Current Sheet Dynamics of High Guide-Field Magnetic Reconnection

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We measured detailed current sheet dynamics of two merging high-guide field flux tubes using newly developed high-resolution magnetic field measurement by Printed-Circuit-Board (PCB) coils in TS-6 merging tokamak experiment. We found that the sheet ejection occurred twice, increasing their merging ratio, the toroidal current density J_t, the toroidal electric field E_t, and the effective resistivity η of current sheet. The possible explanation for this result is that the mass ejection from the current sheet drives the reconnection inflow, due to the mass conservation law. Especially, after the second sheet ejection, the effective resistivity increased significantly, probably because the sheet thickness compressed up to the ion Larmor radius.

Keywords: magnetic reconnection, fast reconnection, current sheet, anomalous resistivity, plasma pile-up

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Magnetic reconnection is the fundamental physical phenomenon in a highly conducting plasma. During the process, the anti-parallel magnetic field lines approach together, reconnect at X-point, and change their topology of magnetic configurations. Since the reconnection time scale is much shorter than that estimated from the Sweet-Parker model [1], its acceleration mechanisms: such as anomalous resistivity and plasmoid ejections have been key research subjects. It is known that the local microscopic instabilities inside the current sheet cause a significant increase in its effective resistivity as well as fast reconnection [2]. Another candidate for acceleration is the plasmoid ejection caused by the current sheet dynamics. The plasmoid activities were reported in MRX experiments at Princeton Univ. [3] and in Big Red Ball experiments at Univ. Wisconsin [4]. Those plasmoids were obtained in "pull-type reconnection" which transforms the common flux into private flux. However, we observe the sheet ejection in the "push-type reconnection" which transforms private flux to the common flux. We examined the detailed structure of the current sheet using the newly Printed-Circuit-Board (PCB) type magnetic probe array [5] and investigated how the dynamic sheet structure including the sheet ejection and the anomalous resistivity influenced the reconnection speed.

Tokyo Spherical Torus 6: TS-6 device can axially merge two torus plasmas through magnetic reconnection. Figure 1 shows the schematic view of the vertical cross-section of TS-6. A pair of poloidal field (PF) coils are used to form two torus plasmas and to collide them together. In this experiment, the distance between the two PF coils is as short as 427 mm, almost equal to a torus plasma diameter, providing the largest colliding force in TS-6 [6]. To investigate the detailed two dimensional current sheet structure during reconnection, we installed the newly developed PCB type magnetic probe array [5] around the mid-area in the R-Z plane (-1.28×10^{-1} m $< z < 1.28 \times 10^{-1}$ m, 0.06 m $< r <$ 0.34 m). The PCB type probes have Bz pickup coils whose spatial resolution is as high as 5 mm in r direction and 10 mm in z direction which are the order of ion Larmor radius (ρ_i). Using these 13 probe arrays, we measured the detailed magnetic field structure around the current sheet including contours of poloidal flux ψ, toroidal current density J_t, toroidal electric field E_t, and effective resistivity η at X-point. We defined the merging ratio as the ratio of the reconnected poloidal flux at

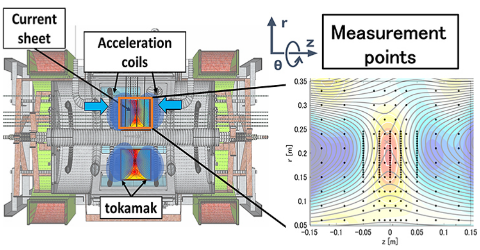

Fig. 1. Vertical cross-section of TS-6 torus plasma merging device. The blue dots in the measurement area show positions of Bz pickup coils.

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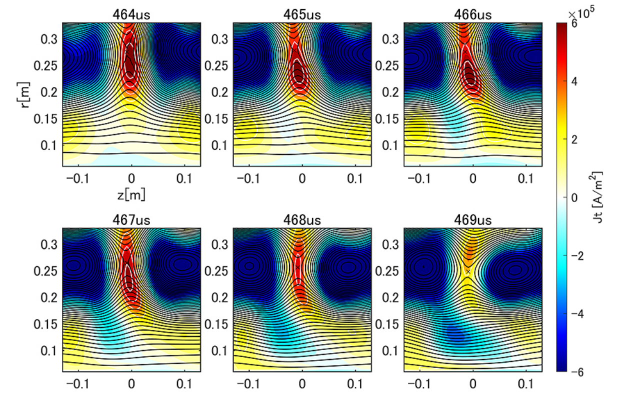

Fig. 2. R-Z contours of the current sheet (color contour: toroidal current density J_t, black lines: magnetic flux lines). The sheet is elongated and ejected.

