Direct Access to Burning Spherical Tokamak Experiment by Pulsed High-Power Heating of Magnetic Reconnection

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Abstract. The merging/ reconnection startup of high-beta ST has been developed in the TS-3/4 experiments, leading us to its new extension to the pulsed high-power heating for burning plasma formation. Two STs were produced inductively by swing-down of two or four PF coil currents without using any center solenoid (CS) and they were merged together for high-power reconnection heating. The reconnection outflow speed equals to the Alfven speed under no guiding field condition. The outflow energy is converted mostly into ion thermal energy through ion viscosity and/or fast shock, indicating that the ion temperature increment (and the thermal energy increment) scales with squares of reconnecting magnetic field (Alfven speed). This unique method has the highest heating power MW-GW among all CS-less startups and the heating time much shorter than the energy confinement time and the electron-ion collision time. These facts indicate that the merging of two STs possibly provides a direct path to the burning plasma formation. The TS-3/4 scaling data suggest that two merging STs with B=1-3T, $n=10^{20}m^{-3}$ will be transformed into an ITER-like ST with T≈20keV within reconnection time.

1. Introduction

Since 1986, the reconnection startup of high-beta Spherical Tokamaks (ST) has been developed in the TS-3 and TS-4 merging experiments using high power heating of magnetic reconnection[1-7]. As one of the CS(center solenoid)-less startup, it provides highest heating power useful for ultra-high-beta ST and CT formation[1-7]. We initiated the first laboratory experiment of magnetic reconnection by use two merging toroids in 1986 and have already demonstrated the ST merging for initial heating and current drive and the counterhelicity merging of two spehrioamks for slow formation of FRC (Field-Reversed Configuration). The transformation of the produced FRC to ultra-high-beata ST was the first demonstration of the second-stable ST formation[6,7].

As shown in Fig. 1, two STs were produced inductively by swing-down operation of two (or four) PF (poloidal field) coil currents without using any center solenoid (CS), and they were merged together for high-power heating. Since 1994, the cohelicity merging of two or three STs has been demonstrated also in the START experiment for the ST startup [8-11] and its successful result with neutral beam (NB) heating was extended to the up-scaled experiment MAST[11]. However, it is noted that the detailed mechanism for reconnection

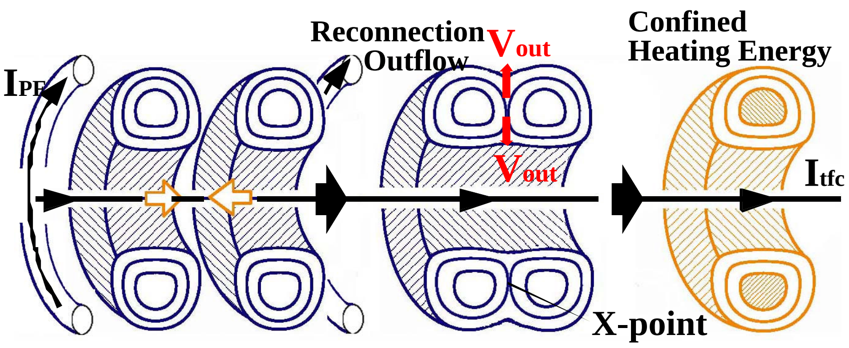

FIG.1. Merging startup/ heating of CT/ST by PF coil induction.

heating is left unsolved as well as its future perspective for pulsed high-power heating method for STs.

This unique method enables us to produce the highest heating power MW-GW among all CS-less startups, forming high-beta STs (20-50%) within short reconnection time[4,6,7]. It leads us to developing a new pulsed heating for high-beta ST formation. This heating process is caused by conversion from magnetic energy to plasma thermal energy during magnetic reconnection[4]. An important question arises as to whether this extremely high-power heating/ energy transformation realizes a direct access to the burning plasma regime or not. This paper addresses (1) heating energy scaling of reconnection/ merging, (2) characteristic time scale essential to this heating method, and (3) comparison with the other startup methods. We measured for the first time 2-D profiles of ion temperature (T_i) to calculate thermal energy increment during the merging startup. Finally, we found a promising scaling law of reconnection outflow heating. These facts lead us to more detailed study of pulsed merging formation of STs: (4) cause and mechanism for the ST formation by swing-down of PF coil currents, and (5) an optimised condition of external toroidal field B_t for the merging startup.

