Spatiotemporal dynamics of cross-field ejection events in recombining detached plasma

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Abstract

Three-dimensional spatiotemporal dynamics of detached helium plasma parameters along time, radius, and magnetic field were revealed in the linear device NAGDIS-II. To measure plasma parameters before and after the radial plasma ejection that was enhanced around the volume-recombining region, the conditional averaging technique was applied. The radial ejection was found to correlate with low-frequency changes of plasma-column parameters, which seemed to suppress the axial movement of the recombining region. Moreover, an azimuthal charge separation inside the ejected structure was observed, similar to the typical edge transport phenomenon: blobby plasma transport. The neutral flow effect was suggested as a candidate of the driving force.

Keywords: cross-field transport, detached plasma, conditional averaging, double probe, spatiotemporal dynamics, recombination front

Some figures may appear in colour only in the online journal

1. Introduction

Plasma detachment is regarded to be inevitable for future fusion devices to reduce the heat flux to the divertor target by volume-recombination processes \cite{1}. In detached plasmas, plasma parameters have significant gradients along the magnetic field, and highly-occurred plasma-gas interactions could influence cross-field plasma transport dynamics. It has been observed that the plasma detachment increases non-diffusive cross-field transport around the detached divertor in various devices including tokamak \cite{2,3}, heliotron \cite{4}, and linear devices \cite{5–7}. Such the enhanced cross-field transport should affect the detached plasma formation by changing the transport paths of particle and heat fluxes toward the wall. Therefore, it is important to understand the transport mechanism and its effect for the accurate prediction of target heat flux in future fusion devices.

In the linear plasma device NAGDIS-II, axially localized fluctuation and radially broadened profile of ion flux were observed in the detached plasma \cite{8}. The azimuthal mode number of $m = 0$ in the plasma column is thought to be related to the radial plasma ejection which has $m = 1$ in the periphery \cite{7,9}. An observation with a fast framing camera revealed that the ejected plasma forms spiral structure across the magnetic field and rotates in the $E_r \times B$ drift direction \cite{10}, where $E_r$ and $B$ are radial electric field and magnetic field, respectively.

Although a series of studies have revealed the dynamics of the plasma structure, the mechanism to enhance the radial transport is still unknown. For the elucidation of the transport phenomenon, it is quite important to clarify spatiotemporal evolutions of the plasma parameters of electron density, $n_e$, electron temperature, $T_e$, and plasma (space) potential, $V_s$, during the ejection event. Although a single Langmuir probe measurement is known as a convenient technique to measure...
plasma parameters, it is not adequate to apply to detached plasmas because of an anomalous current-voltage characteristic [11, 12]. Recently, the validity of double probe measurements in low-temperature detached plasmas has been confirmed by comparing with laser Thomson scattering (LTS) [13]. To detect the plasma ejection, however, these measurements are difficult to deduce high-temporal-resolution time series from conventional approaches.

In this study, we applied conditional averaging (CA) method to two-dimensional (2D) movable multi-pin Langmuir probe consisting of double probe and an additional single probe in a steady-state detached helium plasma in NAGDIS-II. The CA is a powerful statistical tool and has been applied to electrostatic probes [14] and LTS measurements as well [15, 16] in several devices. Reference signal for CA was acquired in the periphery to detect ejected plasma structures. By changing the 2D movable probe position, 3D spatiotemporal dynamics of detached plasma parameters along time, radius, and magnetic field in response to the plasma ejection were firstly revealed.

2. Experimental setup

2.1 Measurement system

Figures 1(a) and (b) show a schematic of the experimental setup. The thin linear plasma with a diameter of \( \sim 20 \) mm, which is determined by the diameter of the hollow intermediate electrode located between a disc cathode and a hollow anode, can be generated in a steady state. By increasing the neutral gas pressure around the target plate, plasma disappears in front of the target plate due to the detachment [8]. On the side of the vacuum vessel, a reciprocating probe, which can scan the radial position \( r_{\text{ref}} \), was equipped. This probe was used to obtain the reference signal for the CA analysis. The ion saturation current \( I_{\text{ref}} \) was acquired with a sampling frequency of 1 MHz. In addition, another electrostatic probe was inserted from the target side (see figure 1(b)). The probe had multiple electrodes on a ceramic shaft with the diameter of 2.8 mm and can be moved axially and radially to obtain 2D plasma parameters. The 2D movable probe head had three electrodes, whose length and diameter were 1 and 0.5 mm, respectively. Two of them were used for a double probe measurement to measure \( n_e \) and \( T_e \). The sweeping frequency of the voltage was 50 Hz, and a resistee of 100 \( \Omega \) was used for the voltage-to-current conversion. Another electrode was used to measure the floating potential, \( V_f \). By using \( V_f \) and \( T_e \), \( V_s \) was deduced from

