Ion and Electron Heating Characteristics of Magnetic Reconnection in TS-3 and UTST Merging Startup Experiments

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Abstract. The high-power heating of magnetic reconnection has been applied to the ultra-high-beta ST formation in the TS-3, TS-4 and UTST merging experiments. Two low-beta ST plasmas were formed inductively by two or four PF coils without using any central solenoid (CS) and were merged for high power MW-GW reconnection heating. Cause and mechanism for the reconnection heating were directly measured for the first time by two dimentional ion and electron temperature measurements. While electrons were quickly heated inside current sheet by its ohmic heating power, ions were heated in the downstream area by shock or viscosity damping of the reconnection outflow. The magnetic reconnection transformed the magnetic energy of reconnecting magnetic field to the ion thermal energy, increasing the plasma beta of ST up to 0.5.

1. Introduction

The axial merging of spherical tokamak (ST) has been optimized in TS-3 and TS-4 devices for high-power reconnection heating/ startup without center-solenoid (CS) coil [1-8] and was upscaled to UTST device[8]. As shown in Fig.1, two ST plasmas with major radius~0.2m (TS-3), 0.5m (TS-4) were merged together in the axial direction under magnetic compression provided by two acceleration coils. Based on this merging toroids, we initiated the first laboratory experiment of magnetic reconnection in 1986 and have studied causes and mechanisms for fast reconnection observed during the ST merging. For the past 20 years, our TS-3 and TS-4 experiments explored the ST merging startup for high-power reconnection heating/ startup without center-solenoid (CS) coil[7,8]. The magnetic reconnection was found to transform the magnetic energy of reconnecting magnetic field through the outflow energy finally to the ion thermal energy, increasing the plasma beta of ST up to 50%. The counterhelicity merging of two spehrioamks is now used widely 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[7,8]. Since 1994, the cohelicity merging of two or three STs has been demonstrated also in the START experiment for the ST startup[9-12] and its successful result with neutral beam (NB) heating was upscaled to the largest-class ST experiment: MAST[12].

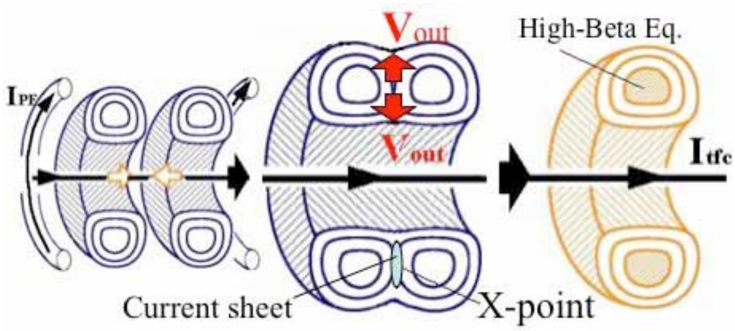

FIG. 1. Magnetic reconnection heating by two merging ST plasmas and their current sheet and reconnection outflow.