2. Experimental Setups

The axial merging of two STs was used to perform the CS-less startups of high-beta STs in the TS-3 device [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 sets of eight electrode pairs only for toroidal flux injection into low-q STs including spheromaks. Two STs with $R \approx 0.2$m $R/a \approx 1.5$ were merged together in the axial direction. The plasma heating powers for the ST mergings were ranging from 2MW to 30MW[6,7]. Each merging toroid initially had plasma parameters: $T_i \approx T_e \approx 10$eV, $n_e \approx 2\text{-}10 \times 10^{19}$m^{-3} and $B \approx 0.5$kG. Their

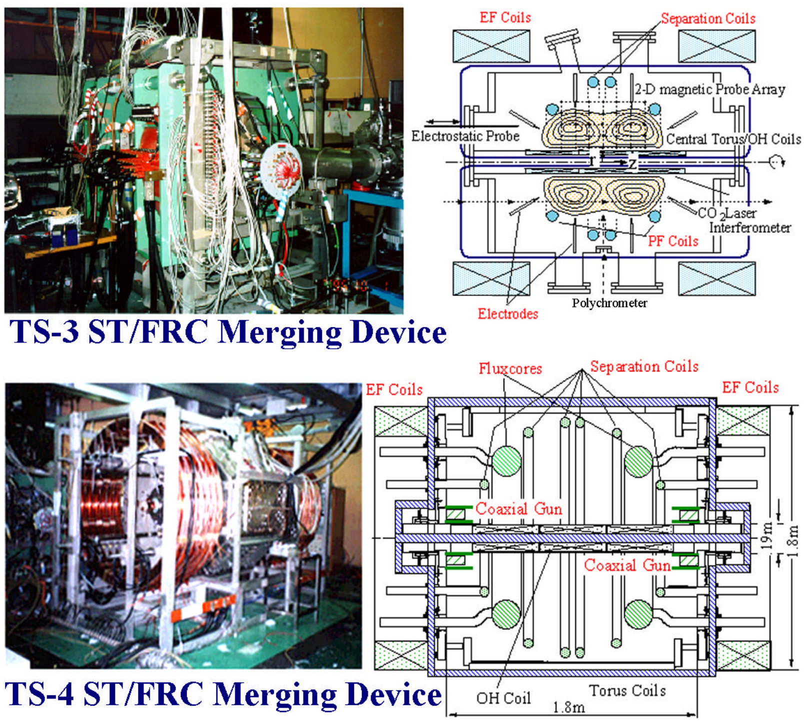

FIG. 2. Photos and vertical cross-sections of TS-3 and TS-4 ST/CT merging devices.

merging speed was controlled by magnetic pressure of the PF coil currents and 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 was used to measure radial profiles of ion temperature T_i and velocity V_i by means of the Doppler width and shift of herium and carbon lines. An electrostatic probe array was inserted to measure the radial profiles of electron temperature T_e and density n_e. Poloidal flux contours, current density profiles and plasma pressure profiles were calculated from those 2-D magnetic field profiles and T_i, T_e, and n_e profiles.

