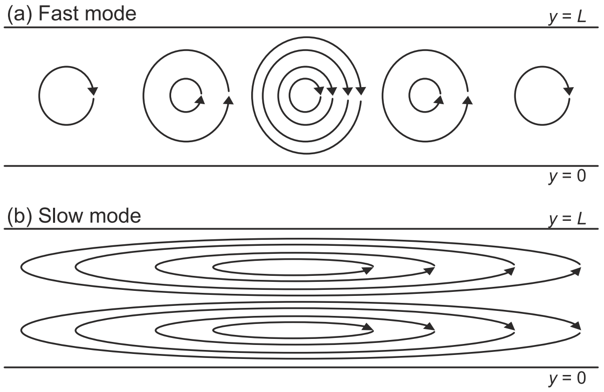

Fig. 1 Streamlines for the (a) fast and (b) slow modes derived from a nonlinear Schrödinger equation based on the Hasegawa-Mima model, with the case of $n = 1$ and $k_x = k_n$.

Hasegawa-Mima model [3]. The fast mode corresponds to the streamer structure when x and y directions are interpreted as poloidal and radial directions, respectively. According to Ref. [3], a pair of fast mode and slow mode including a streamer structure is derived as follows. In the Hasegawa-Mima model, the plasma density is given by $n_0 \exp \phi$, where ϕ is an electrostatic potential. When n_0 is a slowly varying function of y, i.e., $(\mathrm{d}n_0/\mathrm{d}y)/n_0$ is a small constant, the Hasegawa-Mima model equation in the coordinates (x, y) takes the form

$$\frac{\partial}{\partial t}(\Delta\phi - \phi) - \left(\frac{\partial \phi}{\partial y}\frac{\partial}{\partial x} - \frac{\partial \phi}{\partial x}\frac{\partial}{\partial y}\right)\Delta\phi - b\frac{\partial \phi}{\partial x} = 0, \quad (1)$$

where b is a constant proportional to $(\mathrm{d}n_0/\mathrm{d}y)/n_0$. The second term is the nonlinear Reynolds stress term, $[\phi, \Delta\phi]$. When the unperturbed potential is $\phi^0 = -c_0 y$, a dc electric field exists in the y direction, the plasma drifts in the x direction, and the disturbance $\delta\phi$ is excited on the drift motion. When the fixed boundary conditions are assumed at the plasma boundaries, $\delta\phi(x, 0) = \delta\phi(x, L) = 0$ (L is the plasma length), $\delta\phi$ has the form $\delta\phi = X(x, t)Y(y)$, where $Y \propto \sin k_n y$, $k_n = n\pi/L$, and n is a natural number. It is anticipated that if $\delta\phi$ is small, wave-modulations in the x direction will be described by a nonlinear Schrödinger equation. When ϕ is expressed as

$$\phi = \phi^0(y) + \sum_{\alpha=1} \varepsilon^\alpha \phi^\alpha, \quad (2)$$

the one-soliton solution is that ϕ^1 and ϕ^2 take the forms

$$\phi^1 \propto \mathrm{sech}\kappa(x - \lambda t) \cdot \cos k_x x \cdot \sin k_n y, \quad (3)$$

$$\phi^2 \propto \mathrm{sech}^2\kappa(x - \lambda t) \cdot \sin k_{2n} y, \quad (4)$$

where $\lambda = \mathrm{d}\omega/\mathrm{d}k_x$ and κ is a function of k_x, k_n, c_0 and b. Figures 1 (a) and (b) are the schematic views of contours ϕ^1 = constant (the fast mode) and ϕ^2 = constant (the slow mode), respectively. Figure 1 (a) shows a train of small convective cells placing at intervals of $1/k_x$ in the x direction. The magnitudes decrease towards $|x| \to \infty$. Figure 1 (b) shows a pair of vortices of large scale. When x and y are taken as the poloidal and radial directions, respectively, the fast mode is coincident with a solitary envelope structure localized in the poloidal direction (a streamer). This model also predicts the existence of large-scale vortices having doubled value of k_y compared to the fast mode.

