INTERMITTENT MERGING OPERATIONS OF SPHERICAL TOKAMAK PLASMAS FOR RECONNECTION HEATING AND HELICITY INJECTION

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For the first time, the sustainable intermittent merging operation of spherical tokamak (ST) plasmas is demonstrated in the TS-4 device by controlling two poloidal field (PF) coil currents. The key is the natural rectification effect of the ST plasma formation by oscillating PF coil currents. The intermittent merging operation dramatically extends the plasma merging application from startup of high-beta ST plasmas to additional ion heating, current drive, and plasma profile control.

The University of Tokyo group has studied the ST plasma merging operation in TS-3, TS-4, TS-6, START, UTST, MAST, and ST-40 experiments [1-3] for (1) high-power reconnection plasma heating and (2) magnetic helicity injection / current drive. The merging operation can directly study high-beta burning ST plasma formation followed by ST plasma sustainment by bootstrap current. An important question is whether we can extend the pulsed merging operations to continuous or intermittent merging operations. In this paper we demonstrated the first intermittent ST plasma formation and merging using oscillating PF coil currents.

Figure 1 shows the schematic evolution of the field line contours and waveform of oscillating PF coil current I_{PFC} of our intermittent ST plasma merging operation. We used the sine wave form for I_{PFC} as a simple first-step demonstration, and the merging and ST formation time intervals are controlled by adjusting the waveform. After the first ST merging plasma formation is completed, we swing down the two PF coil currents I_{PFC} to form two new ST plasmas on the top and bottom of the main ST plasma (Fig. 1(b) A, B) and then push them to merge with the main ST plasma (C). When we swing up I_{PFC}, small plasmoids may appear around the PF coils but disappear later because they are not MHD stable (D). This natural rectifying effect of ST plasma formation is due to oscillating I_{PFC} under opposing equilibrium field (EF) coil current I_{EFC}.

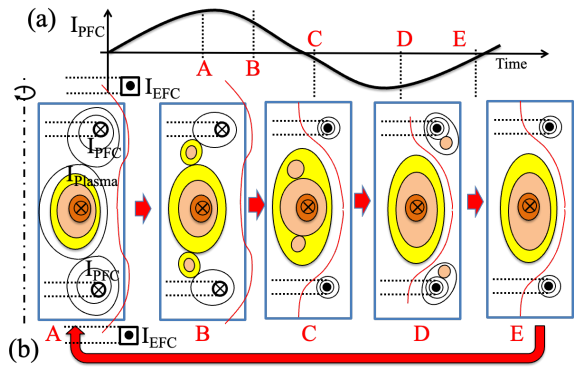

Fig. 1 (a) Waveform of PF coil current I_{PFC} and (b) schematic magnetic field-line contours for the intermittent ST merging operation in TS-4 ST merging experiment. The main ST plasma is formed by two merging ST plasmas before the intermittent merging cycle starts.

Figure 2 shows the poloidal flux contour evolution of ST plasma under intermittent merging operation after the merging formation of the main ST plasma with a central q-value of 2. It was measured by 2D magnetic probe array installed in the upper half of R-Z plane in the TS-4 ST merging device. The secondary ST plasmas are formed by swinging down I_{PFC} before t~0.52ms and then are pushed to merge with the main ST plasma from t=0.52ms to t~0.58ms. We used the decaying LC oscillation of I_{PFC} because the PF coil currents are driven by the capacitor banks. Unlike Fig. 1(a), the second peak of I_{PFC} sine wave form is as small as 30% of the first peak, indicating that the secondary ST magnetic flux is much smaller than the main ST flux. The magnetic reconnection is observed to merge the private flux of the two secondary ST plasmas into the main ST plasma common flux, completing the merging/ reconnection process. Intermittently, the decaying oscillation of I_{PFC} produces small ST plasmas to merge with the main ST plasma.

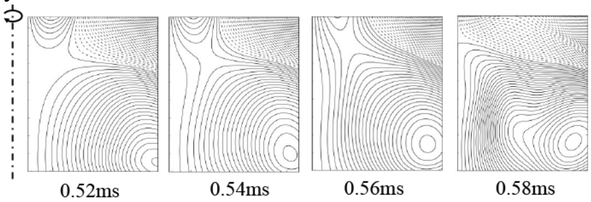

Fig. 2 Poloidal flux contours of ST plasma under intermittent ST merging operation in TS-4 ST merging experiment. The contour evolution shows one cycle of additional small ST plasma merging with the main ST plasma after the first merging formation of the main ST plasma.