3. Experimental Results

The first question is why and how the merging/ reconnection produce the significant heating power for the high-beta ST formation. We have developed a new 2-D Doppler broadening measurement of ion temperature T_i using 72 (8×9) optical fibers, three polychromators and three ICCD cameras and found significant ion heating caused by reconnection outflow. Nine radial chords of line-integrated HeII spectrums were transformed into a radial T_i profile by use of the modified Avel inversion technique at eight axial positions. Figure 3 shows time evolutions of thermal energies W and core ion temperatures T_i for

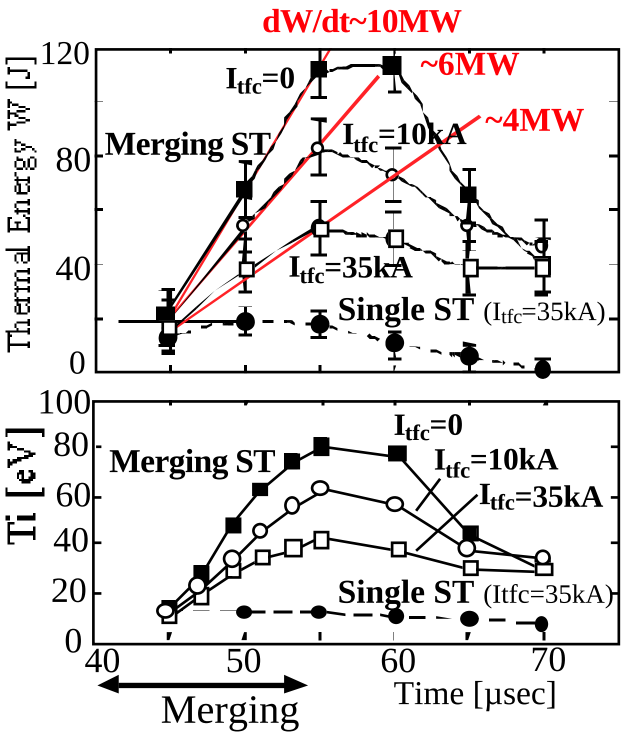

FIG. 3. Time evolutions of thermal energies W (a) and core ion temperatures T_i (b) of two merging STs with different I_{tfc} ($B_{t,ext}$), where W was calculated from measured profiles of T_i, T_e and n_e. (TS-3 experiment).

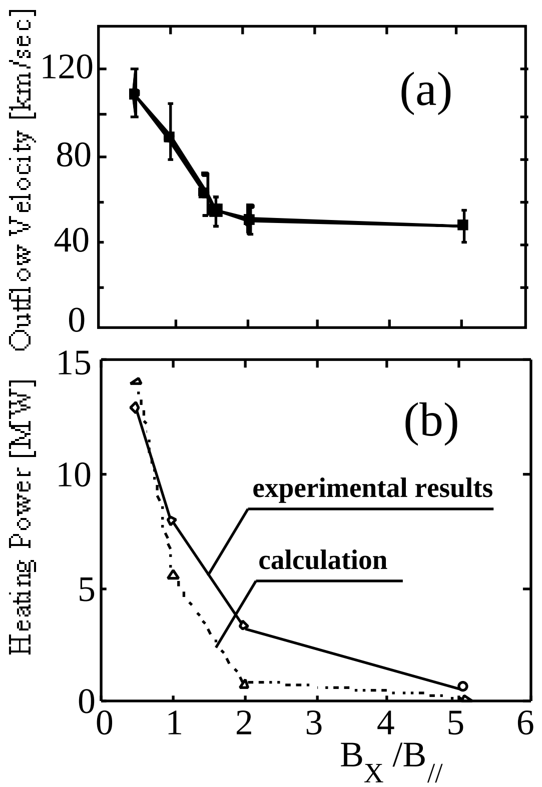

FIG. 4. Dependence of ion outflow velocity (TS-3 experiment) (a) and ion heating power (TS-3 experiment and calculation) (b) on guiding (toroidal) field B_x normalized by reconnecting field $B_{//}$.

mergings of two spheromaks (center toroidal coil current I_{tfc}=0), two low-q tokamaks (I_{tfc}=10kA) and two high-q STs (I_{tfc}=35kA). The rapid increases in total thermal energies W of two merging STs were calculated from the 2-D Doppler broadening measurement of T_i mentioned above and electrostatic probe measurements of T_e and n_e. The large heating power ranging from 4MW to 10MW was obtained during the magnetic reconnection of two ST plasmas. The 80-90% of the heating energy was caused by the ion heating effect of reconnection. The heating power increased inversely with q-value (or I_{tfc}), because the speeds of reconnection and outflow decreased with magnetic pressure of the guiding field B_X(=B_t) (or I_{tfc})[2-7].

