Transient and Intermittent Magnetic Reconnection in TS-3 / UTST Merging Startup Experiments

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Abstract. The high-power reconnection heating has been developed in the TS-3 merging experiments, leading us to a new pulsed high-beta spherical tokamak (ST) formation. Two ST plasmas were produced inductively by two or four PF coils without using any central solenoid (CS) coil and were merged together for MW-GW reconnection heating. The magnetic reconnection transformed the magnetic energy of reconnecting magnetic field through the outflow kinetic energy finally to the ion thermal energy, increasing the plasma beta of ST up to 0.5. A new finding is that ejection of current sheet (or plasmoid) causes high-speed merging/ reconnection as well as high-power heating. In the high-q ST merging, the sheet resistivity was almost classical due to the sheet thickness much longer than ion gyroradius. Large inflow flux and low current-sheet dissipation resulted in flux pileup followed by rapid growth of the current sheet. When the flux pileup exceeded a critical limit, the sheet was ejected mechanically from the squeezed X-point area. The reconnection (outflow) speed was slow during the flux pileup and was fast during the ejection, indicating that intermittent reconnection similar to the solar flare increased the averaged reconnection speed. These transient effects enable us to have the fast reconnection as well as the high-power reconnection heating, even if the merging high-q tokamaks have low current-sheet resistivity.

1. Introduction

We initiated the laboratory experiment of magnetic reconnection in 1986 using two merging spherical tokamaks (STs) and spheromaks and have been studying its mechanisms and applications. For the past 20 years, our TS-3 and TS-4 experiments explored the merging startup of STs and CTs for high-power reconnection heating/ ramp-up without using any center-solenoid (CS) coil[1-7]. Two STs with major radii~0.2m (TS-3), 0.5m (TS-4) were merged together in the axial direction under magnetic compression provided by two PF acceleration coils. The magnetic reconnection was found to transform the magnetic energy of reconnecting magnetic field through the outflow kinetic energy finally to the ion thermal energy, increasing the plasma beta of ST up to 50%. The counterhelicity merging of two spehromaks is now used widely for slow formation of FRC (Field-Reversed Configuration). Transformation of the produced FRC to ultra-high-beta ST was made successfully as the first demonstration of the second-stable ST formation[6,7]. Since 1994, the cohelicity merging of two or three STs has

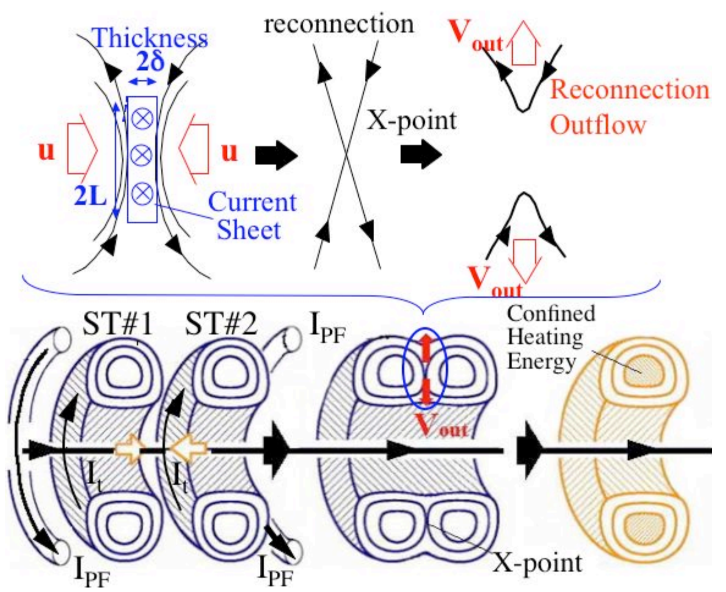


FIG.1. Two merging ST plasmas for reconnection heating and their X-point and current sheet structure.

been demonstrated also in the START experiment for the ST startup[8-11]. Its successful result with neutral beam (NB) heating was extended to the up-scaled experiment MAST and now variety of startup operations have been optimized in MAST[11].