Figures 3(a) and (b) show the time evolutions of the total plasma current and toroidal flux inside the separatrix during the initial merging formation of the main ST plasma and the second / third merging of additional ST plasmas by the decaying oscillation of I_{PFC}. The black, blue, red, and green curves show the operation without additional merging, with second and third merging events at 0.45, 0.55ms, with second merging at 0.55ms, and with second merging at 0.65ms, respectively. The red curve corresponding to Fig. 2 indicates that the plasma current increases in the second merging/ reconnection phase. The plasma current and toroidal flux are found to increase by 10-20% when the second and third ST plasmas merge with the main ST plasma in sharp contrast with the case without intermittent merging shown by the back curves. These results clearly indicate that the additional ST merging operations have the effect of helicity injection and current drive. Because we are using decaying LC oscillation of I_{PFC} as the first demonstration of intermittent merging operation, the flux of secondary ST plasmas is too small to maintain the main ST plasma current.

Figure 4 shows the core ion temperature T_i evolutions of ST plasma under the intermittent merging operation (red curve) and the operation without additional merging (back curve), respectively, which corresponds to the red and black curves in Fig. 3. The ion Dopper spectroscopy is used to measure T_i. In the former case, the ion temperature clearly increases twice: from 0.4ms to 0.45ms and from 0.55ms to 0.6ms. These two periods correspond to the first and second ST merging periods determined by the swing-down of oscillating I_{PFC}. The second increase in ion temperature ΔT_i~8eV is much smaller than the first increment ΔT_i~25eV, simply because the magnetic energy of the second merging ST plasma is much smaller than the first one. Our experimental results verified the ion heating effect of intermittent ST merging operation. Our FEC2023 paper showed that the ion heating energy of merging is about 40% or 5-10% of poloidal magnetic energy W_{mp}, depending on whether the reconnection current sheet thickness δ is thinner than ion gyroradius ρ_i or not, respectively [3,4]. As shown in Fig. 2, our present intermittent merging operation compresses slowly δ from 10cm to 2cm (on the order of ρ_i). Its heating power is 25% of W_{mp}, because the merging is mostly for magnetic helicity injection in the early merging phase but becomes mostly for ion heating in the late merging phase.

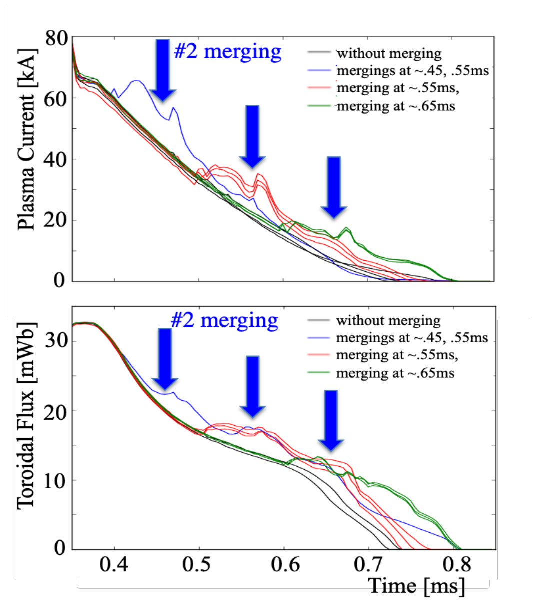

Fig. 3 Time evolutions of plasma current I_{plasma} and toroidal flux inside the separatrix for three types of intermittent merging ST plasma, and that without intermittent merging after the merging formation of main ST plasmas. The black, blue, red, and green curves show the operation without additional merging, one with the second and third merging at ~0.45, 0.55ms, one with the second merging at ~0.55ms, and one with the second merging at ~0.65ms, respectively.

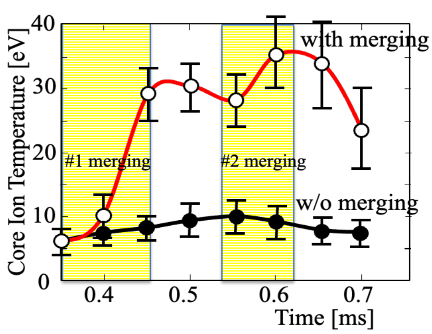

Fig. 4 Core ion temperature evolutions of ST plasma with intermittent merging corresponding to the red curve in Fig. 3 and that without merging corresponding to the black curve in Fig. 3.

In summary, our results show the current drive and ion heating effects of intermittent ST plasma merging operation performed in the TS-4 device. The intermittent merging/ reconnection operation enables not only for the initial startup formation / heating of ST plasma, but also for additional heating, current drive, and profile control during the sustainment phase of ST plasma. Our FEC2023 paper shows that a single ST merging can form burning ST plasmas which can be sustained by the bootstrap current based on the B_{rec}^2-scaling of reconnection ion heating [3]. The recent ST-40 experiments at Tokamak Energy Inc. used the ST plasma merging to obtain ion temperature T_i ~1-3keV which then increases to 9.6keV by utilizing NBI heating. However, in this paper we showed that the intermittent merging operation can be employed to obtain additional ion heating and current drive, extending the application of merging operation for ST reactor plasmas. Since the high-power ion heating by ST plasma merging can obtain high-beta ST plasmas with reversed-shear and absolute minimum-B profile, we will investigate more detailed profile control of ST plasma using the intermittent merging operation.

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