Figure 4(a) shows the dependence of measured ion outflow velocity (experiment) (a) and ion heating power (experiment and calculation) (b) on guiding (toroidal) field B_X(=B_t) normalized by the constant reconnecting field $B_{//}$. The reconnection outflow (V_{out} in Fig. 1), was driven by pressure of reconnecting magnetic field. In agreement with the theory, the outflow speed was as fast as the Alfven speed under no guiding field B_X condition. During the reconnection, two hot T_i (≈70eV) spots were produced around two downstream areas of reconnection, indicating the ion heating by reconnection outflow similar to the solar coronal heating observed by Yohkoh satellite[12]. After the merging, the hot T_i area was spread out along the flux surfaces and was confined by the reconnected flux surrounding the whole X-point region. It is noted that the reconnected flux surfaces of merging STs confine the ion heating energy of reconnection, unlike the stochastic magnetic field lines in RFP plasmas with dynamo activity and anomalous ion heating. It is simply because the whole reconnecting area are surrounded by the reconnected closed field lines. The ion heating energy of outflow was estimated to be 80J in the case of I_{tfc}=10kA, which was much higher than the ohmic heating energy of current sheet ≈9J. Figure 4(b) compares measured and calculated values of the ion heating powers averaged over reconnection period. Using a classical viscosity, the ion heating power P is calculated from

$$P = \int \mathbf{v} \cdot div\Pi dV = \int \{\eta_D (div\mathbf{v})^2 + \eta_R (rot\mathbf{v})^2\} dV$$

where $\mathbf{v}$ is ion velocity, $\eta_R = 0.3 n_i T_i / \omega_{ci}^2 \tau_{ii}$, $\eta_D = \{1 + (\omega_{ci}\tau_{ii})^2\}\eta_R$ and n_i, T_i are ion

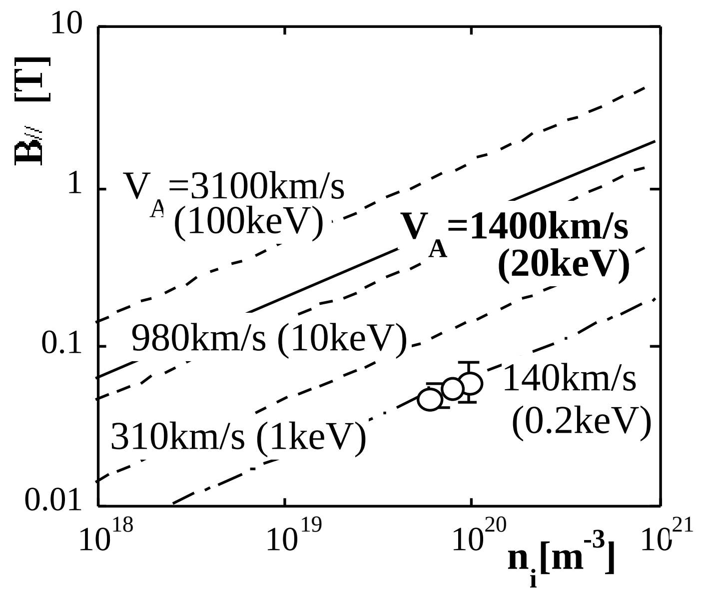

FIG. 5. Alfvenic outflow speed of reconnection in the space of reconnecting magnetic field $B_{//}$ and ion density n_i under no guiding field B_X(=B_t) condition. The data points represent maximum outflow velocities for two merging spheromaks with counterhelicity (I_{tfc}=B_X=0) in TS-3.

densities and temperatures. The ion heating power is consistent roughly with ion viscosity heating calculated from 2-D velocity (***v***) measurement by Mach probe array.