An important question arises as to whether this high-power reconnection heating is still available when high guiding field (high-q) suppresses the anomalous resistivity of current sheet. The fast reconnection mechanism in the high guiding toroidal field B_t is left unsolved, which is essential to the high-power heating by reconnection outflow. While this unique method provides the highest heating power MW-GW within short reconnection time among all CS-less startup methods, the guiding field is a main cause to decrease the reconnection speed of merging STs[4-7]. This paper addresses three key issues: (1) fast transient reconnection mechanisms under high guiding field B_t condition and comparison with the conventional steady state reconnection like the Sweet-Parker model, (2) current sheet ejection as a fast transient reconnection mechanism, and (3) transformation of the steady reconnection to the transient and intermittent reconnections. We found for the first time that the ejection of current sheet (or plasamoid) similar to the solar flare causes fast reconnection/ merging as well as high-power heating. These facts lead us to a more reactor-relevant merging startup experiment, UTST by use of sets of external coils.

2. Experimental Setups

The TS-3 device was used to perform the CS-less startups and merging/ reconnection heating for high-beta STs formation[1-7]. As shown in Fig. 2, its cylindrical vacuum vessel with length of 1m and diameter of 0.8m has two poloidal (PF) coils for poloidal flux injection and two STs with R≈0.2m R/a≈1.5 were merged together in the axial direction. The plasma heating power of ST merging was ranging from 2MW to 10MW, depending on the guiding field B_t [6,7]. Each merging ST initially had plasma parameters: $T_i \approx T_e \approx 10$eV, $n_e \approx 5\times10^{19}$m^{-3} and B≈0.5kG. Their merging/ reconnection was accelerated by the PF coil currents provided by the new power crowbar circuit and decelerated by the separation coil currents on the midplane. A CS (or OH) coil with diameter ≈0.12m was used to provide volt-second only for current sustainment (≈200μsec) after the high-beta ST formation. Seven thin arrays of magnetic pickup coils were inserted on the r-z plane of the vessel to measure directly the 2-D magnetic field profile. A 1m polychrometor with an optical multi-channel analyzer (OMA) was used to measure 2-D profiles of ion temperature T_i by means of the Doppler width of helium and carbon impurity lines. An electrostatic probe array was inserted to measure the radial profiles of electron temperature T_e and density n_e. Poloidal flux contours, profiles of

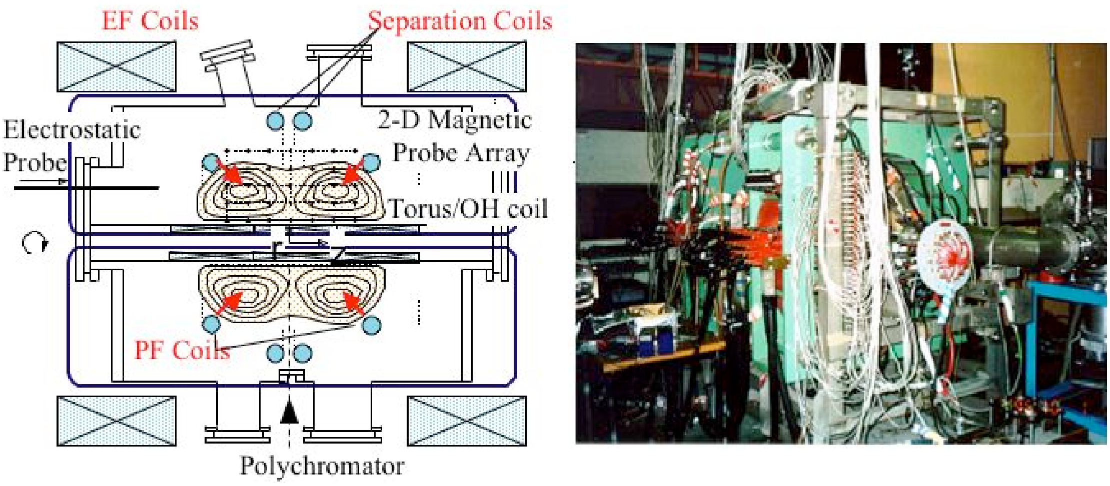


FIG. 2. Cross-section and photo of TS-3 merging device with a pair of PF acceleration coils.

current density and plasma pressure were calculated from the 2-D magnetic field profiles and the profiles of T_i, T_e and n_e.