\[
V_s = V_f + \left( -\frac{1}{2} \ln \left[ \frac{2\pi m_e}{m_i} \left( 1 + \frac{T_i}{T_e} \right) \right] + 0.5 \right) T_e \sim V_f + 3.7 T_e,
\]

where \( T_e \) and the ion temperature, \( T_i \), are assumed to be the same in the detached plasma, and \( m_e \) and \( m_i \) are electron and helium ion masses, respectively [8].
In this study, the axial position of the 2D movable probe was moved at three locations: upstream, midstream, and downstream, which were distanced every 165 mm, as shown in figure 1(b). The midstream position was approximately 165 mm from the target plate. The rotating angle of the 2D movable probe head was changed from $-4^\circ$ to $+18^\circ$ by every $2^\circ$, corresponding to the radius ($r$) from $-5.4$ to $+24.1$ mm, where the positive direction is the one to the reference probe (see figure 1(a)). When the probe is rotated $18^\circ$, the height of the probe head becomes $3.8$ mm lower than the plasma midplane. Therefore, the measurement position is shifted up to $\sim 9^\circ$ in the azimuth direction from the midplane. This shift affects the detection time of a rotation motion at different radii by up to $1/40$ ($=2.5\%$) of the rotation period, which is small enough compared to the time scale discussed below in this paper.

2.2. Discharge condition

The previous study which used the 2D movable probe suggested that the non-diffusive cross-field transport was enhanced near the recombination front \[8\], where the electron-ion volume recombination strongly occurs. The line emission from a highly excited state (He I: $^2\text{P}_3\rightarrow^2\text{D}_3$, wavelength: 370.5 nm) was used to assess the position of the recombination front. At first, the line-integrated intensity of the line emission was continuously measured from opposite side of the reference probe at the midstream ($z = 1.72$ m) with varying the neutral pressure. This line emission has a local maximum along $z$ \[8\], and its axial position depends on the neutral pressure. Therefore, we searched the neutral pressure condition where the maximum intensity was observed during the pressure changes. At this pressure condition, the recombination front would exist near the spectroscopic measurement position. As a result, the recombination-front location was adjusted around the midstream when the neutral pressures at $z = 1.06$ m and near the target plate were 10.0 and 15.2 mTorr, respectively. Magnetic field strength, discharge current, and discharge voltage were 0.1 T, 60 A, and 119 V, respectively.

Figure 1(c) shows power spectra of $I_{\text{ref}}$ as functions of the frequency $f$ and $r_{\text{ref}}$. There are a low-frequency component at $f < 10$ kHz near the plasma center and high-frequency peak at $f \sim 24.5$ kHz around $r_{\text{ref}} \sim 5-10$ mm. Furthermore, several-kilohertz peak is observed at $r_{\text{ref}} > 15$ mm and is slightly shifted as changing the radius. The peripheral region at $r_{\text{ref}} > 10$ mm has no plasma source along the magnetic field. Therefore, the several-kilohertz fluctuation reaching far away ($r_{\text{ref}} > 30$ mm) is related to the non-diffusive transport across the magnetic field. Figure 1(d) shows power spectra at $r_{\text{ref}} = 0, 10, 20,$ and $30$ mm. The power spectrum at $r_{\text{ref}} = 0$ mm has a convex shape with a flat top at $f = 3-7$ kHz. It is likely attributed to the mixture of two fluctuation components with different frequencies; the higher frequency roughly corresponds to the spectral-peak frequency observed in the periphery. Because these low-frequency components have no clear spectral peak, they would appear non-periodically or quasi-periodically. On the other hand, the $f \sim 24.5$ kHz

![Figure 2. Schematic of the CA procedure to obtain the plasma parameters at $\tau = \tau_0$.](image-url)
component has a sharp profile; this would appear periodically. Spatiotemporal dynamics of three frequency components of \( f_1 = 3.5 \text{ kHz}, f_2 = 6.5 \text{ kHz}, \) and \( f_3 = 24.5 \text{ kHz} \) will be discussed later using the CA technique.