The next question is how the heating energy of reconnection/ merging can be upscaled for the future reactor size experiments. The magnetic reconnection was observed to transform the reconnecting field energy of merging toroids into ion thermal energy depending on its guiding (toroidal) field $B_X(=B_t)$ (or q-value). The most of magnetic energy is released by the reconnection outflow from the X-point area, as mentioned Ref. [4,5]. The reconnection outflow speed theoretically equals to the Alfven speed V_A, when the guiding (toroidal) field $B_X(=B_t)$ is zero. Merging of two spheromaks with counterhelicity had zero B_X at the X-point and its outflow was as fast as the Alfven speed, as shown in Fig. 5, in agreement with the theoretical prediction. The ion viscosity and/or fast shock are considered to convert the outflow kinetic energy into ion thermal energy $\Delta W_{th} \approx \Delta W_i$. This fact indicates that the ion temperature increment ΔT_i and the thermal energy increment ΔW_{th} scale with $B_{//}^2$ or V_A^2, as shown in the following equations:

$$\Delta T_i \approx \alpha\beta m_i V_A^2/\kappa = \alpha\beta B_{//}^2/\mu_0 n_i \kappa \qquad \text{and}$$

$$\Delta W_{th} \approx \Delta W_i = 3/2\int n_i k \Delta T_i dv = \alpha\Delta W_m = \alpha\beta W_m = \alpha\beta\int B_{//}^2/2\mu_0 dv,$$

where n_i, $B_{//}$, α and β are ion density, reconnecting component of magnetic field, conversion efficiency of dissipated magnetic energy ΔW_m into ion thermal energy ΔW_i ($0 \le \alpha \le 1$) and ratio of ΔW_m to reconnecting field energy W_m ($0 \le \beta \le 1$), respectively. Since ΔT_i as well the outflow speed decreases with the guiding field $B_X(=B_t)$, the β parameter represents the outflow slow-down effect of B_t. The α parameter also includes the confinement degradation (typically α=0.7-0.9 for STs and FRCs) during the merging process. In TS-3, $\alpha\beta$ was measured to increase from 0.1 to 0.8 with decreasing q_0 from three to zero. Figure 6 shows the increment of ion temperature ΔT_i during the magnetic reconnection as a function of the reconnecting field $B_{//}$. The experimentally measured core ion temperatures are also plotted for the no guiding field case (counterhelicity) and the high guiding field (high-q ST merging) case. Tßhe TS-3 and TS-4