3. Experimental Results

Figure 3(a) shows dependence of reconnection rate γ of two merging STs on the guiding toroidal field B_{t0} normalized by the constant reconnecting field $B_{//}$, where γ is defined as growth rate of the reconnected poloidal flux normalized by peak poloidal fluxes of two merging STs. It has been generally observed in TS-3, TS-4, SSX and MRX merging experiments that the reconnection speed decreases with B_{t0}[2,3,6,12,13]. Its main reason is that anomalous resitivity of current sheet increases significantly when the current sheet (thickness δ) is compressed shorter than the ion gyroradius ρ_i. Decrease in compressibility of the current sheet is another reason why γ increases inversely with B_{t0}. Under the present experimental condition, the sheet thickness δ was compressed down to the size of ion gyroradius ρ_i when $B_{t0}<2.4\,B_{//}$. As shown in the black circles in Fig. 3(a), γ was in high level $\gamma = 1.9\times10^6$[sec^{-1}] for $B_{t0}<2.4B_{//}$ and was in low level $\gamma = 1.2\times10^6$[sec^{-1}] for $B_{t0}>2.4B_{//}$, in agreement with the fast reconnection mechanism mentioned above. If this mechanism holds true for all experimental regime, the reconnection speed as well as the outflow speed stay slow under the high B_{t0} condition. The reconnection heating is determined by reconnection outflow speed proportional to the reconnection inflow speed. For our high-beta ST startup experiment, the first question is whether we can expect the fast inflow/ outflow and significant ion heating during high-q (high-B_{t0}) ST merging.

In this experiment, two high-q STs were over-compressed axially using the two acceleration PF coils and the capacitor banks with new power-crowbar circuit. Figures 4(a) and (b) show r-z contours of poloidal flux and toroidal current density j_t when two merging STs with center q_0~2.5 (q_{90}~35) were compressed low and high by the PF acceleration coils. These flux contours were measured by 2-D magnetic probe array on r-z plane whose maximum special resolution was 5mm in z-direction and 40mm in r-direction. In the low compression case (a), shape and position of the current sheet were maintained during the merging, just like the conventional steady-state Sweet-Parker reconnection. However, in the high compression case (b), the current sheet was observed to grow and was ejected inward from the X-point region in sharp contrast with the mentioned quasi-steady case. It is noted that the reconnected flux increased significantly during the sheet ejection in Fig. 4(c). As indicated by the "X" marks in Fig. 3(a), γ during the ejection was about 2.8×10^6 [sec^{-1}], which was three times higher than γ without sheet ejection. Though this high reconnection rate was obtained transiently during the ejection, the time-average reconnection rate was also higher than the steady-state case.

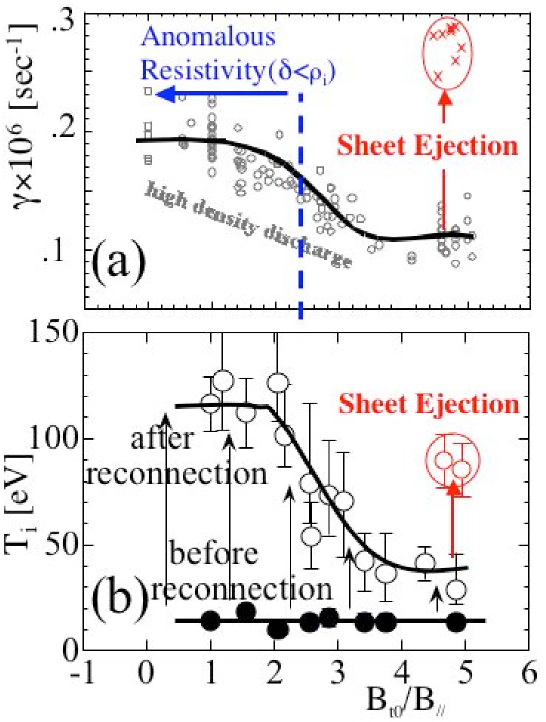


FIG. 3. The reconnection rates γ (a) and ion temperatures T_i (b) as a function of toroidal field B_{t0} normalized by reconnecting poloidal field $B_{//}$ (constant). The transient γ and T_i during the sheet ejection are also plotted.

The sheet ejection was observed once or twice, depending on magnetic fluxes of the merging STs. We observed reproducibly the sheet ejection twice, when the initial fluxes of merging STs were larger than 3mWb under the present experimental condition. After the growth and ejection of the current sheet, the same cycle occurred during the second ejection. These facts indicate that intermittent reconnection similar to the solar flare occurs when plasma inflow is over-accelerated by an external coils[14,15]. The sheet ejection was found to increase the time-averaged reconnection rate. It is concluded that the intermittent reconnection caused by the sheet ejection is a new fast reconnection mechanism without using the anomalous resisitivity of the current sheet.

