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

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Abstract

For the first time, the sustainable intermittent merging operation of spherical tokamak (ST) plasmas is demonstrated in TS-4U ST merging device by controlling poloidal field (PF) coil currents. The key is the natural rectification effect of the ST plasma formation by oscillating PF coil currents under equilibrium magnetic field. We observed the intermittent ST plasma formation and merging two or three times using decaying LC-circuit oscillation of PF coil currents. At each ST plasma merging period, both of plasma current and ion temperature increase, indicating current-drive and ion heating effects of magnetic reconnection and merging. 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.

1. INTRODUCTION

We have developed high-power reconnection heating of plasma ions using two merging spherical tokamak (ST) plasmas in TS-3, TS-4, TS-6 and UTST at the University of Tokyo [1-7] and also in MAST at UKAEA and in ST-40 at Tokamak Energy Inc. based on UK-Japan collaboration program [8]. The ion thermal/ kinetic energy

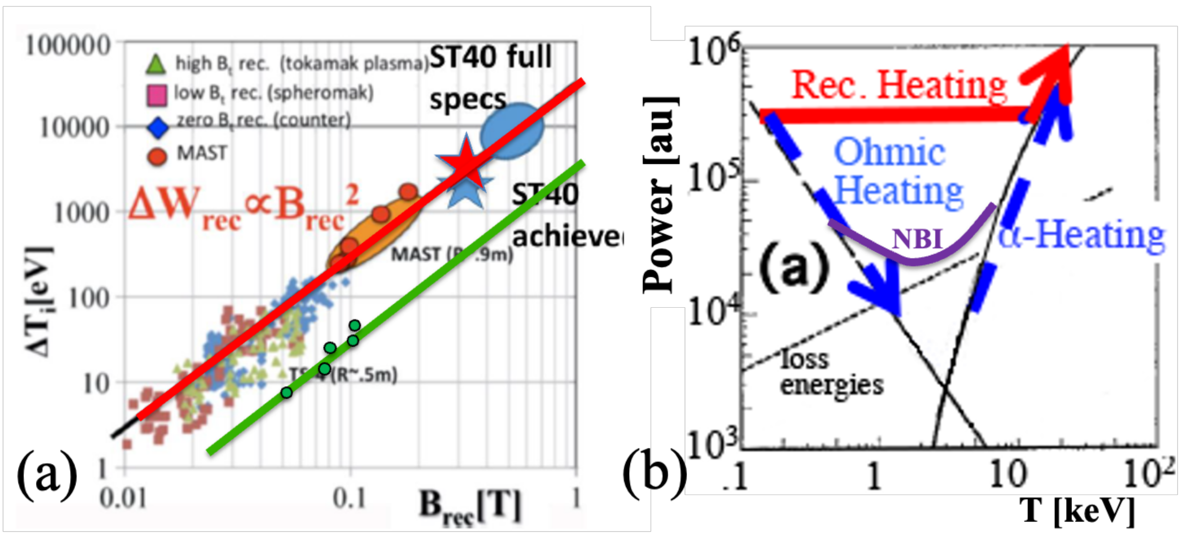

FIG. 1. (a) Dependence of ion temperature increment ΔT_i on the reconnecting magnetic field (B_{rec}) of two merging Spherical Tokamak (ST) plasmas under constant electron density n_e~$1.5x10^{19}m^{-3}$. The red line is obtained under high compression of current sheet thickness δ to ρ_i. The low current sheet compression experiment with δ>>ρ_i was made only in TS-3U and the ΔT_i dependence on B_{rec} is shown by the green line [4], (b) temperature dependence of the conventional tokamak plasma heating power composed of ohmic and alpha heating (blue curve) which needs the additional NBI heating (purple curve) and temperature dependence of the merging/reconnection heating power (red curve) which can directly turn on the alpha heating [3].