X-point (common flux) to the peak flux of a torus plasma before merging (private flux + common flux), $\frac{\psi_{common}}{min(\psi_{peak1}, \psi_{peak2})}$ to investigate an influence of the dynamic current sheet structure on the reconnection speed.

Figure 2 shows the R-Z contours of poloidal flux (by black lines) and the toroidal current density J_t (by red and blue colors) of two merging torus plasmas. Their toroidal field B_t is about five times higher than the reconnection magnetic field $\simeq$ poloidal magnetic field B_p. Figure 3 shows the time evolution of (a) the merging ratio ($\frac{\psi_{common}}{min(\psi_{private1}, \psi_{private2})} \times 100$), (b) the toroidal current density J_t and the toroidal electric field E_t at X-point, (c) the effective resistivity at the X-point, and (d) the current sheet thickness and the ion Larmor radius. The current sheet thickness is calculated as the half-width of gauss-fitting of the axial (z) profile of J_t through X-point. These results suggest that the behavior of the current sheet during the reconnection could be divided into three periods (shown as blue, red, and yellow areas in Fig. 3).

In the first phase of reconnection (the blue area in Fig. 3), the current sheet begins to grow right after the reconnection starts (Fig. 2 at 464 μs). As shown in Fig. 3 (b), J_t at X-point increases, suggesting that the plasma piles up in the current sheet due to the external inflow drive. And the enhancement of E_t at X-point is also observed in Fig. 3 (b). In Fig. 3 (c), the effective resistivity η slightly increases as the external force compresses the current sheet thickness to the ion Larmor radius as shown in Fig. 3 (d) [2]. The speed of reconnection, described as the slope of merging ratio in Fig. 3 (a), increases a little at around 464 μs. Since the energy dissipation is likely to be low due to the low resistivity, this first increase in the merging ratio is mainly caused by the current sheet compression to the ion Larmor radius by the external inflow. In the second phase of reconnection (the red area in Fig. 3), the current sheet is ejected in the r direction at around 466 μs in Fig. 2, and the reconnection speed slows down after 466 μs in Fig. 3 (a). The effective resistivity η at X-point decreases along with J_t and E_t in Figs. 3 (b) and (c). This phenomenon suggests that plasma pile-up in the current sheet is resolved through the sheet ejection after the plasma density pile-up reaches its limit. In the third phase of reconnection

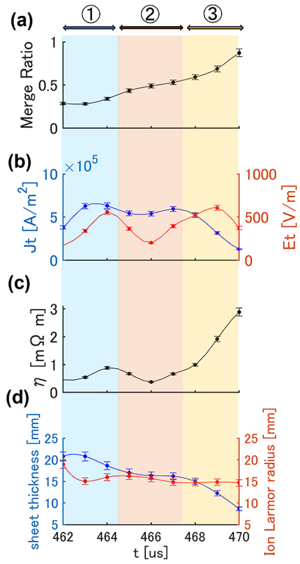

Fig. 3. Time evolutions of (a) merging ratio, (b) toroidal current density J_t and toroidal electric field E_t at X-point (c) effective resistivity at X-point and (d) sheet thickness and ion Larmour radius.

(the yellow area in Fig. 3), the current sheet growth restarts due to the continuous external inflow drive at 467 μs after the first sheet ejection. At around 468 μs, the current sheet is ejected again and then disappears. The effective resistivity η rapidly increases immediately after this ejection (Fig. 3 (c)), which is considered to be the onset of anomalous resistivity higher than the classical Spitzer resistivity [7], 0.5 mΩ m ~ 1 mΩ m where the electron temperature Te = 10 eV ~ 20 eV, the Coulomb logarithm $\ln \Lambda = 38$, and $Z = 1$. Figure 3 (d) shows that the sheet thickness becomes thinner than the ion Larmor radius at 468 μs. The possible cause for this phenomenon is that the mass ejection enhances the inflow into the current sheet, compressing the current sheet to the ion Larmour radius followed by the onset of anomalous resistivity.

In summary, the current sheet ejection occurs twice during the merging of two torus plasmas, and both ejections occur when the plasma pile-up exceeds the limit. Specifically, the anomalous resistivity increases also twice after the first and second ejections, due to sheet compressions to the ion Larmor radius. As a result, the sheet ejection and the anomalous resistivity are found to contribute to the increases in reconnection speed, respectively. These results also indicate that the current sheet pile-ups and ejections are possible causes for intermittent reconnection with plasmoid ejections when the external inflow drives the reconnection continuously.

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