Transition in Plasma Fluctuation between Attached and Detached Plasmas

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The static and dynamic behaviors of detached plasmas have received considerable attention because the use of a detached divertor is thought to provide a promising method for reducing the heat flux to plasma-facing components. In this study, fluctuations were measured with an electrostatic probe as the plasma was changed from attached to detached states by increasing the neutral gas pressure. The transition from an attached plasma to a detached plasma was found to change the phase relation between the density and the potential.

Keywords: Detached plasma, fluctuation, turbulence, non-diffusive transport, statistical analysis

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A detached divertor will be used in next-generation fusion devices such as ITER to reduce the great heat and particle fluxes. The detached divertor uses a plasma detachment phenomenon, which is achieved by increasing the neutral gas pressure in the divertor region, to reduce the plasma heat flux by the plasma-gas interaction [1]. The static and dynamic behaviors of detached plasmas have been comprehensively investigated in the linear divertor plasma simulator NAGDIS-II [2–4]. These studies noted that bursty fluctuations in plasma density increase with increasing neutral gas pressure. Therefore, an instability is thought to occur in the detached plasma, and the blobby plasma generated because of this large instability drives strong convective radial transport. However, the mechanism to onset the instability is not yet understood. In this study, we performed an electrostatic probe measurement while changing the state of the plasma from an attached to a detached state by increasing the neutral gas pressure. Then, we investigated the time evolutions of the characteristics of the fluctuations in detail in NAGDIS-II.

NAGDIS-II has two 2000 L/s turbomolecular pumps, which are located beside the discharge region and divertor test region, respectively [3]. To change the neutral gas pressure in this experiment, we operated a gate valve installed between the divertor test region and the pump, as shown in Fig. 1. When we closed the gate valve, the neutral gas pressure increased from approximately 1 to 25 mTorr, and a detached plasma formed. The electrostatic fluctuations and neutral gas pressure were measured at the same time at a distance of 1.06 m from the anode. The working gas species was He.

Figure 2 shows the results of a triple probe measurement at a radius of 15 mm when the neutral gas pressure

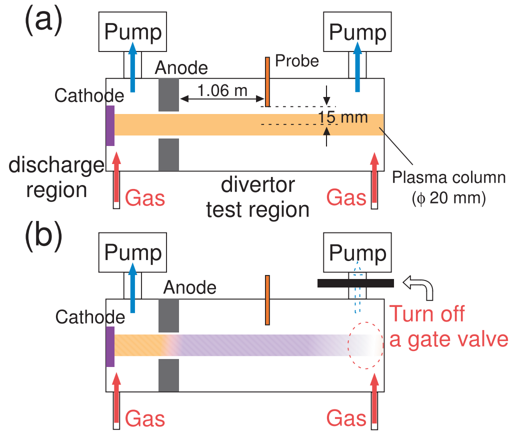

Fig. 1 Schematic illustration of the linear plasma divertor simulator NAGDIS-II. (a) Attached and (b) detached plasma conditions.

P was changed (Fig. 2 (a)). From the probe measurement, the time evolutions of the average electron temperature T_e, electron density n_e, floating potential V_f and space potential V_s were obtained, as shown in Figs. 2 (b) and 2 (c). With increasing P at $t = 0.8$ s, T_e and V_s decreased, and n_e and V_f increased. Subsequently, n_e decreased because of volumetric plasma recombination, and V_f also decreased. On the other hand, the measured T_e increased. This was caused by an anomaly of the probe measurement in the detached plasma condition [5]; thus, the measured T_e was incorrect after plasma detachment occurred.

To investigate the dependence of the phase relation between n_e and V_f on the neutral gas pressure, we analyzed the time evolution of the moving cross-correlation coefficient $R(\tau)$, which is defined by

$$R(\tau) = \frac{\langle \tilde{n}_e(t)\tilde{V}_f(t+\tau)\rangle}{\sqrt{\langle \tilde{n}_e^2(t)\rangle}\sqrt{\langle \tilde{V}_f^2(t)\rangle}}, \quad (1)$$

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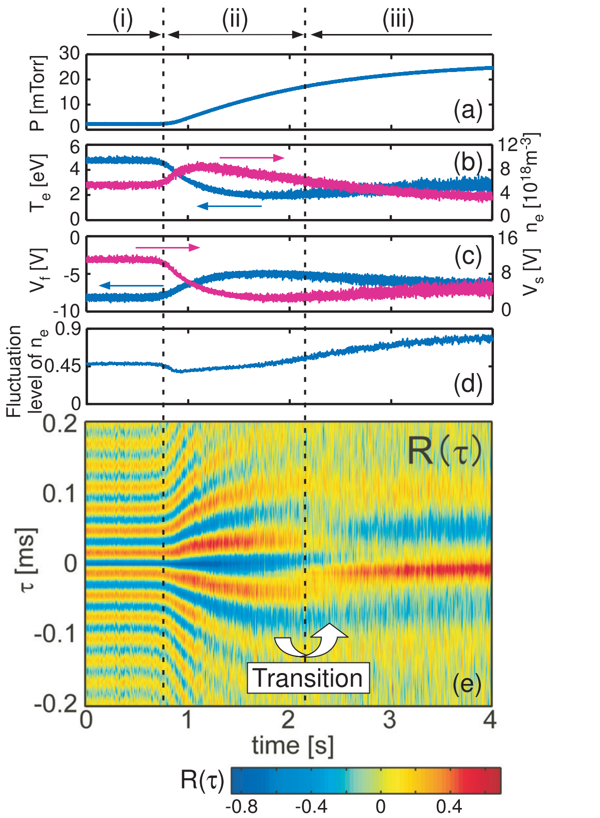