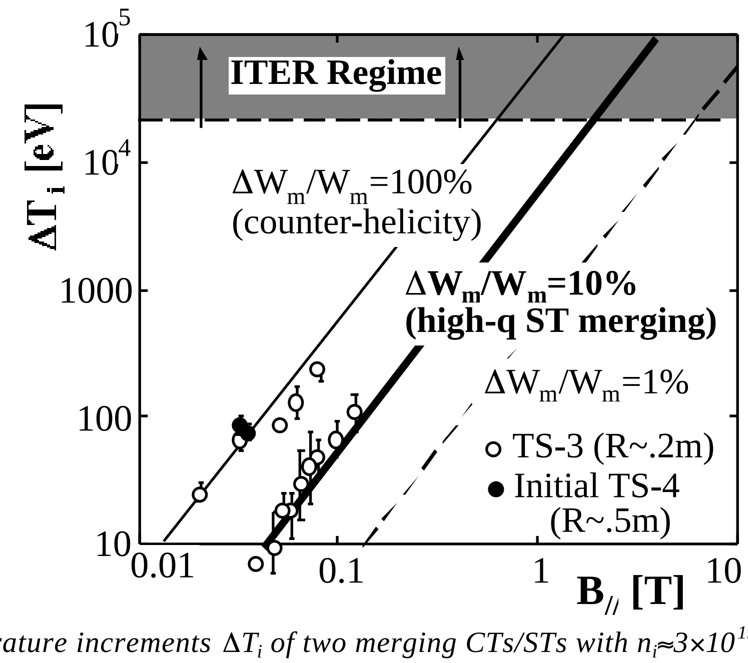

FIG. 6. Ion temperature increments ΔT_i of two merging CTs/STs with $n_i \approx 3\times10^{19} m^{-3}$ as a function of reconnecting magnetic field $B_{//}$. The data points were obtained from two merging spheromaks with counterhelicity and two merging STs in TS-3 and initial TS-4 experiments.

data in Figure 6 suggests that two merging STs with $B_p \approx B_{//}$=1-3T, n=10^{20}m^{-3} will be transformed into an ITER-like ST with $T_i \approx$20keV within reconnection time. It is noted that the ion gyroradius ρ_i $\sqrt{T_i}/B_{//}$ is kept constant when $B_{//}$ $\sqrt{T_i}$ is increased. The finite gyroradius effect does not affect the reconnection heating.

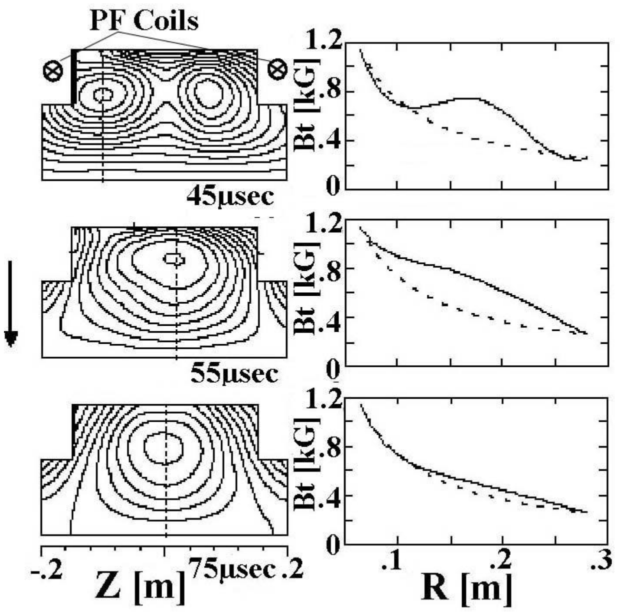

FIG. 7. Poloidal flux contours and radial B_t profiles during the merging startup. The dotted lines represent vacuum B_t (TS-3 experiment).

These facts lead us to more detailed study of the inductive ST formation and merging. Especially, an question is why the two STs with strong paramagnetic toroidal field are formed just by the poloidal flux swing of PF coils. Figure 7 shows the poloidal flux contours and radial B_t profiles during the ST formation and merging in the TS-3 experiment. Without toroidal flux injection, the PF coil induction was observed to produce large paramagnetic toroidal field B_t peaked around the magnetic axis (R≈0.18m) before the following merging process suppressed it by the high power reconnection heating. The internal toroidal flux Φ produced by