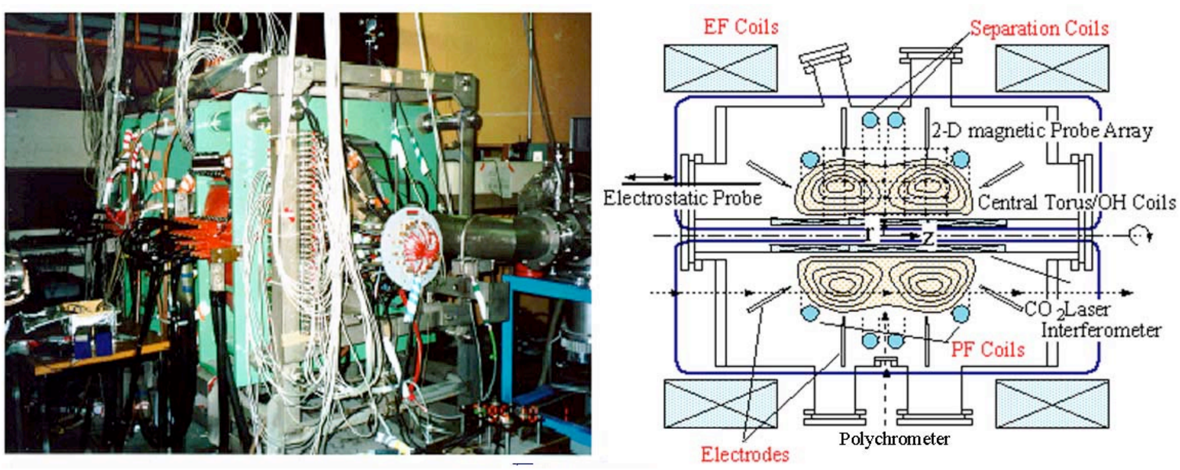

FIG. 2. Photo and cross-section of TS-3 merging devices with a pair of PF and separation coils.

An important question then arises as to how and why the reconnection transformed the reconnecting magnetic field energy into ions and electron thermal energies. It is noted that the heating mechanisms of ions and electrons are left unsolved, which is essential to the high-power reconnection heating. Provided that the reconnection speed is maximized under high-guiding field condition, this unique method provides the most economical and highest-class heating power MW-GW among all CS-less startups, forming high-beta STs (20-50%) within short reconnection time[4-8]. This paper addresses (1) places where ions and electrons are heated by magnetic reconnection, (2) ion heating mechanism by reconnection outflow in the downstream and its dumping mechanism, (3) electron heating mechanism inside the current sheet, and (4) reconnection heating properties for high-beta ST startup. We found for the first time that strong ion heating in the downstream of magnetic reconnection similar to the solar flare and electron heating inside the current sheet. These facts lead us to a new pulsed merging startup experiment, UTST using the reactor-relevant external coils.

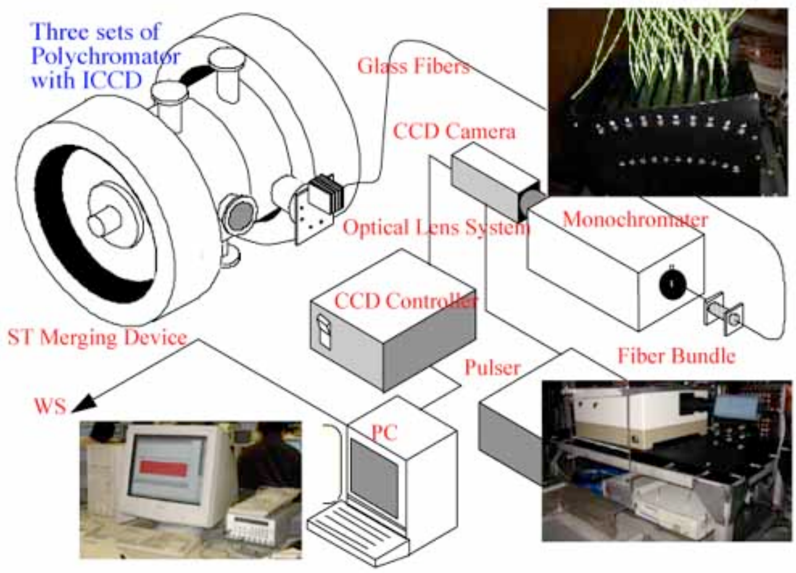

FIG. 3. 36 channel Doppler spectrometer system for 2-D ion temperature measurement on r-z plane.

2. Experimental Setups

The TS-3 device has demonstrated the CS-less startups and merging/ reconnection heating for high-beta STs formation [1-8]. As shown in Fig. 2, its cylindrical vacuum vessel with length of 1m and diameter of 0.8m has two PF coils for poloidal flux injection. Two produced ST plasmas with R≈0.2m R/a≈1.5 were merged together in the axial direction for their initial heating whose power ranges from 2MW to 10MW[7,8]. Before the merging, the two STs had plasma parameters: $T_i \approx T_e \approx 10$eV, $n_e \approx 2\text{-}5\times10^{19}\text{m}^{-3}$ and $B_t \approx 1.5$kG. Their merging/ reconnection was accelerated by the fluxcore 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. The poloidal flux contours, current density profiles and plasma pressure profiles were calculated from the measured 2-D magnetic field profiles. The current sheet was identified by the measured toroidal current density profile j_t and X-point structure.