3. Experimental Results

A streamer structure in a linear plasma experiment was observed for the first time in the LMD-U plasma [15]. A mediator, which is an important mode for creating the streamer structure, was also found [17]. The LMD-U vacuum vessel has an axial (z) length of 3.74 m and an inner diameter of 0.45 m. Under the experimental conditions of 3 kW of 7 MHz radio-frequency wave power, 0.01–0.15 T of axial magnetic field, and 1–6 mTorr of argon pressure inside the source region, which is a quartz tube with an inner diameter of 95 mm, the peak electron density is about 10^{19} m^{-3} and the electron temperature is about 3 ± 0.5 eV inside the plasma. The electron density gradient is steep in the radius of r = 30–40 mm, and produces resistive drift wave instabilities propagating in the positive poloidal direction θ, which is the electron diamagnetic drift direction.

A 64-channel poloidal Langmuir probe array [18] was used to measure the drift wave turbulence at the radius r = 40 mm and the axial position z = 1885 mm. When the axial magnetic field was low and/or the argon pressure was high, the spatiotemporal waveform measured with the poloidal probe array became coherent. By varying the discharge conditions, i.e., increasing the axial magnetic field and/or decreasing the argon pressure, the spatiotemporal behavior changed from a coherent to a turbulent regime, passing through a periodic and solitary regime. By reducing the argon pressure furthermore, a meso-scale streamer structure was formed in the turbulent regime. Figure 2 (a) shows the spatiotemporal of the ion saturation-current fluctuation in the laboratory frame with the axial magnetic field of 0.09 T and the argon pressure of 1.5 mTorr. With this discharge condition, a bunching of waves in the fluctuation waveform at the radius of 40 mm was clearly observed. The dominant modes have poloidal mode number m = 2–3 and frequency $f \sim$ 7–9 kHz. The bunching of waves is poloidally localized, i.e., separated into high-amplitude and low-amplitude regions, and the envelope forms an m = 1 structure in the poloidal space. While the dominant modes propagate in the electron diamagnetic direction, the envelope structure propagates in the ion diamagnetic direction (at least in the laboratory frame). The figure below the spatiotemporal contour is the temporal waveform at the zero poloidal angle position. It consists of bunching waves with a beat frequency of 1.2 kHz and a slow sinusoidal wave with f = 1.2 kHz. The dashed line is the low-passed component and corresponds to the 1.2 kHz sinusoidal wave. The important thing is that this sinusoidal wave also has an m = 1 structure and the phase is locked with the envelope struc-

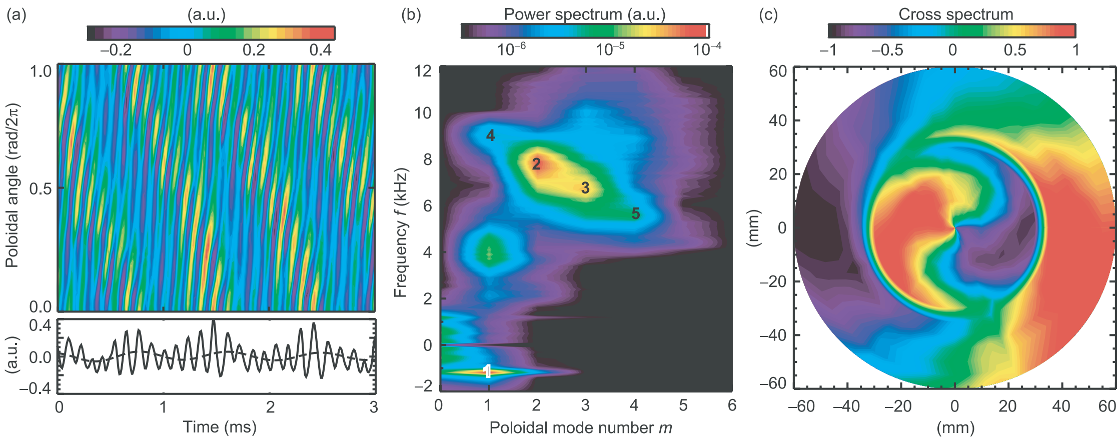

Fig. 2 (a) Spatiotemporal waveform of ion saturation-current fluctuation measured at radius of 40 mm with a 64-channel poloidal probe array. Below is temporal waveform at zero poloidal position. Dashed line is low frequency component. (b) Two-dimensional power spectrum of (a). Mode “1” is mediator and modes “2”–“5” are carrier drift waves of streamer structure. (c) Real part of cross spectrum for mode “1” component between poloidal probe array at r = 40 mm and radially mobile probe. There is a node in radial direction at r = 30 mm.