heated by magnetic reconnection scales with the reconnecting magnetic field component energy ($B_{rec}^2/2\mu_0$) where B_{rec} is almost equal to the poloidal magnetic field B_p in the tokamak merging experiments. This B_{rec}^2-scaling of ion heating energy by reconnection can be understood by the fact that in the reconnection downstream the ion energy is mainly in the form of outflow kinetic energy before ions are thermalized in further downstream. The ion outflow velocity is produced mainly by the large ExB drift velocity associated with large axial (poloidal) electric field E_z in the downstream, resulting from the formation of quadrupolar electrostatic potential structure in the downstream region and E_z depends linearly on B_tB_p as observed in the ST merging experiments [4,7]. Hence, the outflow velocity scales with the reconnection magnetic field B_{rec} ~ the poloidal magnetic field B_p and thus the ion heating energy scales with B_{rec}^2, as shown in Fig. 1(a) [4,7]. When we compress the current sheet thickness δ to ion gyroradius ρ_i, the merging/ reconnection transforms about 40% of the reconnecting (poloidal) magnetic energy to ion thermal/ kinetic energy, while it transforms about 5-10% when we keep δ larger than ρ_i [4]. The former is useful for tokamak plasma heating/ignition and the latter for tokamak helicity injection and current drive.

As shown in Fig. 1(a) and (b) (red curves), the B_{rec}^2-scaling of ion heating of reconnection provides an efficient way to transform the initial 10eV plasmas directly to burning plasmas with ion temperature $T_i > 10$keV by increasing B_{rec} to 0.6T under the electron density n_e~$1.5x10^{19}m^{-3}$ without using any additional heating like neutral beam injection (NBI) [2-4]. The whole CS coil flux can be used for tokamak profile control after the DT burning startup. The reconnection startup without additional heating like NBI is much more cost-effective than the conventional tokamak startup by the ohmic heating of their plasma current and additional heating. The ohmic heating power tends to decrease with temperature but the onset of alpha heating needs a few keV. This is the reason why we need NBI to obtain the burning plasmas. However, the reconnection heating transforms huge (about 40%) amount of poloidal magnetic energy into ion kinetic/thermal energy within the merging/ reconnection time much shorter than the plasma confinement time. It is noted that the reconnection heating has almost no temperature dependence. Once the reconnection heating of two tokamak plasma merging turns on the DT burning, we can maintain the plasma current using the bootstrap current produced by the alpha heating and possibly by low power NBI for profile control [3].

Because of the high heating power, the reconnection heating scheme is used not only in our university and Tokamak Energy (UK) Inc. [8] but also in the following institutes: C2-W FRC experiment at TriAlpha Energy (US) [9], the space propulsion system at Helicity Space Corp (US) [10], SUNEST-2 ST experiment at Tsinghua