2.3. Application of CA technique

To detect the plasma ejection timing in the periphery, the reference probe was determined to be fixed at \( r_{\text{ref}} = 23 \text{ mm} \), where \( f_2 \) fluctuation is the strongest (see figure 1(c)). Thus, the non-diffusive transport could be easily detected at the same radial position. Because there is also a small but finite amplitude of \( f_3 \) component in \( I_{\text{ref}} \) at \( r_{\text{ref}} = 23 \text{ mm} \), a numerical low-pass filter with the frequency range of \([0,\ 20]\ \text{kHz}\) was applied (\( I_{\text{ref}}^f \)) as the reference signal for the CA analysis. Each ejection timing was detected when \( I_{\text{ref}}^f \) has a peak exceeding a threshold value. The threshold was determined to take a value in which a total number of data points that exceeds the threshold becomes 2.5% of the total number of all data points, being \( \mu + 1.85\sigma \), where \( \mu \) and \( \sigma \) are the mean and the standard deviation, respectively.

Figure 2 shows the schematic diagram of the CA analysis procedure. In contrast to the reference probe, the 2D movable probe position was changed to a number of axial and radial locations, as described above. In each position, 50 sets of 1-s time series of double-probe current \( I_p \), double-probe voltage \( V_p \), and \( V_f \) were simultaneously acquired in addition to \( I_{\text{ref}} \). Increase periods of \( V_p \), an average of \( \sim 40000 \) peak points of \( I_{\text{ref}}^f \) exceeding the threshold value were detected. To obtain the plasma parameters at a time delayed by \( \tau = \tau_0 \) from the peak timing (\( \tau = \tau_1, \tau_2, \ldots \)), \( I_p, V_p, \) and \( V_f \) were extracted \( \tau_0 \) after the peak timing. Then, by analyzing the \( I_p-V_p \) characteristic, \( n_e \) and \( T_e \) at \( \tau = \tau_0 \) can be measured. After that, with the averaged \( V_f \) and the obtained \( T_e, V_s \) at \( \tau = \tau_0 \) can be calculated from equation (1).

In this study, \( \tau_0 \) was set to a value between \( -500 \) and \( 500 \) \( \mu s \) every 1 \( \mu s \). As a result, the time series of \( n_e, T_e, \) and \( V_s \) along \( \tau \) was obtained at each position. After that, we applied a simple moving average to the CA results with a sliding window of 10 points (10 \( \mu s \)) to reduce noise components over 100 kHz.

3. Analysis results

3.1. Mean profiles of plasma parameters

At first, mean profiles of \( n_e, T_e, \) and \( V_s \) at upstream, midstream, and downstream were plotted along \( r \) in figure 3. Because the ejection event was observed at \( \sim 200 \) \( \mu s \leq \tau \leq \sim 100 \) \( \mu s \) in the CA results, as mentioned below, mean values were calculated in \( |\tau| > 300 \) \( \mu s \). The error bars indicate standard deviations calculated in the same period. Some of the peak positions are slightly off center, which might be due to disturbance from the probe shaft inside the plasma column, finite misalignment of insertion trajectory, and so on. We can confirm the monotonical decreases of \( n_e \) and \( T_e \) toward the downstream from the upstream. Near the radial center, both parameters decrease to 1/3–1/4 between the 330 mm distance between the upstream and the downstream. On the other hand, \( V_s \) profile becomes shallower as approaching the target plate.

After the next subsection, spatiotemporal dynamics of plasma parameters will be shown.

3.2. Spatiotemporal parameter dynamics near the recombination front

Figures 4(a)–(c) show spatiotemporal dynamics of \( n_e, T_e, \) and \( V_s \), respectively, on \( r-\tau \) plane at the midstream, where the recombination front exists. Radially elongated structure of \( n_e \) is found around \( \tau = 0 \), and then, plasma column seems to be shrunk; this can be attributed to the radial ejection of the plasma density. Near the reference probe position (\( r = 23 \) \text{ mm} at the midstream), \( n_e \) has a peak at \( \tau \sim 0 \). At all-time points, \( T_e \) is much less than 1 eV, suggesting that the three-body recombination process dominantly occur. Before and after the plasma ejection, decrease and increase of \( T_e \) can be seen, respectively, in the plasma column. On the other hand, \( V_s \), which has a hollow radial profile, becomes flatter and then deeper.