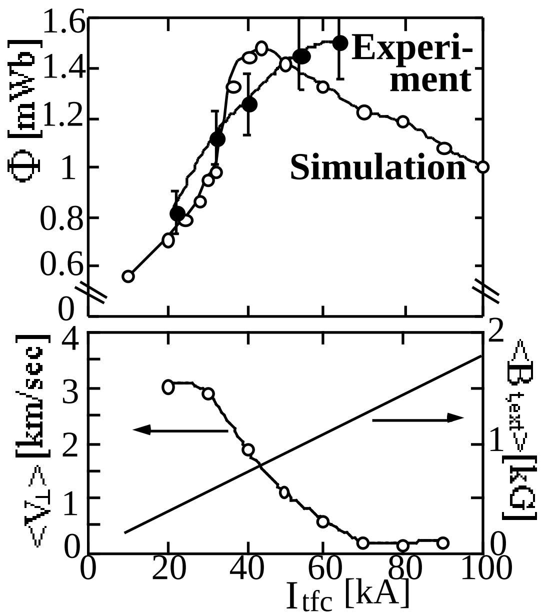

FIG. 8. Internal toroidal fluxes Φ (Top: TS-3 experiment & MHD simulation.), averaged velocity perpendicular to the flux surfaces and external toroidal field B_t (Bottom: MHD simulation) as a function of I_{tfc}.

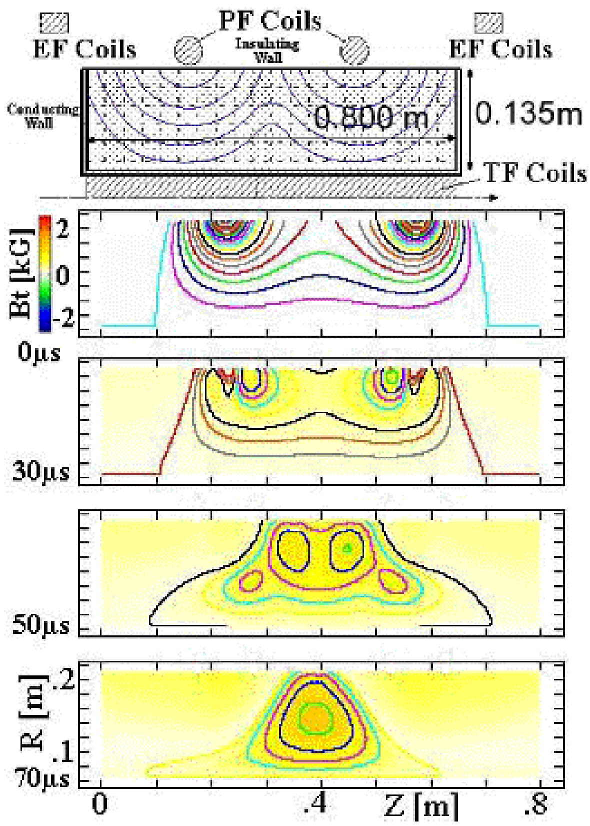

FIG. 9. Poloidal flux contours with internal B_t amplitude (color) during the ST merging startup (2-D MHD simulation).

poloidal plasma current I_p, increased with the center TF coil current I_{tfc} and saturated around I_{tfc}≈70kA, as shown in Fig. 8. The 2-D MHD simulation modeled the swing-down process of the PF coil currents in TS-3, as shown in Fig. 9. Its poloidal flux contours with B_t field amplitudes revealed generation of the internal toroidal flux Φ (or I_p). Large internal B_t shown by yellow color was generated by $\mathbf{v}\times\mathbf{B}_{t,ext}$ electric field, where **v** was plasma velocity perpendicular to magnetic surfaces and $B_{t,ext}$ was the external toroidal field by the TF coil current. The perpendicular velocity is caused by shrinking motion of poloidal flux during the swing-down of PF coil current. An important finding in Fig. 8 is that the maximum Φ: the most efficient operating condition was obtained around I_{tfc}≈40kA (q_0≈2) in the simulation. It was because the shrinking and merging speeds of poloidal flux decreased with $B_{t,ext}$, due to its toroidal field pressure. The experimentally measured Φ looks saturating around I_{tfc}≈70kA, probably due to longer flux decay time of high-q tokamak.