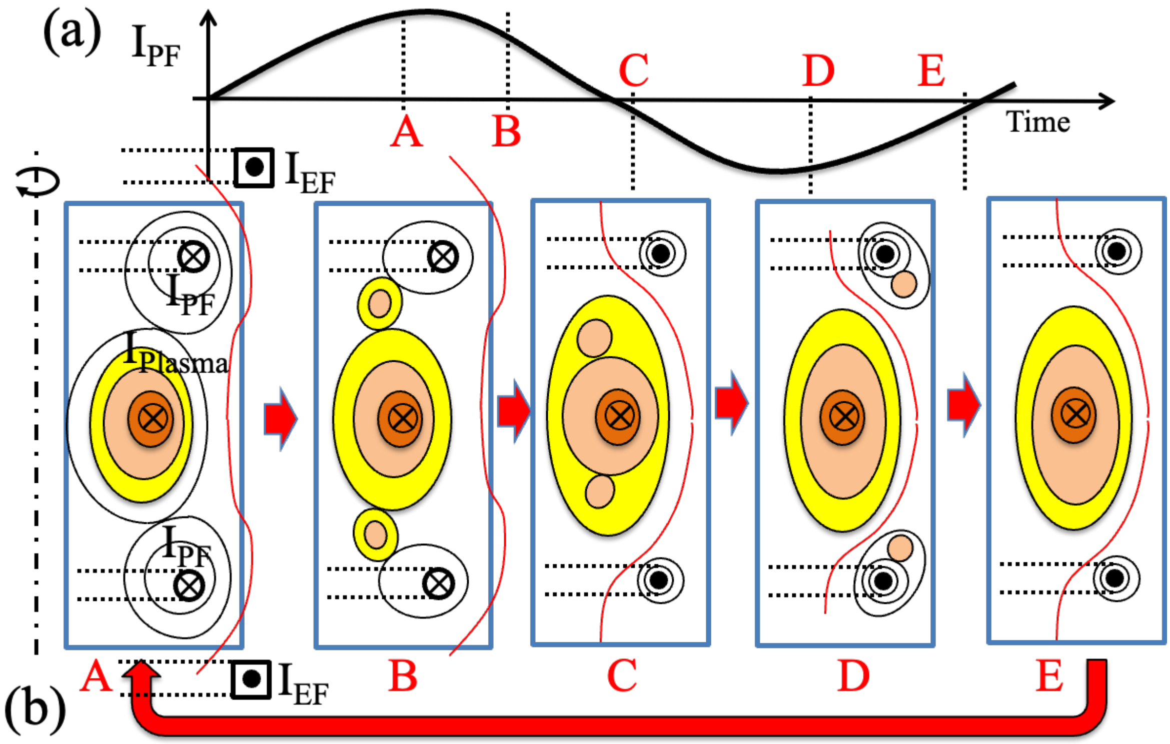

FIG. 2. (a)Waveform of PF coil current I_{PF} and (b) schematic magnetic field-line contours for the intermittent ST merging operation in TS-4U ST merging experiment. The main ST plasma is formed by two merging ST plasmas before the intermittent merging cycle starts.

University and Startorus Fusion (China) [11], VEST ST experiment at Seoul National University (Korea) [12] and finally Japanese DT burning tokamak projects related with the FAST project. The University of Tokyo group has studied the ST plasma merging operation in TS-3, TS-4, TS-6, UTST experiments [1-6] for (1) high-power reconnection plasma heating shown by the red line scaling in Fig. 1(a) when we compress the current-sheet thickness δ to the ion gyro radius ρ_i and (2) magnetic helicity injection / current drive by the green line scaling in Fig. 1(a) when $\delta > \rho_i$ [4]. The former merging transforms about 40% of poloidal magnetic energy to ion thermal/kinetic energy, while the latter does only 5-10%. 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. It dramatically extends the plasma merging application from startup of high-beta ST plasmas to additional ion heating, current drive, and plasma profile control.

Figures 2(a)(b) shows the waveform of oscillating PF coil current I_{PF} and the schematic evolution of the field line contours during our intermittent ST plasma merging operation, respectively. We used the sine wave for I_{PF} as a simple first-step demonstration, and the time interval of ST mering are controlled by adjusting the waveform of LC-circuit current I_{PF}. After the first ST merging plasma formation is completed, we swing down the two PF coil currents I_{PF} to form two new ST plasmas on the top and bottom of the main ST plasma (Fig. 2 A, B) and then push them to merge with the main ST plasma ((Fig. 2 C). When we swing up I_{PF}, small plasmoids may appear at around the PF coils but disappear later because they are not MHD stable (Fig. 2 D). This natural rectifying effect of ST plasma formation is due to oscillating I_{PF} under opposing equilibrium field (EF) coil current I_{EF}. The oscillating currents of PF coil currents I_{PF} produce two ST plasmas when I_{PF} is swung down but does not when I_{PF} is swung up, indicating that the oscillating I_{PF} current has the natural rectifying effect of ST formation.

2. EXPERIMENTAL SETUPS

We used TS-4U merging device to develop the intermittent merging operation, because its decay time of the produced ST plasma is longer than TS-3U and UTST plasmas [1-5]. As shown in Fig. 3, the TS-4U merging device has the cylindrical vacuum vessel with the length of 1.8m, the diameter of 1.8m, four pairs of poloidal field (PF) coils, the center TF coils and two coaxial plasma guns. The two major PF coils called fluxcores can produce two ST plasmas with major radii of 0.5m and minor radii of 0.3m which attract with each other due to their parallel