To extract the fluctuation components \( \tilde{n}_e, \tilde{T}_e, \) and \( \tilde{V}_s \), mean values at \( |\tau| > 300 \) \( \mu s \) in figure 3 were subtracted from
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Figure 4. Spatiotemporal evolutions of (a) $n_e$, (b) $T_e$, (c) $V_s$, (d) $\tilde{n}_e$, (e) $\tilde{T}_e$, and (f) $\tilde{V}_s$ at midstream.

Figure 5. Spatiotemporal evolutions of $n_e$ with the band-passed frequencies of (a) [3, 4] kHz and (b) [6, 7] kHz.

figures 4(a)–(c), as shown in (d)–(f), respectively. Plasma-parameter fluctuations are clearly observed at $\sim -200 \mu s < \tau < -100 \mu s$. To measure the plasma potential, we assumed $T_e = T_i$. It is noted that the influence of the ambiguity in this assumption on $\tilde{V}_s$ is minor, because $\tilde{T}_e$ is much smaller than $\tilde{V}_s$. From $\tau \sim -200 \mu s$, $\tilde{n}_e$ slightly increases in a wide $r$ range and consequently decreases at $\tau \sim -20 \mu s$ near the radial center. Furthermore, inclined structures with a time period of $\sim 40 \mu s$ periodically appear particularly in $n_e$. This fluctuation corresponds to $f_3 = 24.5$ kHz $\sim (40 \mu s)^{-1}$ component.

The wavelet filter was applied to $\tilde{n}_e$ in figure 4(d) in order to clarify the relationship with $f_1 = 3.5$ kHz and $f_2 = 6.5$ kHz components. The wavelet transform does not require steady-state condition unlike the Fourier transform and can expand the power density in frequency and also time domains. As the mother wavelet, the complex Morlet wavelet ($\psi(t) = \pi^{-1/4} \exp \left[ i 2\pi f_0 t - \left( \frac{f_s^2}{2} \right) t^2 / 2 \right]$, where $f_0$ and $f_s$ are the central frequency of the mother wavelet and the sampling frequency, respectively) was employed. Although a value equal to $f_s$ is often assigned to $f_0$ [17, 18], this study used $f_0 = 0.25 f_s$. By choosing a smaller $f_0$, the time resolution increases, though the frequency resolution decreases.

Figure 5 shows the band-passed fluctuations of $\tilde{n}_e$, $\tilde{V}_s$, at [3, 4] and [6, 7] kHz. The energy spectrum of the Morlet
wavelet has a Gaussian shape, and its typical width (standard deviation) is ~1.42 kHz for $f_1 = 3.5$ kHz and 2.65 kHz for $f_2 = 6.5$ kHz in the present calculating condition. Therefore, it should be noted that the obtained $\tilde{n}_e$ is affected from wider frequency-range component than the band-passed frequency range. From figure 5(a), it is found that $f_1$ component has no time shift at $r < \sim 15$ mm. Its temporal evolution is surely synchronized with $\tilde{T}_e$ and $\tilde{V}_s$ fluctuations in figures 4(e) and (f). An inclined structure at $r > \sim 15$ mm around $\tau \sim 0$, which has a small amplitude and a shorter-duration, would be attributed from the $f_2$ component. Thus, the azimuthal mode number of the $f_1$ component is $m = 0$. In contrast, $f_2$ component in figure 5(b) clearly shows inclined feature. Obtained structures are not in-phase at $r \sim -5$ and $+5$ mm, and low-$m$ mode rotations with $m = 1$ and 2 are dominant in NAGDIS-II [10]. Therefore, these structures are likely due to $m = 1$ mode rotation. Near the radial center, $f_2$ component becomes strong after $\tau \sim 120$ $\mu$s. On the other hand, at $r > 15$ mm, one-period $f_2$ component is found before the plasma ejection at $\tau \sim 0$. This is likely due to the detection of the second rotation of ejected plasmas in the CA analysis procedure.

