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CURRENT REARRANGEMENT IN MERGING START-UP OF SPHERICAL TOKAMAK PLASMAS

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Abstract

Plasma merging technique that provides high power ion heating by magnetic reconnection is expected to significantly expand the operation scenarios of spherical tokamak (ST) fusion reactors. For practical application of the merging technique, it is necessary to establish a smooth transition to high-beta ST equilibrium while being consistent with plasma merging process. In the paper, the plasma current rearrangement mechanism during/after plasma merging was investigated. It was observed that the axial (Z-) component of the plasma current due to the parallel electric field and that due to the polarization current almost cancel each other out in the reconnection current layer, resulting in the condition that only the toroidal current flows. This experimental results suggests that the charge separation is maintained in the reconnection downstream region and the excess electrostatic field component parallel to the magnetic field lines forms the plasma current distribution that sustain the equilibrium of the merged ST.

1. INTRODUCTION

To achieve net energy gain from fusion reactions in magnetically confined plasma, it is important to develop methods for direct heating or accelerating the plasma ions without electron heating. One of the mechanisms that lead to highly efficient energy conversion into ion kinetic/thermal energy is magnetic reconnection [1,2], in which a portion of the magnetic energy stored in the plasma is released and transferred primarily to the ions. The torus plasma merging method [3] is a technique that actively induces magnetic reconnection, and has been used for the dynamic formation of high-beta spherical tokamak (ST) plasmas [4,5] and high-beta field-reversed configuration (FRC) plasmas [6,7]. Since the poloidal magnetic field of the torus plasmas reconnects in plasma merging, the toroidal magnetic field, which is dominant in ST merging case, acts as a “guide” magnetic field that is perpendicular to the reconnecting magnetic field, i.e., parallel to the reconnection electric field at the reconnection X-point.

Under a very strong guide magnetic field applied in ST merging formatio, charged particles remain magnetized even at the X-point where the poloidal magnetic field vanishes, resulting in a distinctive behavior that differs from reconnection of antiparallel magnetic fields in which the Hall effect significantly affects the electromagnetic field structure in the vicinity of the X point [8]. One of the major changes caused by the presence of a guide magnetic field is that the inductive electric field generated by the magnetic flux change is not perpendicular to the magnetic field. They are completely parallel at the X-point, and in the upstream and downstream regions, the inductive electric field has both a parallel component along the magnetic field lines and a component perpendicular to them. In the case of reconnection in the ST merging formation, the parallel component is dominant because the guide magnetic field mostly generated by the external toroidal field coil current is considerably larger than the reconnection magnetic field [9].

In a steady-state reconnection model, the electric field component along the magnetic field lines must be balanced. Assuming ideal MHD condition in upstream and downstream regions, the electrostatic field should develop to cancel out the component of the induced electric field parallel to the magnetic field lines. However, in torus plasma merging experiments, the initial torus plasmas contain finite amount of magnetic fluxes, so it is necessary to consider the transient process without assuming a balance of electric fields along the magnetic field lines. During the transient phase, the parallel electric field is not always canceled and the direction and magnitude of the residual parallel electric field are determined both by the toroidal inductive electric field due to the poloidal flux change and by the poloidal electrostatic field. Assuming that most of the parallel component of the inductive electric field is canceled by the electrostatic field even during the transient phase, the poloidal electrostatic field is expected to be approximately the guide field ratio (toroidal guide magnetic field/reconnection magnetic field) times larger than the toroidal inductive electric field. This trend has been confirmed in previous studies [10], suggesting that in high guide field reconnection during ST merging formation, the poloidal electrostatic field has a significant impact on the overall system behavior and the reconnection process is largely affected by controlling the electrostatic field in the reconnection downstream region [11].

In the ST merging formation, a smooth transition to final high-beta ST equilibrium with appropriate current density profile is required. In the reconnection current layer, a thin sheet-like current flows in the opposite direction to the plasma currents of the initial STs to prevent them from approaching each other. In the downstream region, poloidal magnetic flux is supplied during the magnetic reconnection and the direction of the induced toroidal electric field is in the opposite direction to the plasma current required to maintain the ST equilibrium; however, experimental results show that a current density distribution that maintains the ST equilibrium is self-organized during/after the merging process. An analysis that considers the influence of the electrostatic field is necessary to understand the current distribution formation process during ST merging formation. In the paper, the plasma current rearrangement mechanism is investigated based on the electromagnetic field measurements.