ture. Figure 2 (b) is the two-dimensional power spectrum $S(m, f)$ of the turbulence. The dominant modes in the electron diamagnetic direction are (m, f) = (2, 7.8 kHz), (3, 6.6 kHz), (1, 3.9 kHz), (4, 5.4 kHz), (1, 9.0 kHz), and so on (some of the modes are labeled as “2”–“5”). From Fig. 2 (a), it is clear that modes “2” and “3” are the fine structures in the spatiotemporal waveform and they are the carriers for the formation of the poloidally localized structure. There also exists a large amplitude mode in the ion diamagnetic direction labeled as “1”, that is, (m, f) = (1, −1.2 kHz), which has the same property as the envelope structure. The phase structure of mode “1” in the whole plasma cross section was investigated. Figure 2 (c) shows the real part of the cross spectrum of f = 1.2 kHz component between the 64-channel poloidal probe array at r = 40 mm and a radially mobile probe. It consists of two large-scale structures neighboring in the radial direction and propagating in the ion diamagnetic direction [counterclockwise in Fig. 2 (c)]. The propagating direction was confirmed by shifting the time series between the probe array and mobile probe. The phase jumps at r = 30 mm. Compared to the theoretical work, when the y direction in Fig. 1 (b) is taken as the radial direction, these two structures become similar.

Next, it can be considered that mode “1” nonlinearly couples with a carrier wave, creates another quasi-mode carrier, and the carriers form a beat structure with the same property as mode “1”. The accumulation of these nonlinear couplings forms a bunching of waves. If this is true, the phases of mode “1” and carriers must be locked and that can be examined by bispectral analysis. To investigate the phase locking between mode “1” and the envelope, bispectral analysis was applied to the Fourier transformed expressions $Z_1 = Z(1, -1.2\,\text{kHz})$, $Z_2 = Z(2, 7.8\,\text{kHz})$, and $Z_3 = Z(3, 6.6\,\text{kHz})$ of the three pronounced modes “1”, “2”, and “3”. The results for 390 ensembles yield a squared bicoherence value of 0.57, which clearly proves that the three modes are nonlinearly coupled, since it is higher than the confidence level, 0.003 (= 1/390). In other words, the three modes exist independently, and their phases are locked. The strong bicoherence values were also confirmed in the mode pairs of “135” and “142”. Mode “1” also strongly coupled with other coherent modes. Therefore, mode “1” is an important mode for forming the poloidally localized structure and can be called a mediator for meso-scale formation [7].

A streamer is a localized structure of the fluctuation in the poloidal direction, and it must have a radially elongated structure. To confirm that the poloidally localized structure measured in LMD-U is a streamer, the radial structure of the envelope was investigated. The structure is mainly generated by modes “2” and “3”. The biphase between modes “1”, “2”, and “3” indicates the phase difference between mode “1” and the envelope. When mode “1” measured at the radius of 40 mm with the poloidal probe array is taken as a reference signal, and the biphases between this and modes “2” and “3” at different radii are calculated, the phase structure of the envelope along the radial direction can be determined. Since the radially mobile probe makes a single-point measurement, $Z_1 = Z(1, -1.2\text{ kHz})$, $Z_2 = Z(7.8\,\text{kHz})$, and $Z_3 = Z(6.6\,\text{kHz})$ are taken for the biphase calculation. Figure 3 shows the radial profile of the biphase between mode “1” at r = 40 mm and the local modes “2” and “3”. The radially mobile probe was scanned from 10 to 60 mm along the radial direction. The biphase was almost constant around 0.1 (rad/2π) inside the plasma. With the same method, the radial biphase profiles for other pairs “135” and “142” were also calculated and plotted in Fig. 3. Both pairs also have flat biphase profiles. Thus, it became clear for the first time that several coherent modes nonlin-