A new 2-D ion temperature T_i diagnostics was developed by combining the Doppler broadening measurement with the (vector) tomography technique[13]. The 2-D line-integrated data of spectral lines were measured by 36 optical fibers, polychromators and ICCD cameras, as shown in Fig. 3. They were transformed into local T_i data using the tomography reconstruction (Avel inversion) at each wavelength. Each Doppler width of spectrum line was calculated by the Gausian function fitting algorithm to plot 2-D profile of T_i on r-z plane. The 2-D electron temperature profile was also measured by 2-D electrostatic probe array inserted on the r-z plane. Triple probes were used to measure electron temperature T_e and density n_e without assuming the plasma reproducibility.

3. Experimental Results

Figure 4 shows the poloidal flux contours of two merging ST plasmas whose center q-value was about 2. Two STs were merged together due to their parallel plasma currents and reversed currents of PF coils. Their reconnection time was as short as 20μsec, which almost equals to the Sweet-Parker reconnection time with measured anomalous resistivity. It was found that the large paramagnetic toroidal magnetic field of initial STs was suppressed by the large pulsed plasma heating of reconnection / merging. About 20% of magnetic energy of merging STs was transformed mainly into ion thermal energy.

The 2-D ion temperature T_i measurement was based on combination of the Doppler broadening measurement and the (vector) tomography technique[13]. The 2-D line-integrated data of spectral lines were measured by 36 optical fibers, a polychromator and an ICCD camera, and were transformed into local T_i data using the tomography reconstruction at each wavelength.

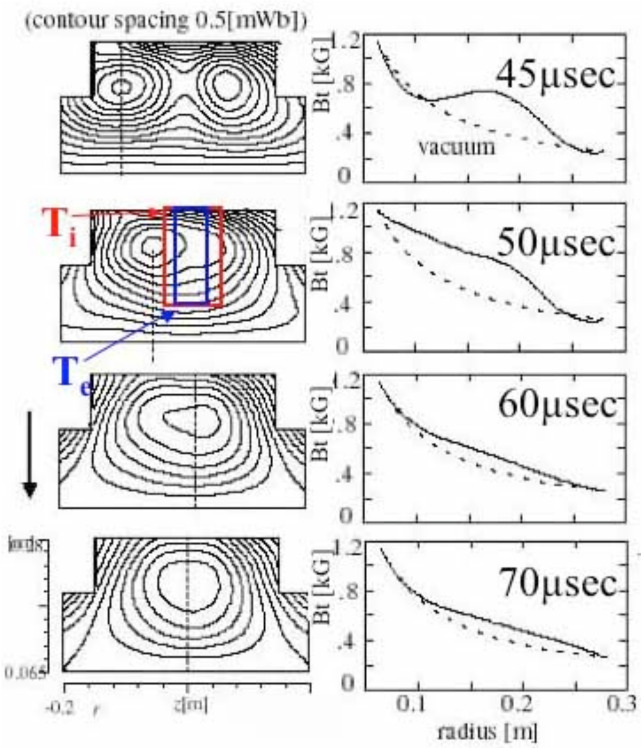

FIG. 4. r-z contours of poloidal flux and radial toroidal field B_t profiles of merging high-q ST (I_{tfc}=35kA) measured by 2-D magnetic probe array.