Fig. 2 Experimental results of triple probe measurement at r = 15 mm. Time evolutions of moving average deviations in (a) P, (b) T_e, n_e, (c) V_f, V_s and (d) fluctuation level of n_e, and (e) time evolution of the moving cross-correlation coefficient $R(\tau)$ between n_e and V_f.

where $\langle x\rangle \equiv \bar{x}$ denotes the average of x, and the fluctuation about the mean is given by $\tilde{x} = x - \bar{x}$. From the resulting $R(\tau)$ in Fig. 2 (e), the correlation between n_e and V_f can be categorized into three characteristic time domains: (i) $t < 0.8$ s, (ii) $0.8\text{ s} < t < 2.3$ s, and (iii) $t > 2.3$ s. In period (i), an attached plasma was generated. In this period, a negative correlation was observed around $\tau = 0$ s. In period (ii), although the phase relation between them does not change, the period of the fluctuation of $R(\tau)$ along τ becomes long. In period (iii), a transition in the phase relation appears. The fluctuation level of n_e, $\langle\tilde{n}_e^2\rangle^{1/2}/\langle n_e\rangle$, increased with the advent of the transition in the phase relation, as shown in Figs. 2 (d) and 2 (e).

To obtain the phase difference between the fluctuations in n_e and V_f, the cross-spectral method was used. Figure 3 (a) shows the cross spectrum $CS(f)$ of n_e and V_f under the attached [period (i)] and detached [period (iii)] conditions. Spectral peaks in $CS(f)$ appeared at approximately 32 kHz and 8.5 kHz in the attached and detached states, respectively. With increasing P, the spectral peak of $CS(f)$ shifted to the low-frequency range, as observed in period (ii). The phase differences between the fluctuations in n_e and V_f are shown in Figs. 3 (b) and 3 (c) as a function of the frequency. The phase difference was found to be approximately $-170°$ in the attached state. After the transition, it became approximately $-18°$ in the detached state.

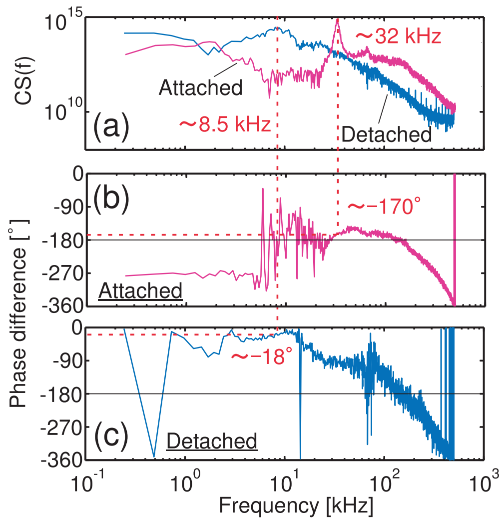

Fig. 3 (a) Cross spectrum $CS(f)$ of n_e and V_f under the attached and detached conditions. Frequency dependence of the phase differences between n_e and V_f fluctuations under the (b) attached and (c) detached conditions.

In NAGDIS-II, coherent structures with high density rotated around the plasma column because of an $\boldsymbol{E}_\mathbf{r} \times \boldsymbol{B}$ drift with the radial electric field $\boldsymbol{E}_\mathbf{r}$ and the magnetic field $\boldsymbol{B}$ [4]. Thus, the spectral peaks of $CS(f)$ were determined mainly by the frequency of the plasma rotation. After the ramp-up of P, the peak frequency decreased, indicating that the plasma rotation slowed in period (ii) in Fig. 2 (e). This result is consistent with a previous report showing that $\boldsymbol{E}_\mathbf{r}$ became small in the detached state [6]. We can conclude that the plasma instability changed when the plasma rotation slowed to a certain speed associated with the transition in the phase relation between n_e and V_f. It is an important future work to specify the plasma instabilities.

In this experiment, we analyzed the fluctuations in V_f, which are determined by those in both T_e and V_s. To understand the instability in more detail, we must consider a method that could obtain the fluctuations in V_s directly.

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