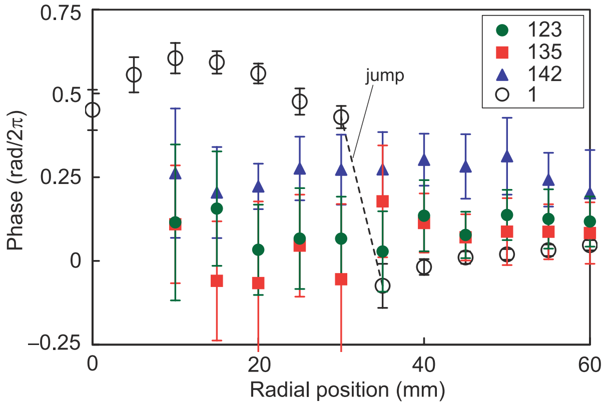

Fig. 3 Radial profiles of the biphase between modes "123" (closed circles), "135" (squares), and "142" (triangles). $Z_1 = Z(1, -1.2\,\text{kHz})$, measured with 64-channel poloidal probe array (reference signal), and $Z(f)$ measured with a radially mobile probe for the others, were used for the calculation. Three results indicate that the poloidally localized structure is almost radially independent. Open circles indicate radial phase profile of mode "1", which jumps π radians at $r = 30$ mm.

early coupled with the mediator mode and the biphases of the mode couplings had nearly flat radial profiles. It means that these coherent modes contribute to form the poloidally localized structure, which is elongated in the radial direction. It is clearly shown that this poloidally localized structure is confirmed to be a streamer. In addition, the radial phase profile of mode "1" was also calculated by taking the cross phase of the 1.2 kHz component between the poloidal probe array and the mobile probe. As is shown by open circles in Fig. 3, the phase jumps for π radians at $r = 30$ mm, indicating that it has a node in the radial direction.

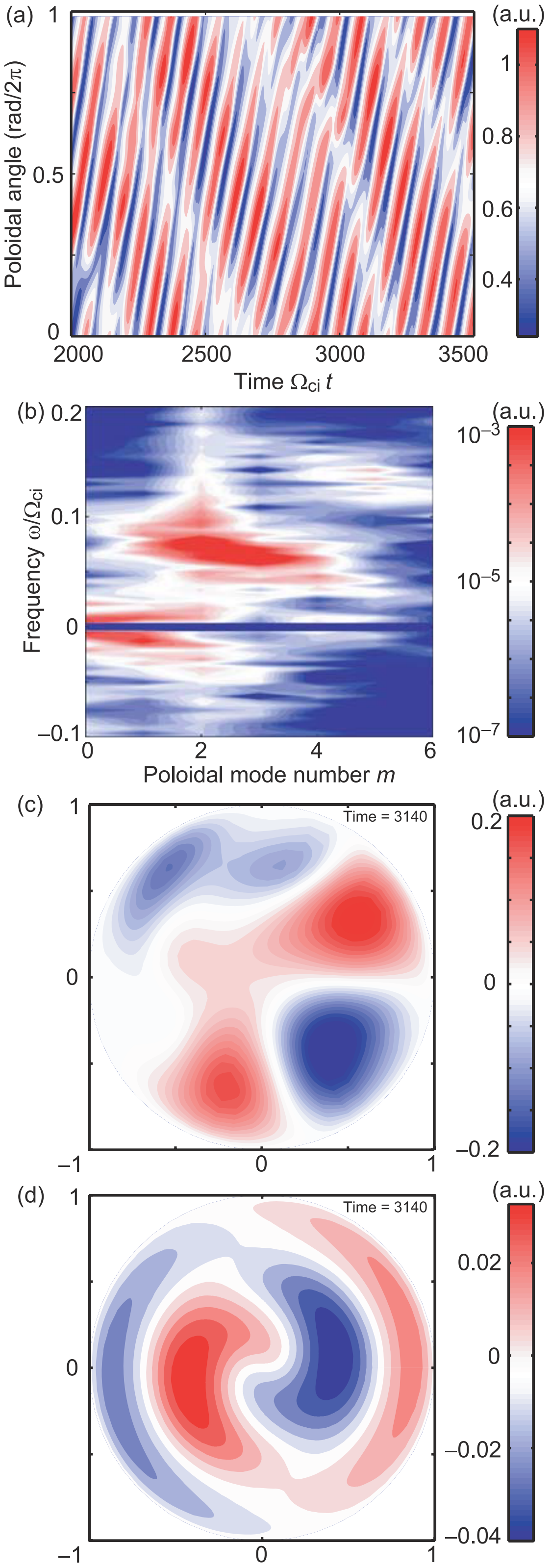

Fig. 4 (a) Spatiotemporal, (b) two-dimensional power spectrum, and screenshots of (c) whole turbulence and (d) $(m, n) = (1, -2)$ mode of electron density fluctuation calculated by NLD simulation code.