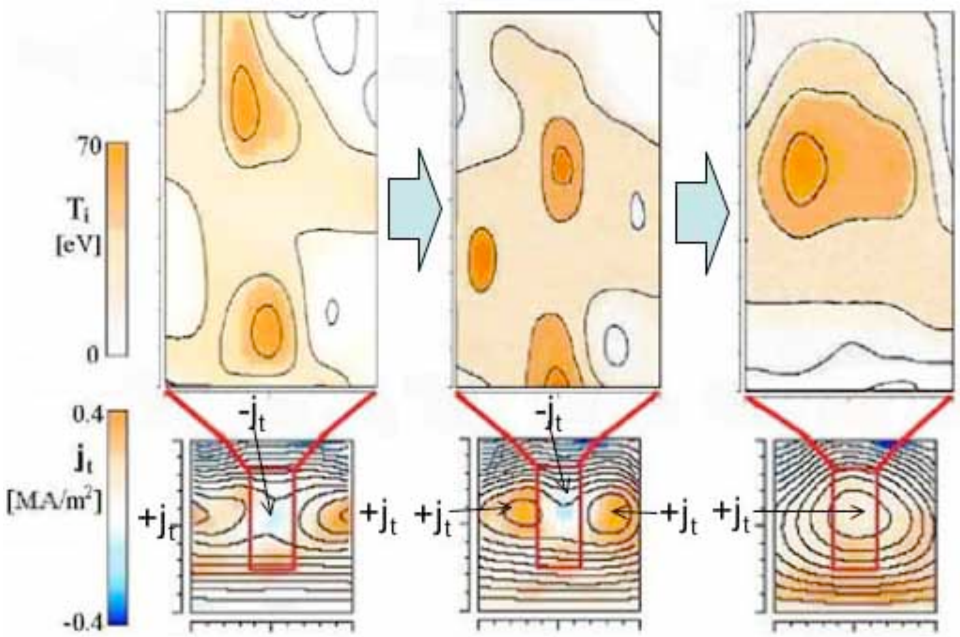

FIG. 5. r-z contours of ion temperature during high-q ST merging (I_{tfc}=35kA) which was reconstructed from 2-D Doppler broadening measurement (top) and corresponding 2-D contours of poloidal fluxes measured by 2-D magnetic probe array on r-z plane (bottom).

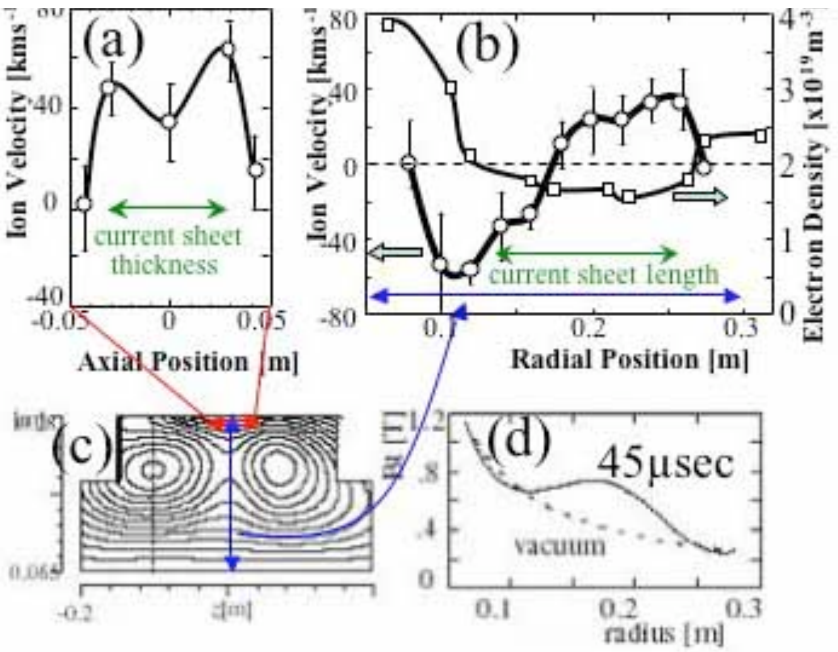

FIG. 6. Axial and radial profiles of reconnection outflow velocities measured by 1-D scan of Doppler probe array together with axial electron density profile (a),(b) and r-z contours of poloidal flux and radial toroidal field B_t profiles of merging high-q ST (I_{tfc}=35kA) measured by 2-D magnetic probe array (c), (d).