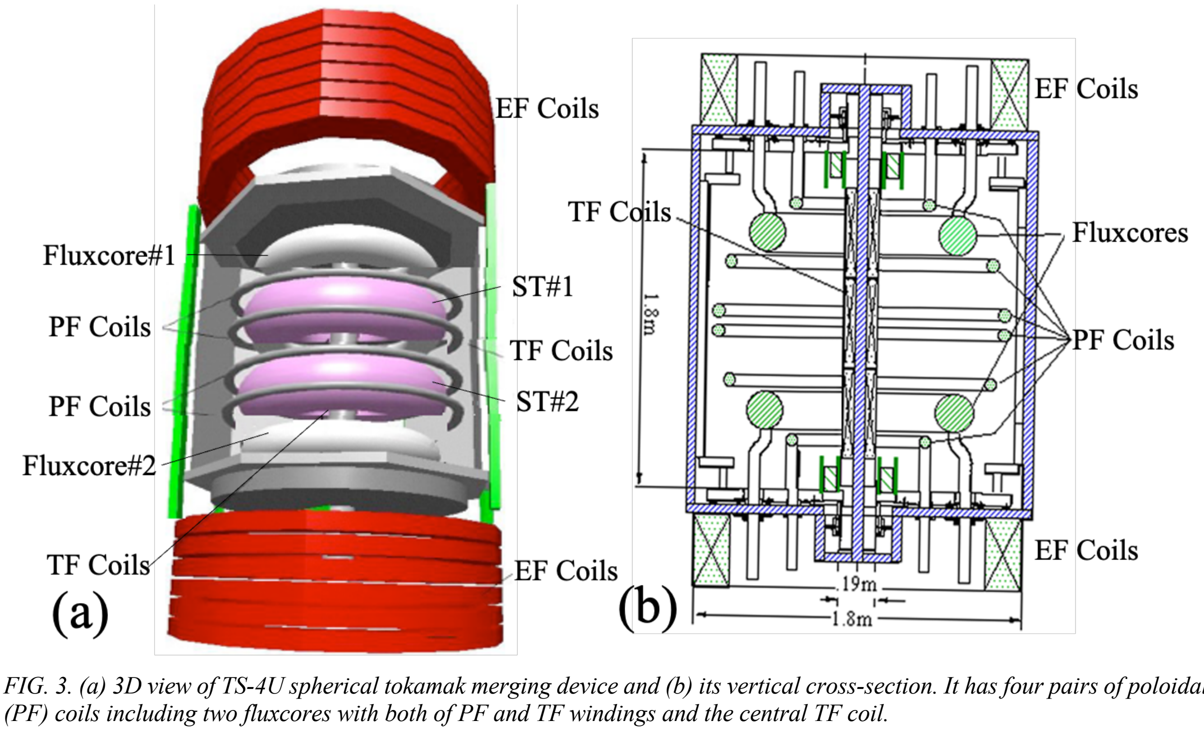

FIG. 3. (a) 3D view of TS-4U spherical tokamak merging device and (b) its vertical cross-section. It has four pairs of poloidal (PF) coils including two fluxcores with both of PF and TF windings and the central TF coil.

currents. Their detailed merging processes are controlled by all of PF coils. As shown in Fig. 2, the PF coil currents I_{PF} have the natural rectifying effect of ST formation, which is useful for our intermittent merging operation.

Four important 2D diagnostics were developed to measure the kinetic mechanisms of reconnection heating. The 2D removable array of magnetic field is installed on the r-z planes of the vacuum vessel for 2D measurement of magnetic field, which is used to obtain the 2D contours of poloidal flux, current density and safety factor q. The ion Doppler tomography system is composed of 90 optical fibers connected with the multi-slit polychromator with ICCD camara. The tomography software transformed the measured line-integrated signals of line spectrum into the local spectrum at each wavelength to obtain the 2D contours of ion temperature. The 2D Thomson scattering measurement utilizes the multiple reflection of YAG laser light to cover the r-z plane and the time of flight of laser light to save the number of polychromators. At present, the scattered lights from seven measurement points are measured by the single polychromator. Since the distance to the next measurement point is 3 m, the scattered light at that point arrives at the spectrometer with a delay of 10 ns. The 2D soft X-ray measurement is composed four pinhole cameras with different filters whose phosphors are connected with high-speed cameras by four optical image fibers. This system is used to analyze 2D contour of high energy electrons with four energy ranges.