2. EXPERIMENTAL SETUP

In the UTST device [12], the formation and merging of initial plasmas are achieved using only the poloidal field (PF) coils located outside the vacuum vessel as shown in Fig. 1. Under a strong toroidal magnetic field generated by a toroidal field (TF) coil current, the currents in the PF coils are varied to form two initial ST plasmas simultaneously, one in the upper and one in the lower regions of the UTST device. Then, the two plasmas approach each other and merge via magnetic reconnection at the device equatorial plane of $Z = 0$. The merging process is monitored by a two-dimensional array of pickup coils, Langmuir probes and Rogowski coils. The pickup coils measure both vertical (axial) component B_z and toroidal component B_t. By assuming axisymmetry, the two-dimensional distributions of poloidal magnetic flux Ψ, toroidal current density j_t, and inductive toroidal electric

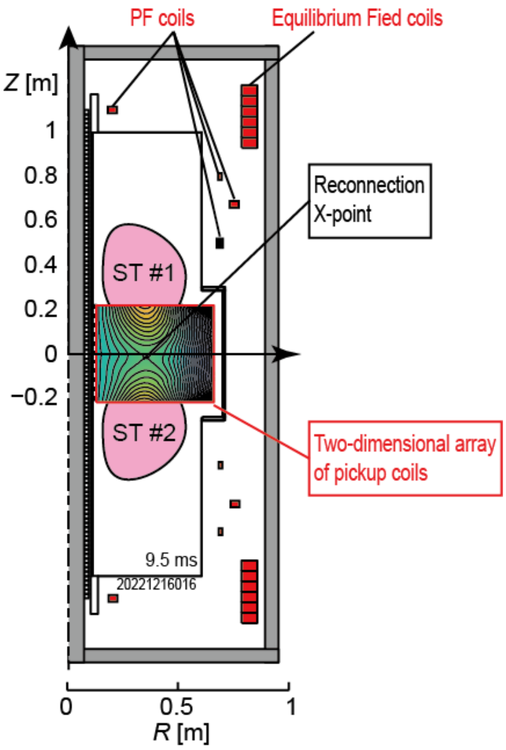

FIG. 1 Schematic cross-sectional view of the UTST device.

field E_t are calculated. In addition to the toroidal electric field E_t obtained from magnetic field measurements, the vertical electric field E_z on the $Z = 0$ plane is calculated from the floating potential difference measured by a Langmuir probes, allowing us to determine the electric field components parallel $(E_{//})$ and perpendicular $(E_{\perp})$ to the magnetic field lines within the magnetic surface.

3. EXPERIMENTAL RESULTS

3.1. Overall behavior of ST plasma merging

Typical waveforms of total plasma current I_{plasma}, the toroidal electric field E_t, and the toroidal current density j_t observed at the reconnection X-point, are shown in Fig. 1(a-c). The plasma merging occurs at t ~ 9.5 ms just before the plasma current peaks. Fig. 1(b) and (c) show magnified views around the time of the plasma merging. A strong toroidal electric field $|E_t| > 50$ V/m was observed for approximately 0.03 ms. The merging process or the magnetic reconnection is completed at t ~ 9.53 ms when the inductive electric field E_t at the X-point changes from negative to positive. Since the ST plasma current flows in the positive toroidal direction, a thin negative current layer is formed between the two initial ST plasmas during merging as shown in Fig. 1(c). It should be noted that the toroidal current density j_t at the X-point reverses direction earlier than the inducutive toroidal electric field E_t.