A new finding is that the magnetic reconnection heats ions in the down-stream area and electrons in the current sheet, respectively. Figure 5 top shows the time evolution of 2-D ion temperature T_i contour during and after the high-q ST merging. Corresponding 2-D polodal flux contours measured by 2-D magnetic probe array are also shown in the bottom. During the reconnection, two hot spots were clearly formed in two downstream areas of reconnection. The ion temperature of the current sheet was higher than that of the upstream area but still lower than that of the downstream area. The high temperature area was extended along the magnetic field lines, forming four-leg high temperature area. The most probable interpretation for this phenomenon is that the bipolar reconnection outflow collided with the closed (reconnected) field lines surrounding the hot spots. It suggests that some damping mechanism of reconnection outflow must exists in the downstream area.

Figures 6(a) and (b) show axial and radial profiles of ion velocities measured by Doppler probe during the ST merging. They clearly show the bipolar reconnection outflow ejecting plasma inward and outward from the current sheet in agreement with the conventional reconnection model. The maximum outflow speed was about 40km/sec, which was about 70-80% of the local Alfven speed. The bipolar outflow was accelerated up to 40km/sec at both ends of current sheet and then was decelerated abruptly down to zero at around r=0.1, 0.25m. Around these points, the electron density n_e changes abruptly together with the magnetic field strength. the Rankine-Hugoniot relations. The fast shock and/or ion viscosity are the most probable damping mechanism of reconnection outflow. The measured heating power ~4MW roughly agrees with that calculated from classical viscosity. Using a classical viscosity, the ion heating power P is calculated from

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

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 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 hard X-ray image of solar flare reconnection also revealed the similar hot spots in the downstream area[14]. Though the solar satellite cannot measure detailed ion temperature profile around the reconnection point, this fact suggests that similar damping mechanism of outflow causes the coronal heating. As shown in Fig. 5, the heated ions were spread out along the flux surfaces and were mostly confined inside the produced ST. In Fig. 4, the large paramagnetic B_t of merging STs observed at 45μsec was fully suppressed in the produced ST at 60μsec, in agreement with the measured increase in beta from 5% to 40%. It is noted that the hot T_i area in the downstream is fully surrounded by the thick closed flux surfaces. It is simply because the reconnection proceeds from the peripheral field line to the core lines in the case of two ST merging. The hot ions heated by reconnection are confined after the completion of merging in sharp contrast with the anomalous ion heating observed in RFP plasmas. Their sawtooth activities tend to reconnect the internal field

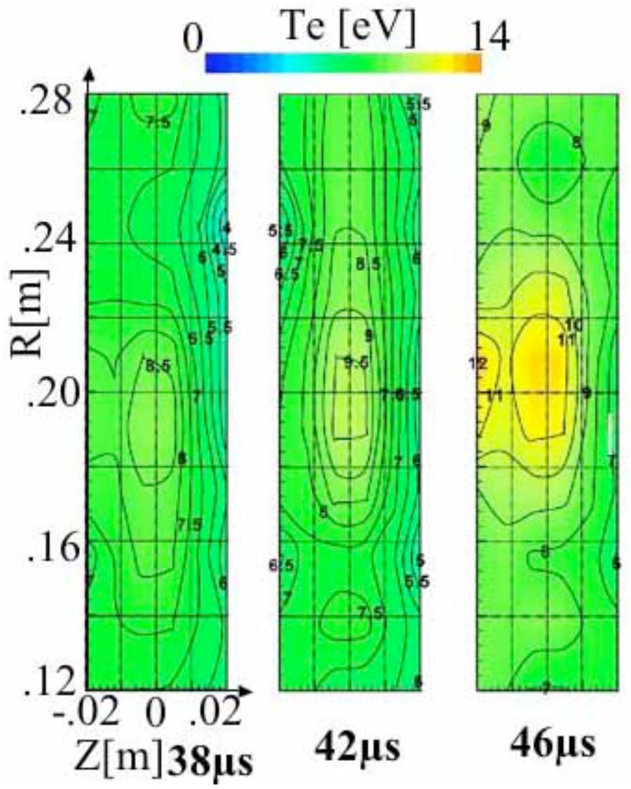

FIG. 7. r-z contours of electron temperature around the current sheet during high-q ST merging (I_{tfc}=35kA).

lines to the open field line outside the separatrix.

