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Analysis of plasma turbulence transition phenomena using multipoint correlation analysis

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Anomalous transport in plasma, a central challenge in nuclear fusion research, is thought to be caused by drift-wave turbulence and the meso-scale structures excited by their coupling.[1] This study, in particular, focuses on "streamer" structures, which enhance transport in the radial direction of the tokamak cross-section. By experimentally analyzing the transition phenomena between streamers and solitary waves, we aim to elucidate the generation and relaxation processes of these streamers.

The experiment was conducted in the PANTA (Plasma Assembly for Nonlinear Turbulence Analysis) linear device.[2] An argon plasma was produced and sustained under conditions of a 900 G magnetic field, 3 kW of RF power, and a gas pressure of 0.5 mTorr. Spatio-temporal data of the ion saturation current (I_{is}) and the floating potential (V_f) were measured using two electrostatic probe arrays: one consisting of 64 channels in the azimuthal direction and the other consisting of 10 channels in the radial direction. The acquired data were analyzed using methods such as two-dimensional 2D spectral analysis based on frequency and azimuthal mode number, as well as phase correlation analysis.[3]

First, the spatio-temporal structure of the ion saturation current (I_{is}) was visualized using the 64-channel probe array, with the data plotted against time (horizontal axis) and azimuthal position (vertical axis).(fig1) This plot reveals a clear transition from a streamer-like structure to a coherently propagating structure that resembles a solitary wave. Next, we compared the two-dimensional (2D) spectra of the stable streamer and the streamer undergoing this transition. The comparison highlighted two key features in the transitioning streamer: (1) the emergence of a high-frequency streamer component, and (2) an enhanced peak at the frequency corresponding to the fundamental harmonic of the solitary wave. To determine the timing of the high-frequency component's emergence, we then analyzed the time evolution of the 2D spectrum. The results indicate that this high-frequency component is generated only during the intensification phase of the streamer, immediately before the transition occurs

Furthermore, analysis of the time evolution of the 2D spectrum for the m=1 structure revealed a difference in the mediator component that triggers the streamer generation. (fig2) The mediator's frequency was -1.6 kHz before the transition and within the solitary wave region, whereas it shifted to -1.4 kHz immediately before the transition. Phase-plane analysis of these structures uncovered dynamic changes, such as the disappearance of a phase node. Moreover, bicoherence analysis was performed to investigate the nonlinear coupling between these three waves (the two mediator components and the streamer). The results confirmed that the -1.6 kHz mediator is nonlinearly coupled with the low-frequency streamer component, while the -1.4 kHz mediator is coupled with the high-frequency streamer component.

In this study, we found that the mediator structure changes during the transition, and notably, a -1.4 kHz mediator appearing just prior to the transition is nonlinearly coupled with a high-frequency streamer component. This suggests a mechanism whereby the excitation of this -1.4 kHz mediator generates the high-frequency component, which subsequently interacts with other structures to induce the streamer's collapse.

References

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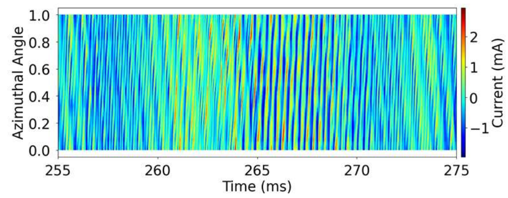

Figure 1: Spatio-temporal structure with the poloidal direction on the vertical axis and time on the horizontal axis

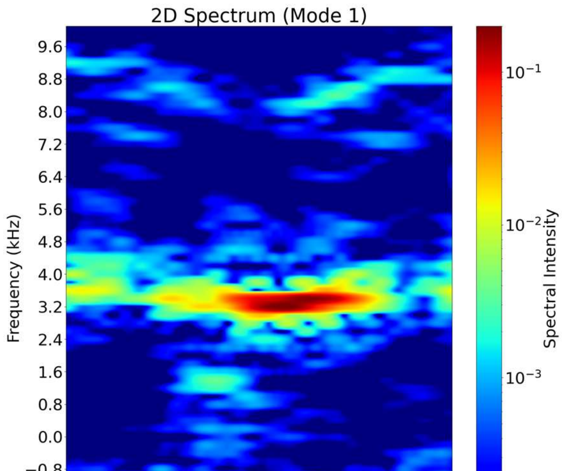

Figure 2: the time evolution of the 2D spectrum for the m=1 structure