A related question is why the sheet was ejected inward in Fig. 4(b). We increased the axial separation length of the two acceleration coils to compress the two merging STs more uniformly. Figure 5(c) shows the r-z contours of poloidal flux and toroidal current density j_t of two merging high-q STs under the high uniform compressions. The separation length of the two acceleration coils was 10cm longer than that in Fig. 4(b). It was clearly observed that the upper and lower halves of current sheet were ejected inward and outward respectively, due to more uniform compression. The inward ejection in Fig. 4(b) was due to axial and inward compression provided by the acceleration coils, while inward and outward ejections in Fig. 5(c) were due to the uniform compression. The larger increase in reconnection speed was obtained in the inward ejection case (Fig. 4(b)), probably because the compression force of the coils was not lost for compression and splitting of the sheet but was used mostly for the sheet ejection unlike the uniform ejection case.

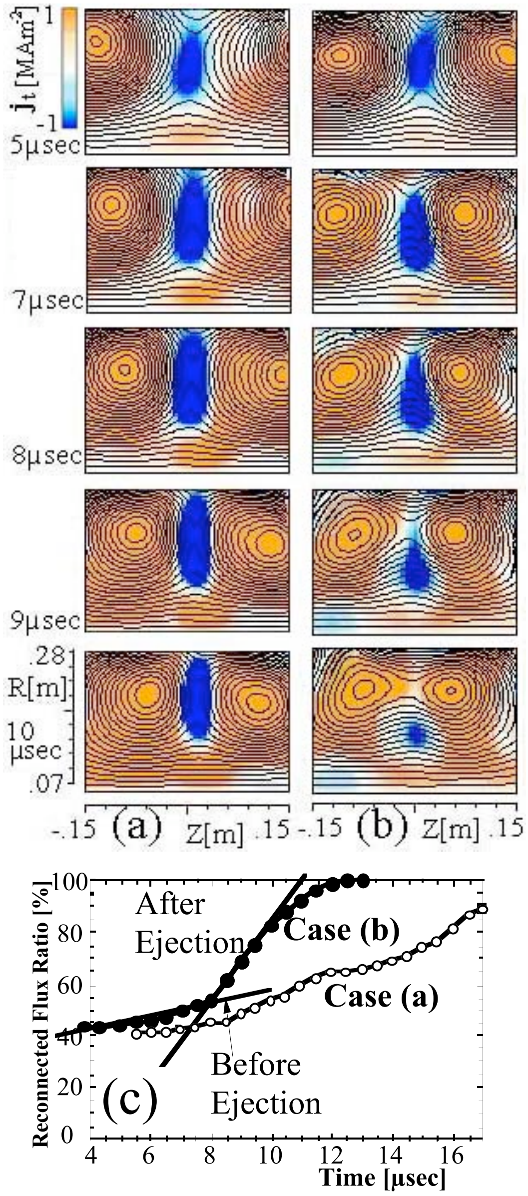
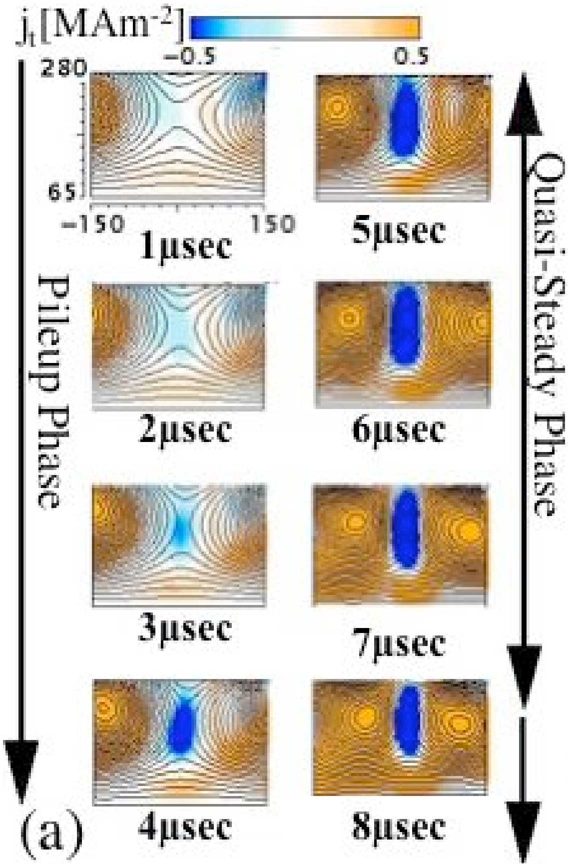