Another finding is that electrons were heated inside the current sheet unlike ions. Figure 7 shows r-z contours of electron temperature T_e during the high-q ST merging. The scanning electrostatic probe array was used to measure the blue-line squared area in Fig. 4. While T_e outside the sheet was uniformly 5-6eV, it clearly peaked inside the current sheet. The ohmic heating power is the most probable cause for this electron heating inside the current sheet. Figure 8 shows the time evolutions of averaged T_i and T_e and total thermal energy calculated from these profiles. It is noted that electrons are heated earlier than ions. While electrons are quickly heated by ohmic heating power of current sheet, the ion heating needs more time probably for damping process of reconnection outflow. The viscosity / shock heating by outflow is the most probable cause for the anomalous ion heating. The ion heating power ~4MW was an order of magnitude larger than the electron heating power ~0.2MW. This heating mechanism is consistent with the B^2-scaling (B: poloidal field) of reconnection heating energy[8], because the outflow speed V_{out} is equal to the Alfven speed $B/(m_0 m_i n_i)^{1/2}$ in the Sweet-Parker model. As shown in Fig. 8, the T_i increment increases inversely with B_t and center coil current I_{tfc}, because toroidal field B_t slows down the reconnection outflow.

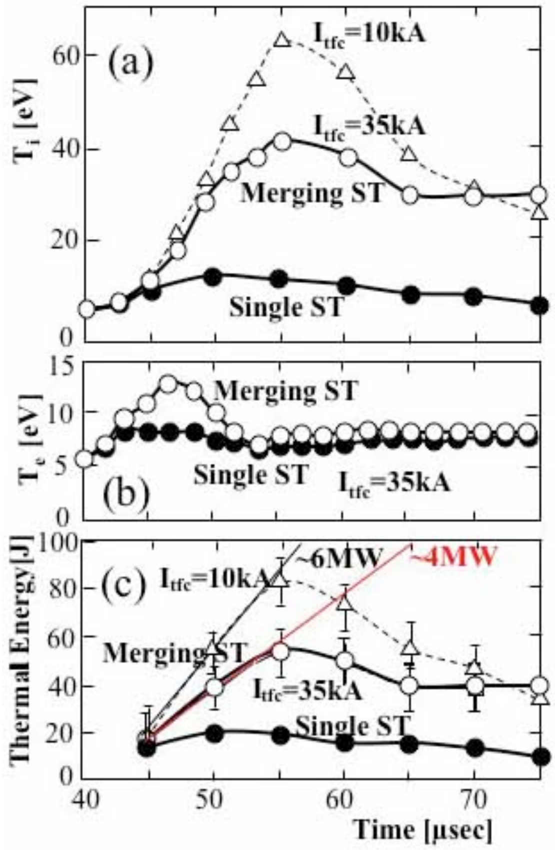

FIG. 8. Time evolutions of averaged ion and electron temperatures T_i, T_e and total thermal energies of single and merging high-q STs with I_{tfc}=35kA. Those for low-q ST with I_{tfc}=10kA are shown by dotted lines.

4. Upscale Experiment: UTST of the Merging Startup

Based on the merging startup experiment in TS-3, we constructed a new upscaled ST device: UTST (R~0.4m) and is now upgrading its power supply. Its technical basis is composed of merging/ reconnection techniques of TS-3 and TS-4, the RF heating/ current drive techniques of TST-2 and NBI techniques of AIST[15] and Nihon University/ Osaka University[16]. As shown in Fig. 9, the UTST device has cylindrical vacuum vessel with R=0.7m and Z=2.5m. The UTST device has all PF coils outside of the vacuum vessel to