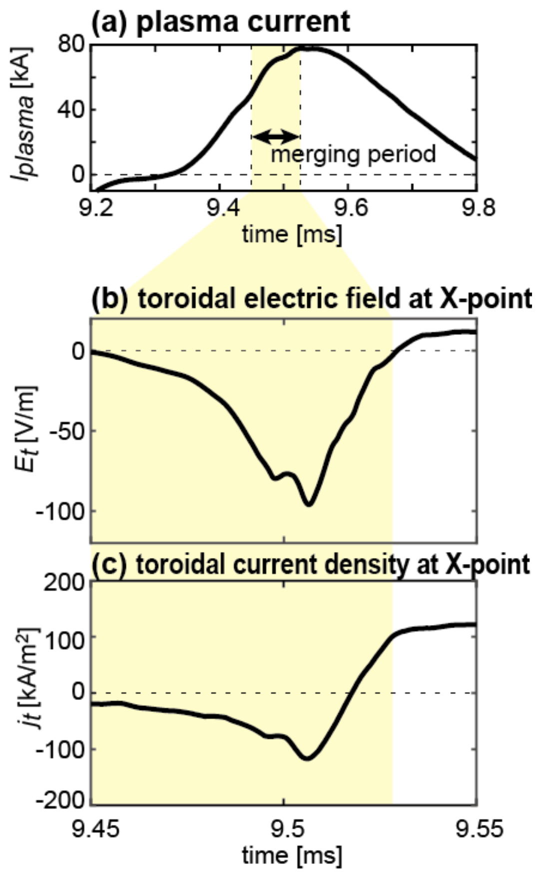

FIG. 2 Typical waveforms of (a) plasma current, (b) toroidal electric field and (c) toroidal current density at the X-point of magnetic reconnection.

The time evolution of the radial profile of the toroidal current density j_t on $Z = 0$ plane is shown in Fig. 3. A negative toroidal current is observed in the early stage of merging (t = 9.49 ms), but a positive current gradually grows in the radially inner region, eventually resulting in a hollow current profile of a merged ST equilibrium (t = 9.52 ms). However, the inductive toroldal electric field E_t remains negative throughout the reconnection process not only at the X-point but in the downstream region. To understand such time evolution of the toroidal current density profile, the electric field structure in the reconnection current layer and the downstream region was investigated.

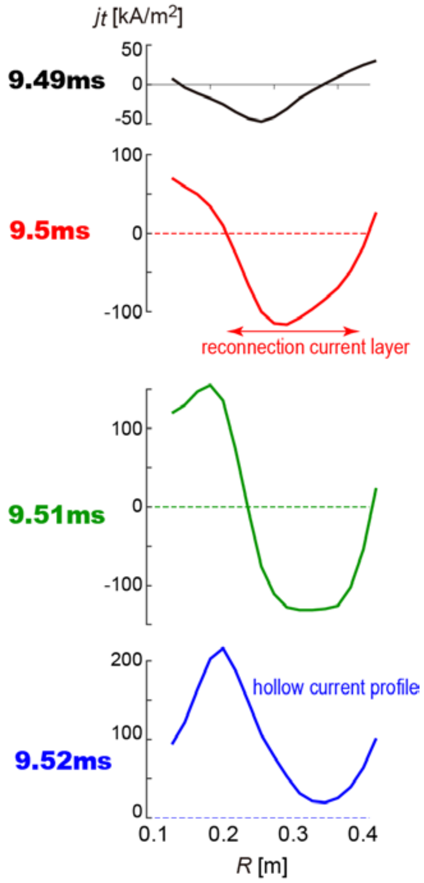

FIG. 3 Time evolution of the radial profile of the toroidal current density on Z = 0 plane.

3.2. Electric field on the magnetic surface

Unlike magnetic reconnection that occurs between antiparallel magnetic fields, reconnection in ST merging includes a guide (toroidal) magnetic field that is perpendicular to the reconnection magnetic fields, which causes the induced toroidal electric field to have a component parallel to the magnetic field. As a result, a quadrupole structure of electrostatic potential is formed spontaneously [13], and the electrostatic field has a significant effect on reconnection process as well as the plasma behavior in the downstream region [14]. In this study, both the inductive and electrostatic fields are measured on the reconnection plane (Z = 0) by using pickup coil array and

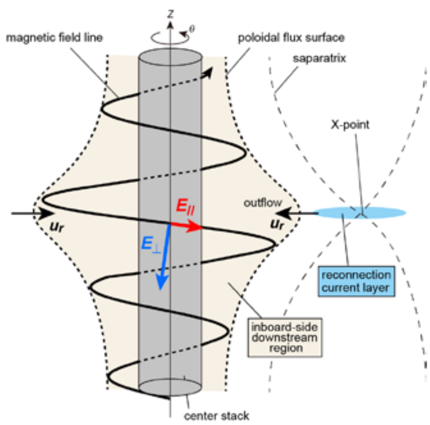

Fig. 4 Schematic view of electric field decomposition in the downstream region.