FIG. 4. r-z contours of poloidal fluxes and toroidal current densities j_t (by red: positive and blue: negative colors) of two merging high-q STs under the conditions of low and high axial-inward compressions (a) (b) and time evolutions of their reconnected fluxes (c).

The second question is whether the fast reconnection caused by the current sheet ejection really heats plasma ions under high guiding field B_{to} condition. Figure 3(b) shows peak ion temperatures before and after the ST merging/ reconnection as a function of B_{to}/ $B_{//}$. The ion temperature T_i after the reconnection was observed to increase inversely with $B_{t0}/B_{//}$, in agreement with the reconnection rate γ. It is simply because the reconnection outflow proportional to reconnection (inflow) speed was transformed into ion thermal energy through fast shock and ion viscosity[6,7]. In the high compression case, T_i increased up to 90eV right after the ejection, in sharp contrast with the low compression cases



without sheet ejection. The increase in outflow was found to cause the high-power ion heating. Based on this fact, the sheet ejection enables us to have the fast reconnection as well as the high-power reconnection heating, even if the merging high-q tokamaks have low current-sheet resitivity.

Final questions are how the transient effect of reconnection influences the plasma inflow and outflow and how it is related with the steady-state reconnection like the Sweet-Parker model. We varied externally the plasma inflow speed from slow to fast, using the acceleration coil current. Figures 5(a)-(c) show r-z contours of poloidal fluxes and j_t for the high compression case (a), the medium compression case (b) and the low compression case (c), respectively. Figures 6(a)-(c) show more detailed evolutions of the inflow fluxes uL and the outflow fluxes $V_{out}\delta$ for the three cases in Figs. 5,