3.3. Axial-position dependence of parameter dynamics

Although the CA analysis emphasizes events near the reference probe position, other events generated at axially different regions could also be detected due to the fluctuation propagation along the magnetic field. To know the fluctuation-amplitude relationship with the axial position, upstream and downstream CA features were investigated, as shown in figure 6. The $f_3$ component is found to be strong in the upstream. In addition, from figure 1(c), this fluctuation is not strong in far periphery but the edge of the plasma column around $r \sim 5$–10 mm. Therefore, $f_3$ fluctuation is attributable to some instabilities such as flute and drift instabilities in the upstream of the recombining region. In contrast, $f_2$ component is outstanding in the downstream by comparing upstream and downstream $\tilde{n}_e$ in figures 6(a) and (d). In contrast to the $\tilde{T}_e$ amplitude at the downstream being smaller than the upstream one (see figures 6(b) and (e)), the amplitude of $\tilde{V}_s$ at the downstream is larger than that at the upstream (see figures 6(c) and (f)). This is because the $\tilde{V}_s$ amplitude at the downstream is sufficiently large compared with $\tilde{T}_e$ from equation (1).

3.4. Rotation and radial motion

By using the obtained $V_s$, radial profile at each $\tau$, radial electric field $E_r$ can be estimated. Moreover, the $E_r \times B$ drift speed and the $E_r \times B$ rotation frequency can be calculated as $v_{E_r \times B} = E_r / B$ and $f_{E_r \times B} = v_{E_r \times B} / 2\pi r = E_r / 2\pi r B$, respectively. In NAGDIS-II, the $E_r \times B$ drift direction is the same with the electron diamagnetism drift direction and points to
the counterclockwise direction viewed from the downstream. In addition, the rotation frequency of the drift instability can be also estimated, although the type of instability was not yet identified in this study. The azimuthal speed corresponds to the sum of the $E_x B$ drift and the ion diamagnetic drift speeds, as $V_{s, E_x B + dia} = E_r / B + (d n_i / dr) / n_i B$, where $n_i$ is the ion pressure. By assuming $T_i = T_e$, the rotation frequency of the drift instability was calculated as $f_3 = V_{E_x B + dia} / 2 \pi r$.

Figure 7 shows $f_{E_x B}$ and $f_{E_x B + dia}$ calculated at $r \sim 9.4$ mm, where $E_r$ has a maximum at $r \tau > 300$ $\mu$s, at all axial positions. A large-amplitude fluctuation particularly at upstream was caused by the $f_3$ component. At $r \tau > 300$ $\mu$s period, $f_{E_x B}$ decreases from upstream to downstream due to the decrease of $E_r$. On the other hand, due to the steep gradients of plasma parameters in the radial direction at the upstream (see figure 3), $f_{E_x B + dia}$ is much smaller than $f_{E_x B}$ at the upstream compared with midstream and downstream. As a result, the upstream $f_{E_x B + dia}$ is almost the same as $f_3$, which is the frequency of strong fluctuation in the upstream. Although this frequency matching implies that the $f_3$ fluctuation was caused by the drift instability with $m = 1$, it should be noted that the plotted $f_{E_x B}$ and $f_{E_x B + dia}$ are merely typical values, because they strongly depend on the radius $r$. Therefore, only qualitative discussions are done below from figure 7.

After the $m = 0$ mode begins to fluctuate at $r \tau \sim -200$ $\mu$s, $f_{E_x B}$ and $f_{E_x B + dia}$ slightly decrease at midstream and downstream. During the plasma ejection at $r \tau \sim 0$, by increasing of $E_r$ at midstream and downstream, $f_{E_x B}$ have a similar value in all axial positions, while $f_{E_x B + dia}$ at midstream and downstream exceed that at the upstream. Then, $f_{E_x B}$ and $f_{E_x B + dia}$ become original values at $r \tau \sim 100$ $\mu$s. Regardless of whether the rotation frequency ($f_{rot}$) was $f_{E_x B}$ or $f_{E_x B + dia}$, the middle and downstream rotation frequencies increase during the plasma ejection.

Focusing on the peripheral region, potential fluctuation synchronized with the plasma ejection was confirmed as follows. Figures 8(a)–(c) show peripheral region of figures 4(f), 6(c) and (f) with a narrower color scale, respectively.
addition to the $m = 0$ structure around the radial center, a decrease and an increase of $V_s$ are found around $\tau \sim 0$ at $r > \sim 15$ mm. Figure 8(d) shows $V_s$ in addition to $\dot{n}_e$ at the midstream at $r = 24.1$ mm. The profile of $\dot{n}_e$, which corresponds to $f_2$ component, has a peak at $\tau \sim 0$, and a gradient of $V_s$ is positive at the same $\tau$. Considering that $m = 1$ structure rotates in the azimuthal direction with $f_{rot} = f_2$, the azimuthal electric field, $E_\theta = (\dot{E}_\theta + 0)$, can be estimated from the $V_s$ gradient: $E_\theta = (dV_s/dt)/2\pi f_{rot}$. Furthermore, the radial speed and fluctuation-driven radial particle flux were deduced from $v_r = E_\theta/B$ and $\Gamma_r = \dot{n}_e V_r$, respectively, as shown in figure 8(e). The outward radial transport parameters were obtained to be $v_r \sim 80$ m s$^{-1}$ and $\Gamma_r \sim 1.7 \times 10^{20}$ s$^{-1}$ m$^{-2}$ at $\tau \sim 0$.