4. Discussion from Simulation

A numerical simulation played an important role to discover the streamer structure [15], and it has clarified a selection rule of turbulent structures [7]. The importance of the comparison between simulation and experiment has been recognized, and turbulence diagnostic simulator project has been developed [16]. Here, we discuss a simulation result on the spatial structure of the mediator in the case when the streamer is observed by the NLD code. The code is based on the three-field (density, electrostatic potential, and parallel velocity of electrons) reduced fluid model with a simple cylindrical geometry [6]. Following parameters are used: plasma radius $a = 70$ mm, length of the device 4 m, electron density at the center of the plasma $10^{19}\ \text{m}^{-3}$, and the electron temperature 3 eV. The calculation is carried out with a fixed particle source, whose profile is given as $S_N(r) = S_0 L_N^{-2}[1-(r/L_N)^2]\exp[-(r/L_N)^2]$, where $S_0 = 0.2$ and $L_N = 67$ mm. The collision frequency between ions and neutrals is a control parameter of instability here, which gives a selection rule of turbulent structure formations such as zonal flows and streamers. The value is chosen as $0.03\Omega_{ci}$ (Ω_{ci} is the ion cyclotron frequency), which gives streamer formation. The mode number and frequency of the observed dominant drift waves are $(m, n, \omega_{m,n}) = (2, 1, 0.007\Omega_{\mathrm{ci}})$ and $(3, -1, 0.005\Omega_{\mathrm{ci}})$. In addition to the linearly unstable drift waves, a wave with $(m, n, \omega_{m,n}) = (1, -2, -0.002\Omega_{\mathrm{ci}})$ is driven by the nonlinear coupling between the dominant drift waves, which is thought to be the mediator. The dominant drift waves and the driven mode satisfy the matching conditions. As shown in Fig. 4 (a), the density fluctuation propagates in the electron diamagnetic drift direction, while its modulation propagates in the ion diamagnetic direction. Here, the positive direction of the poloidal angle is chosen as that of the electron diamagnetic drift. The figures are shown in the laboratory frame, however, the propagating directions do not change with in the plasma frame. Figure 4 (b) shows the two-dimensional (frequency and poloidal mode number) power spectrum. As likely as Fig. 2 (b), there are major $m = 2$–3 modes with positive frequencies and an $m = 1$ nonlinear driven mode with a negative frequency. The frequency of the modulation is as same as the nonlinear driven mode with $(m, n) = (1, -2)$. The bunching of the fluctuation can be seen in the poloidal cross section as shown in Fig. 4 (c). Figure 4 (d) shows the poloidal cross section of the nonlinearly driven mode $(m, n, \omega_{m,n}) = (1, -2, -0.002\Omega_{\mathrm{ci}})$, which propagates in the ion diamagnetic direction [counterclockwise in Fig. 4 (d)]. The radial wavenumber of this nonlinear mode is twice of the drift waves. These characteristics are similar to that of the theoretical prediction [3] and the mediator observed in LMD-U. Especially, both simulation and experiment results have similar comma-shaped structures, of which the tails of the comma shapes are facing in the ion diamagnetic direction, at the inner parts of the plasma cross sections. Such kind of a mediator mode having a node in the radial direction was found for the first time in simulation results. More quantitative comparison with experimental results by configuring the plasma conditions is planned for understanding the mechanism of the mediator.

5. Summary

In summary, a streamer structure and its mediator mode, which plays an important role for the streamer formation, were observed in the LMD-U linear magnetized plasma. The mediator mode propagating in the ion diamagnetic direction nonlinearly couples with other drift wave modes propagating in the electron diamagnetic direction, generates another quasi-drift wave modes, and modulates the drift wave modes by phase locking. The modulation envelope forms the same structure as the mediator mode and propagates in the ion diamagnetic direction. The new finding is that not only the pair of the dominant drift wave modes but also two other pairs of drift wave modes strongly coupled with the mediator mode. Their radial biphase profiles were also nearly constant indicating the radial elongation of the streamer structure. Such kind of modes similar to the mediator was also found in modeling. Nonlinear Shrödinger equation based on the Hasegawa-Mima model derived envelope solitary vortices placing in the drift wave propagation direction, accompanied by a slow mode, which was a pair of large vortices having double value of the radial wavenumber compared to the solitary vortices. The NLD simulation code found a mediator mode having a node in the radial direction for the first time in numerical calculations. The characteristics of these modes from theory and simulation agree well with the mediator mode found in the experiment.

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