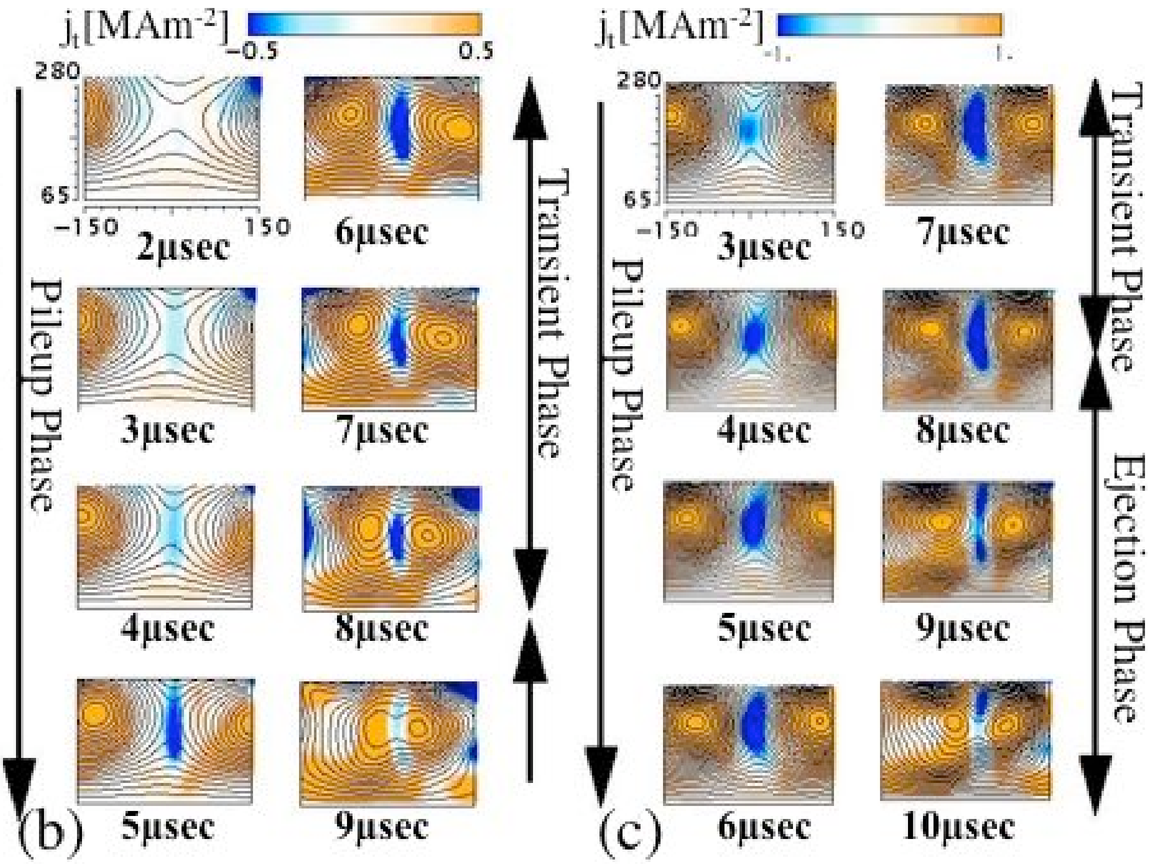


FIG. 5. r-z contours of poloidal fluxes and toroidal current densities j_t (by red: positive and blue: negative colors) of two merging high-q STs under the conditions of low, medium and high axial-uniform compressions (a), (b) and (c).

where u, V_{out} are inflow and outflow speeds, L, δ are length and thickness of the current sheet. In the low compression case (a), the sheet current was formed from t=0μsec to t=5μsec and was maintained in quasi-steady state from t=5μsec to t=10μsec. In this quasi-steady phase, the inflow flux balanced with the outflow flux. This fact indicates that the quasi-steady reconnection ($dB/dt \approx dn/dt \approx 0$) was realized just like the conventional Sweet-Parker model[16]. Its inflow speed is given by

$$u^2 = \eta V_A / \mu_0 L, \text{-------} \ (1)$$

where V_A is the Alfven speed. This theoretical velocity agrees with the measured inflow velocity within 30%, if we use the resisitivity η calculated from electric field E_t and current density j_t at X-point. In the intermediate compression case (b), uL was larger than $V_{out}\delta$ in the early reconnection phase before t=6μsec and became smaller in the late phase after t=6μsec. This fact indicates that the flux pileup increased early reconnection speed during the formation of the current sheet. The current sheet kept growing until t=6μsec and was deformed significantly after t=6μsec. In the high compression case (c), uL exceeded significantly $V_{out}\delta$ before t=7μsec, indicating a significant pileup of plasma flux. This pileup caused the formation of large current sheet with round shape. After t=8μsec, $V_{out}\delta$ became much larger than uL, indicating that huge plasma mass was ejected from the reconnection region. Figure 5(c) indicates that the current sheet was ejected around t=8-10μsec in agreement with this mass ejection time in Fig. 6(c). Since the sheet thickness δ was larger than the gyroradius ρ_i, the sheet resistivity η was almost classical in sharp contrast with the large anomalous resitivity of the sheet when $\delta<\rho_i$[5,6]. The large inflow flux and low current-sheet dissipation resulted in the flux pileup followed by the rapid growth of the current sheet. When the flux pileup exceeded a critical limit, the sheet was ejected mechanically from the squeezed X-point area. Its reconnection speed became larger than the steady-state Sweet-Parker speed due to the pileup and ejection effects.