Langmuir probe array and decomposed into components parallel and perpendicular to the magnetic field as shown in Fig. 3. Since $|B_t| \gg |B_z|$ and $B_r \simeq 0$ on $Z = 0$ plane, the conditions of $|E_{//,t}| \gg |E_{//,z}|$ and $|E_{\perp,z}| \gg |E_{\perp,t}|$ hold.

Figure 5 (a-d) show the evolution of axial (Z-) and toroidal (t-) components of the electric field parallel and perpendicular to the magnetic field. Note that $E_{//}$ exists not only near the X-point indicated by white dashed line (R ~ 0.35 m in (b)) but in the inboard-side downstream region (R ~ 0.2 m in (b)) although its sign is reversed. This fact indicates that the steady MHD condition of $E_{//} \simeq 0$ is broken in the downstream region due to the excessive charge separation [14], which also enhances $E_{\perp}$ in the downstream region (R ~ 0.2 m in (c)(d)). The evolution of radial outflow velocity u_r on the midplane ($Z = 0$) calculated from the $\boldsymbol{E}_{\perp} \times \boldsymbol{B}$ drift is shown in Fig. 5(e). As expected from the reconnection geometry, the radial flow originates from the X-point. However, since a significant electric field component $E_{//}$ parallel to the magnetic field lines exists, the magnitude of the outflow does not match that predicted from the frozen-in flux model.

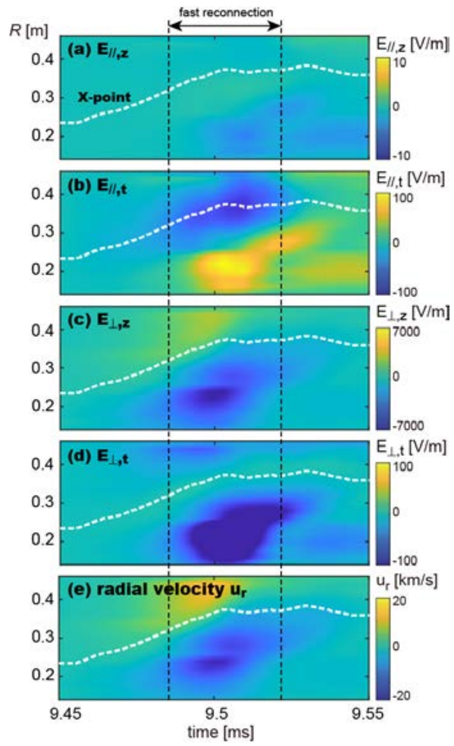

FIG. 5 Spatiotemporal evolutions of (a,b) Z- and toroidal components of the electric field parallel to the magnetic field and (c, d) those of the electric field perpendicular to the magnetic field measured on Z = 0. (e) Radial outflow velocity calculated by $E \times B$ drift.

3.3. Current profile in the downstream region

Based on the observed transient electric fields, electrical currents flowing in the reconnection current layer and in the reconnection downstream region are evaluated based on the parallel current $j_{//} = E_{//}/\eta_{\mathrm{eff}}$ and the polarization current [15] $j_{\perp} = (\rho/B^2)\ \mathrm{d}E_{\perp}/\mathrm{d}t$, where η_{eff} is the effective parallel resistivity and ρ is the mass density. Figure 5 shows the radial profiles of the toroial (t-) and the axial (Z-) component component of the parallel current and the polarization current at t = 9.49 ms and 9.50 ms. Regarding the toroidal component, the contribution of the polarization current is very small and most of the toroidal current is carried by the parallel current as shown in Fig. 6(a) and (c). Negative toroidal current flows at the X-point and in the reconnection current layer (highlighted in light blue) where the toroidal component of the parallel electric field $E_{//,t}$ is negative, while positive toroidal current flows in the inboard-side downstream region (highlighted in light yellow) where the toroidal component of the parallel electric field $E_{//,t}$ is positive as shown in Fig. 5(b) despite the induced toroidal electric field being positive, and thus the hollow current profile shown in Fig. 3 is formed.