3. EXPERIMENTAL RESULTS

As a simple first-step demonstration of intermittent merging operation, we used the decaying sine wave of poloidal coil (fluxcore) current I_{PF} which is the LC circuit current formed by the PF coils and the capacitor banks. Figure 4 shows the poloidal flux contour 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 the mentioned 2D magnetic probe array installed in the upper half of r-z plane in the TS-4U ST merging device. The secondary ST plasmas are formed when we swing down the PF coil current I_{PF} before t~0.52ms and then let them merge with the main ST plasma from t=0.52ms to t~0.58ms. Since we used the decaying LC oscillation of I_{PF}, the second peak of I_{PF} 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 transform the private flux of the two secondary

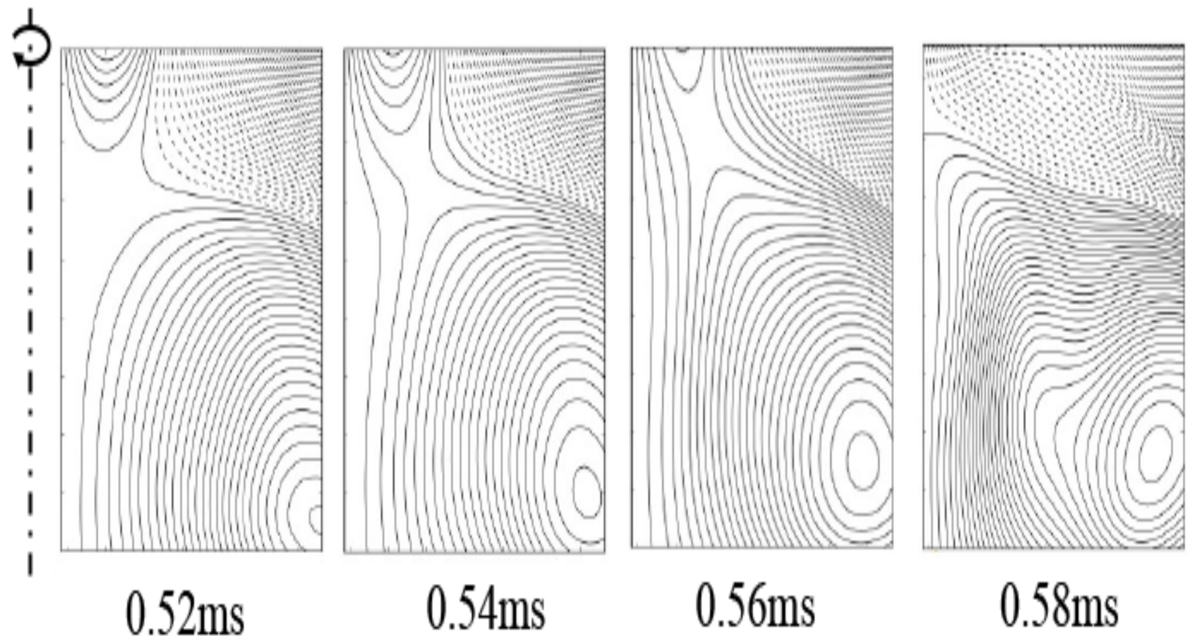

FIG. 4. Poloidal flux contours of ST plasma under intermittent ST merging operation in TS-4U ST merging experiment. The contour evolution shows one cycle of additional small ST plasma formation and merging with the main ST plasma after the first merging formation of the main ST plasma.

ST plasmas into the common flux of main ST plasma, completing the merging/ reconnection process. The decaying oscillation of I_{PF} intermittently produces small ST plasmas to merge with the main ST plasma. The ST formation time and the merging time intervals are controlled by the waveform of I_{PF}.