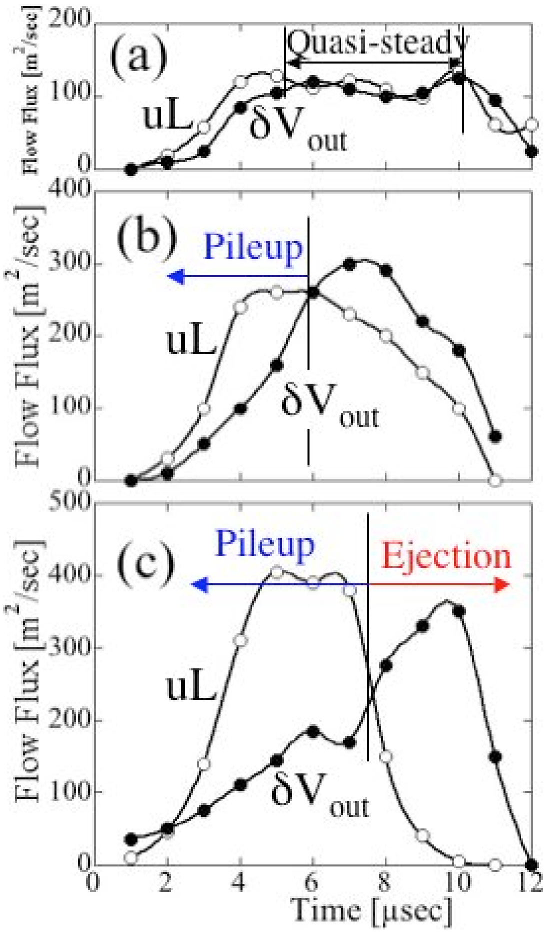


FIG. 6. Time evolutions of inflow and outflow fluxes uL, $V_{out}\delta$ under the conditions of (a) high, (b) intermediate and (c) low axial-uniform compressions.

4. Discussions

The transient effect of magnetic reconnection can be modelled theoretically by extending the conventional Sweet-Parker model. We assume the Sweet-Parker type current sheet with thickness 2δ and length 2L, as shown in Fig. 1. Its basic equations are composed of the magnetic flux dissipation law:

$$u = \frac{\eta}{\mu_0 \delta}, \text{-------} (2)$$

and the mass conservation law:

$$uL = \delta V_A + \frac{L\delta}{n_0}\frac{dn_{sheet}}{dt} + \delta \frac{n_{sheet}}{n_0} V_{eject}, \text{-------} (3)$$

where $n_{sheet} / n_0 \equiv \alpha$ is the electron density pileup factor (electron density of the current sheet normalized by the bulk electron density) and V_{eject} is ejection speed of current sheet. The second term represents the mass pileup inside the current sheet and the third term does the sheet (mass) ejection. Based on Eqs. (2) and (3), the inflow velocity is calculated as follows:

$$u^2 = \frac{\eta}{\mu_0}\left(\frac{V_A}{L} + \frac{1}{n_0}\frac{dn_{sheet}}{dt} + \frac{n_{sheet}V_{eject}}{n_0 L}\right). \text{-------} (4)$$

The first, second and third terms are the conventional Sweet-Parker term, the mass pileup term and the mass ejection term, respectively. When the forming current sheet works as a plasma sink, the pileup term increases the reconnection (inflow) speed transiently. The following preliminary model helps us to understand how Eq. 4 is connected with the increase in the time-averaged reconnection speed. If we assume the mass pileup and ejection speed as follows for simplicity:

$$\alpha = n_{sheet} / n_0 = \alpha_1 (1 + sin\omega t), \text{-------} (6) \quad V_{eject} = V_1\{1 + sin(\omega t + \theta)\}, \text{-------} (7)$$

the following inflow speed is obtained:

$$u^2 = \frac{\eta}{\mu_0 L}[V_{A1} + \alpha_1 \omega \cos\omega t + \alpha_1 V_1 sin\omega t + \alpha_1 V sin(\omega t + \theta) + \alpha_1 V_1 + \alpha_1 V_1 sin\omega t \cdot sin(\omega t + \theta)]. \text{---}(8)$$

The last term contains a steady-state component, indicating that the sheet ejection increases the averaged reconnection speed. This term is maximized at $\theta = 0$, where the ejection occurs when the pileup factor reaches the maximum value. Even if the anomalous resistivity does not increase, the fast inflow causes the fast reconnection by means of the sheet ejection phenomenon. As the inflow flux is increased, the quasi-steady reconnection is transformed to the transient one and finally to the intermittent one with faster averaged reconnection speed.
If we include the transient effect of magnetic field too, we can replace Eq. 2 by

$$u = \frac{\eta}{\mu_0 \delta} + \frac{\partial B}{\partial t}\frac{R}{B}, \text{-------} (5)$$

but lose the analytic solution like Eq. (4), where R is the characteristic scale length.