4. Discussions

The final question is how important the energy loss is during the reconnection heating. It is noted that the reconnection time τ_{MR} is much shorter than the confinement time τ_E. Ratio of the longest theoretical (Sweet-Parker) reconnection time $\tau_{S\text{-}P}$ to the resistive decay time τ_R (≈τ_E) is given by

$$\tau_{S-P}/\tau_R = (L/u)/(SL/V_A) = (L/V_A\sqrt{S})/(SL/V_A) = 1/\sqrt{S} = \sqrt{\tau_A/\tau_R}\ ,$$

where L, η, u, τ_A and $S = \tau_R/\tau_A = \mu_0 L V_A/\eta$ are the neutral sheet length comparable to the characteristic ST plasma size, sheet resistivity, inflow speed, Alfven time and the Lundquist number of sheet, respectively. The typical largest-scale STs have $S>10^7$, indicating $\tau_{S-P}/\tau_R < 3\times10^{-4}$. The anomalous resistivity of current sheet (typically observed) will further make τ_{MR} shorter than τ_{S-P} by another one or two orders. In the ITER-like parameter regime, τ_{MR} is also shorter than the equi-partition time τ_{ie} between electrons and ions. These facts indicate that the reconnection heating of two merging STs/CTs possibly provides a direct

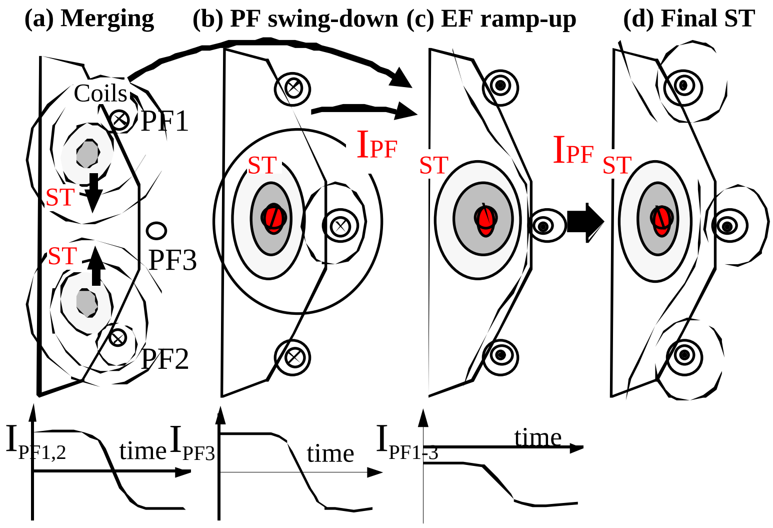

FIG. 10. Field lines and coil currents for (a) merging, (b) PF swing-down, (c) EF ramp-up startups.

path to the burning plasma regime transiently within $\tau_{MR} << \tau_R$, τ_E, τ_{ie}. After τ_{ie}, T_i will decrease by half. After τ_E, T_i will depend on τ_E and additional heating power. This method is useful probably for fast startup of the burning STs/CTs without or less using additional heating and also for experimental test of their confinement properties.

5. Summary and Conclusions

In summary, we extended the merging/ reconnection startup of ST into the burning plasma formation, by means of the significant ion heating power of reconnection outflow and the reconnection time shorter than the confinement time τ_E. This high-power/ electrode-less ST startup by axisymmetric merging has significant advantages over the present CHI, RF, PF-swing and EF-rampup startups. The RF startup needs the day order startup time and low density, while the merging has the shortest startup time≈1-100msec and no density limitation. Among the other inductive startup schemes, the merging method with the maximum linked flux between STs and PF coils has the maximum formation efficiency (Fig. 10(a)), in sharp contrast with the EF ramp-up with the minimum linked flux (Fig.10(c)). The merging startup uniquely provides the maximum heating power MW-GW and the multiple merging will further increases the plasma thermal energy ΔW_{th}. The CHI needs some 3-D reconnection between open and closed fluxes through 3-D deformation of flux tubes, indicating some of outflow energy is lost through the open field lines. The symmetric merging confines most of the heating energy by means of the closed reconnected flux surrounding the X-point region.

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