Transition in Plasma Fluctuation between Attached and Detached Plasmas

Katsuya OKAZAKI, Hirohiko TANAKA1), Noriyasu OHNO and Shin KAJITA
Nagoya University, Nagoya 464-8601, Japan
1) National Institute for Fusion Science, Toki 509-5292, Japan
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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.

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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 $P$ 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 $V_f$ decreased, and $n_e$ and $V_s$ 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

$$R(\tau) = \frac{\langle n_e(t) V_f(t + \tau) \rangle}{\sqrt{\langle n_e^2(t) \rangle} \sqrt{\langle V_f^2(t) \rangle}},$$

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

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 $V_t$ can be categorized into three characteristic time domains: (i) $t < 0.8 \text{ s}$, (ii) $0.8 \text{ s} < t < 2.3 \text{ s}$, and (iii) $t > 2.3 \text{ s}$. In period (i), an attached plasma was generated. In this period, a negative correlation was observed around $\tau = 0 \text{ s}$. In period (ii), although the phase relation between them does not change, the period of the fluctuation of $R(\tau)$ along $\tau$ 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 $V_t$, the cross-spectral method was used. Figure 3(a) shows the cross spectrum $CS(f)$ of $n_e$ and $V_t$ under the attached [period (i)] and detached [period (ii)] 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 difference between the fluctuations in $n_e$ and $V_t$ are shown in Figs. 3(b) and 3(c) as a function of the frequency. The phase difference was found to be approximately $-170^\circ$ in the attached state. After the transition, it became approximately $-18^\circ$ in the detached state.

In NAGDIS-II, coherent structures with high density rotated around the plasma column because of an $E_r \times B$ drift with the radial electric field $E_r$ and the magnetic field $B$ [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 $E_r$ 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 $V_t$. It is an important future work to specify the plasma instabilities.

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

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