5. Summary and Upscale of the Merging Startup Experiment

In summary, we studied experimentally the transient effects of magnetic reconnection: (1) the pileup effect and (2) the current sheet ejection effect as new fast reconnection mechanisms. When the externally driven plasma inflow flux exceeds the plasma outflow flux, the plasma pileups inside the current sheet, increasing the plasma inflow. As the inflow flux is increased, the quasi-steady reconnection like the Sweet-Parker model is transformed to the transient one and finally to the intermittent one. The transient effects such as the flux pileup and the ejection enable us to have the high reconnection speed as well as the high-power reconnection heating, even if the merging high-q tokamaks have low current-sheet resistivity.

We are now up-scaling the mentioned merging startup experiments and also the RF heating/ current drive experiment of TST-2 to a new ST experiment: UTST (R~0.4m). Figure 7 shows the photo and vertical cross-section of the UTST device. Its main objects are to demonstrate (1) the double-null startup of STs without CS coil, (2) their reactor-relevant reconnection heating for high-beta ST formation and (3) their sustainment by advanced RF and NBI heating/ current-drive techniques. In order to make the reconnection heating method reactor-relevant, all PF coils are located outside of the vacuum vessel in sharp contrast with TS-3, 4 and MAST whose PF coils are located inside the vacuum vessel. In UTST, two X-points are formed by the two sets of PF coils to form two merging ST plasmas. Figure 8 shows the preliminary 2-D magnetic probe measurement of vacuum X-point structure produced by two PF coils (PF#1-1 and #1-2). Each pair of PF coils was observed to form and maintain an X-point for 300μsec for the UTST double-null startup and merging scheme. The first plasma discharge will be demonstrated in October after installation of new capacitor bank. The mega-watt heating power of reconnection is expected to transform the initial low-beta merging STs to the high-beta ST (30-50%).

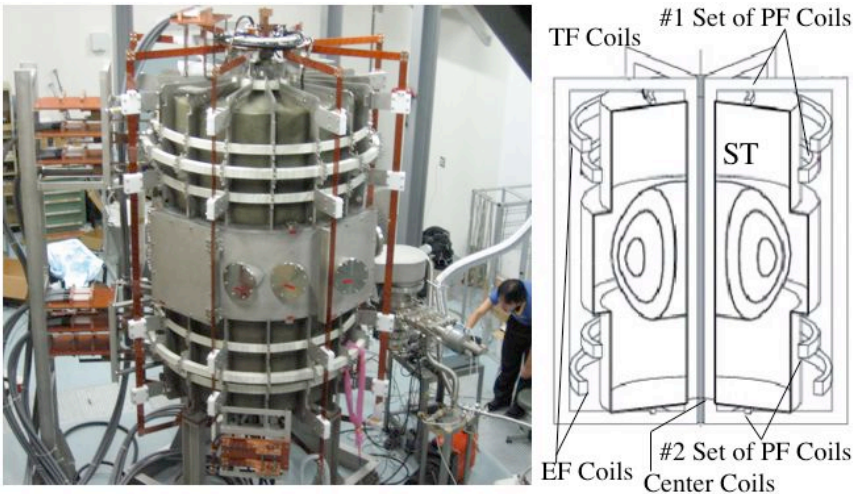


FIG. 7. Photo and vertical cross-section of the UTST device.

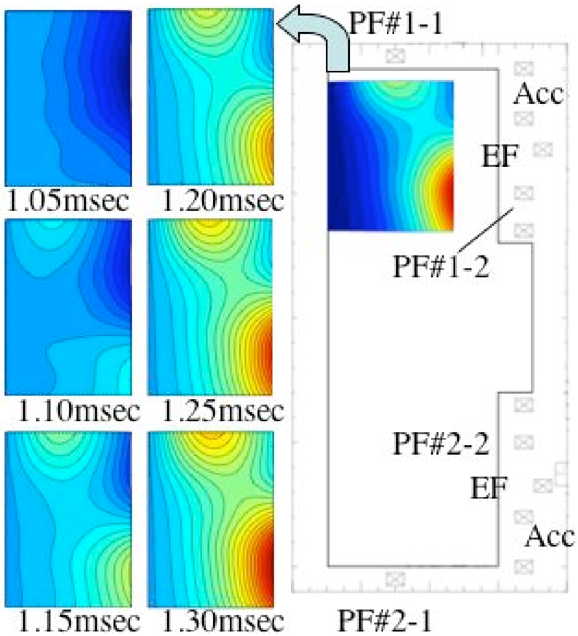


FIG. 8. r-z contours of vacuum poloidal flux during the double-null point formation at UTST device and its vertical cross-section.

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