Figures 5(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 oscillations of poloidal coil (fluxcore) currents I_{PF}. The blue, red, and green curves indicate the intermittent merging operation with second and third merging events at 0.45, 0.55ms and that with second merging at 0.55ms, and that with second merging at 0.65ms, respectively. For comparison, the black curves show the operations without additional merging. The red curve corresponding to Fig. 4 indicates that the plasma current increases in the second merging/ reconnection phase, while the black curves do not have any plasma current increase. The plasma current and the toroidal flux are found to increase by 10-20% when the second and third ST plasmas merge

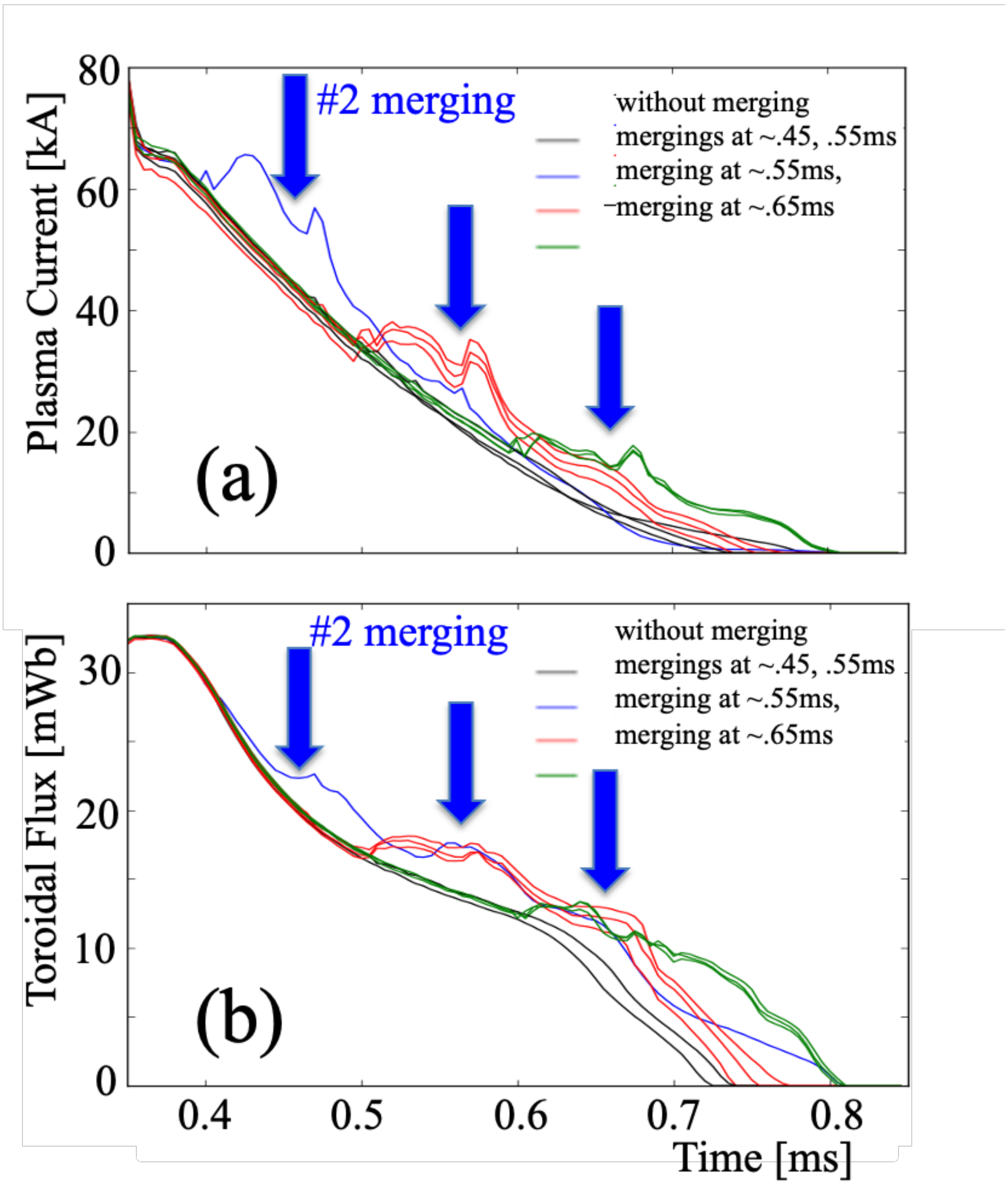

FIG. 5. Time evolutions of (a) plasma current I_{plasma} and (b) toroidal flux inside the separatrix for three types of intermittent merging operations, and that without intermittent merging after the merging formation of main ST plasmas. The black, blue, red, and green curves show the operation without additional merging, that with the second and third merging at ~0.45, 0.55ms, that with the second merging at ~0.55ms, and that with the second merging at ~0.65ms, respectively.