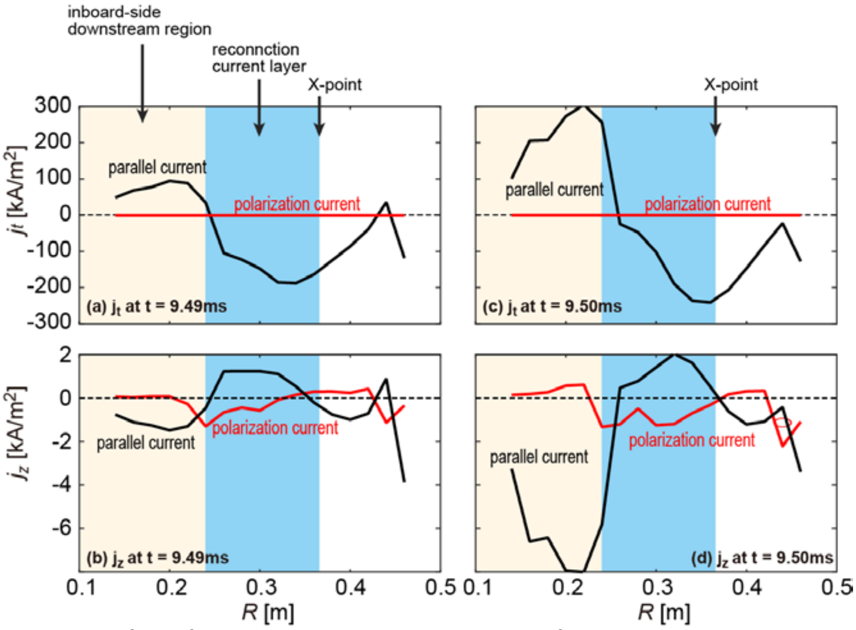

FIG. 5 Radial profiles of (a) toroidal and (b) Z-components of the current density evaluated from the parallel current and the polarization current.

Regarding the *Z*-component, on the other hand, a non-negligible amount of the polarization current flows in the reconnection current layer as shown in Fig. 6(b) and (d). The polarization current almost cancels out the *Z*-component of the parallel current, and as a result, only the toroidal current exists in the reconnection current layer. In other words, the electrical current flowing in the reconnection current layer where the magnetic field lines have concave shapes has only a minor affect on the charge separation in *Z*-direction that is required to maintain the macroscopic plasma motion. Then in the downstream region where the magnetic flux accumulates, parallel current is driven in the negative *Z*- and positive *t*-direction by the parallel electric field due to the excess charge separation that reverses the parallel component of the inductive toroidal electric field, forming a convex magnetic field line shape of the merged ST. The toroidal current density profile that forms the magnetic surfaces of the merged ST plasma is primarily carried by the parallel current due to the magnetic field-aligned component of the electrostatic field within the poloidal plane, which is sustained by the excessive charge separation in the downstream region of magnetic reconnection.

4. CONCLUSION

In merging start-up scheme of ST plasmas, the magnetic flux in the reconnection downstream region increases during merging process, resulting in a negative inductive toroidal electric field. However, a quick growth of positive toroidal plasma current was observed in the downstream region which helps to maintain the ST equilibrium after merging. In this study, by decomposing the electric field in the reconnection current layer and downstream region into components parallel and perpendicular to the magnetic field lines, and examining the contribution of each component, we confirmed that the *Z*-component of the plasma current is almost cancelled out in the reconnection current layer, suggesting that the charge separation along the magnetic field lines connected to the reconnection current layer is maintained. The plasma current in the downstream region is on the other hand driven by the parallel electric field along the magnetic field lines. These experimental results suggest that both the inductive electric field and the electrostatic field play an essential role not only in maintaining the macroscopic plasma flow associated with plasma merging, but also in forming the current profile that maintains the high-beta ST equilibrium after merging.

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