4. Discussion

From the CA analysis, the plasma ejection process can be considered as follows. Before the consideration, from previous studies with a fast framing camera [10] and segmented electrodes [7], ejected plasmas are thought to form spiral shape across the magnetic field. In addition, synchronized appearances of a $m = 0$ mode and an enhanced $m = 1$ fluctuation were observed in [7], and mode numbers of $f_1$ and $f_2$ components would be $m = 0$ and 1, respectively, as mentioned above.

Figure 9 shows a schematic diagram organizing the obtained results around the midstream, where the recombination front exists. The ejection process is divided into six phases from (i) to (vi). Phase (i) is a steady-state phase without the plasma ejection. After $\tau \sim -200$ $\mu$s in phase (ii), $n_e$ and $V_s$ abruptly increase and $T_e$ decreases with $m = 0$. At $\tau \sim -120$ $\mu$s, $m = 1$ structure becomes strong and rotates with the rotation frequency of $f_{rot} \sim f_2$. Until $\tau \sim -20$ $\mu$s in phase (iii), the plasma parameters in radial center change slightly. During the plasma ejection in phase (iv), $n_e$ decreases in the plasma column; in addition, $V_s$ decreases, $T_e$ increases, and $f_{rot}$ increases. At the same time, an azimuthal electric field causing the radial transport was confirmed in the radially elongated plasma structure. After $\tau \sim 50$ $\mu$s in phase (v), central plasma parameters start to recover. In phase (vi), remaining structure in the periphery rotates a few times, and then, the plasma ejection process returns to phase (i).

In the above process, the $m = 0$ fluctuation should be important to trigger the non-diffusive radial transport. Before the plasma ejection, a decrease in $T_e$ occurs, and the $T_e$ reduction leads to a shifting of the recombination front toward the upstream. In contrast, $T_e$ increases after the plasma ejection, which leads to the movement of the recombination front toward the original axial position. Therefore, the appearance of the radial transport seems to have a role to prevent the upstream movement of the recombination front. The observed
Figure 10. Spatiotemporal evolutions of $S_{rec}$ at (a) upstream, (b) midstream, and (c) downstream.

In summary, 3D spatiotemporal dynamics of detached plasma parameters along time, radius, and magnetic field were revealed in the linear plasma device NAGDIS-II. To measure the temporal evolutions of $n_e$, $T_e$, and $V_s$, the CA technique was applied to a number of electrostatic fluctuations measured with 2D movable probe that has three electrodes and a reference single probe. It was found that the radial ejection of high-density plasma with $m = 1$ was closely correlated with $m = 0$ fluctuation in the radial center; $n_e$ and $V_s$ increased and $T_e$ decreased before the plasma ejection. Furthermore, after the plasma ejection, these parameters fluctuated in opposite signs. Ejected plasma contained a charge separation in the azimuthal direction, which moves the plasma structure radially outward. Considering the profile of the neutral production rate by the recombination processes, the contribution of the neutral-flow effect was suggested as one of the candidates for driving the radial transport. Time evolution of the rotation frequency implies that the centrifugal force gave some effect for the charge separation during the plasma ejection.

Although the mechanism that causes the $m = 0$ fluctuation is unknown, the $m = 0$ parameter dynamics seem to move the recombination front to upstream before the growth of the $m = 1$ mode evolving into the radial transport. Furthermore, the appearance of the radial transport seems to prevent the upstream movement of the recombination region by reducing $n_e$ inside the plasma column due to the density ejection. Therefore, the localized non-diffusive radial transport would have key roles for position control and formation of the recombination front in the detached plasma.

Obtained results also suggest that an application of the spatially non-uniform transport coefficient across the magnetic field should be considered to improve accuracy of the detached plasma simulations. Locally increased transport coefficient
around the recombination front broadens and decreases parallel ion particle flux flowing into the target plate.

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