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 the decaying LC circuit oscillation of I_{PF} as the first demonstration of intermittent merging operation, we cannot control the flux/current of the secondary ST plasma. At present, the flux of secondary ST plasmas is too small to maintain the main ST plasma current.

Figure 6 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. 5, respectively. The mentioned ion Doppler spectroscopy is used to measure the core ion temperature which is averaged over about 30% of core poloidal flux area at around magnetic axis. In the intermittent merging 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 PF coil current I_{PF}. 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 clearly verified the ion heating effect of intermittent ST merging operation. Our PPCF 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 [4]. As shown in Fig. 4, our present intermittent merging operation takes time to compress the thickness of current sheet δ from 10cm to 2cm (on the order of ion gyroradius ρ_i). Its ion heating energy is still as low as 25% of the poloidal magnetic energy W_{mp}, because the merging is mostly for magnetic helicity injection in the major merging phase but becomes mostly for ion heating in the late merging phase.

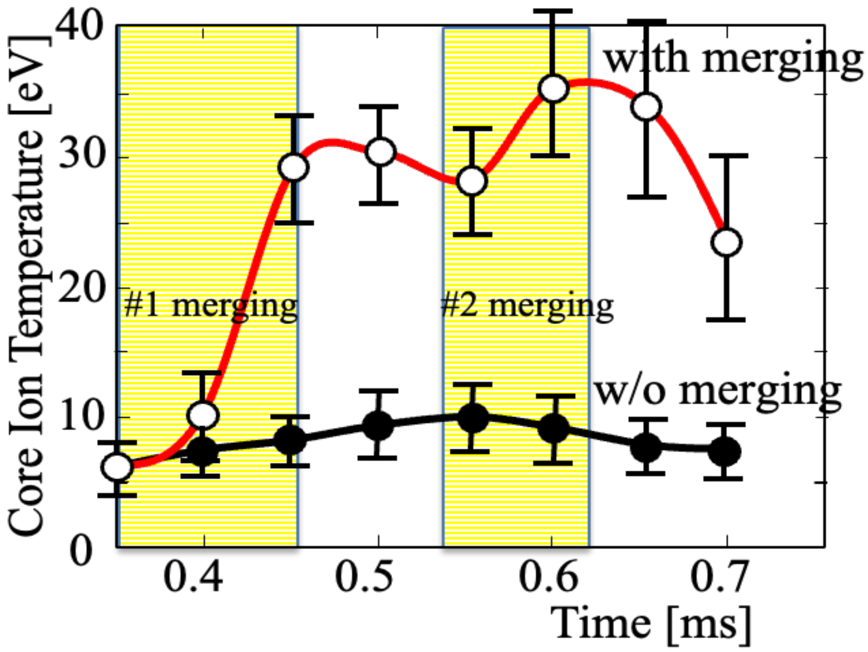

FIG. 6. Core ion temperature evolutions of ST plasma with intermittent merging corresponding to the red curves in Fig. 5 and that without merging corresponding to the black curves in Fig. 5.

4. CONCLUSIONS

In summary, our experimental results clearly indicate the current drive and ion heating effects of intermittent ST plasma merging operation. The ST plasma merging/ reconnection is 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 Nuclear Fusion paper [3] shows that a single merging of two tokamak plasmas can form burning plasmas which can be sustained by the bootstrap current based on the B_{rec}^2-scaling of reconnection ion heating [1-6]. The recent ST-40 experiments at Tokamak Energy Inc. used the ST plasma merging to obtain ion temperature T_i ~1-2keV which then increases to 9.6keV by additional usage of NBI heating. However, our scaling result indicates that we can obtain 10keV plasmas using the single merging of two tokamak plasmas. This paper also indicates 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 can make more detailed profile control of ST plasma using the intermittent merging operation.

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