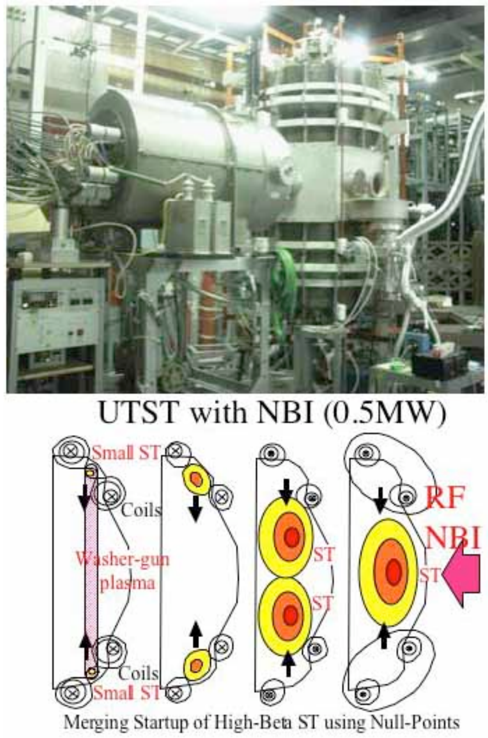

FIG. 9. Recent UTST device with NBI (0.5MW) and its merging startup scheme.

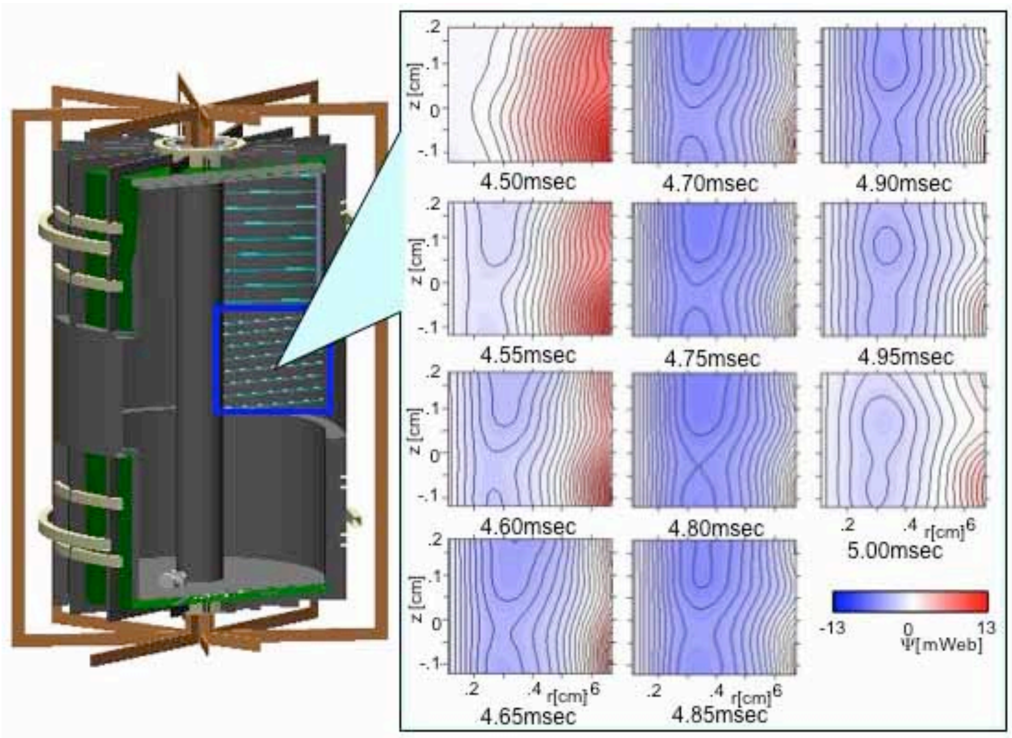

FIG. 10. Merging ST startup experiment of UTST: time evolution of poloidal flux contour of merging ST plasmas measured by the removable 2-D array of magnetic probe.

demonstrate (1) double-null startup of STs without CS coil, (2) their high-power reconnection heating for high-beta ST formation and (3) their sustainment by advanced NBI and RF techniques. In our initial experiment, the merging process was directly measured by a removable 2-D array of magnetic probe located on r-z plane. Figure 10 shows the time evolution of poloidal flux contour during the two ST merging startup in UTST experiment. Under the preionized plasma of washer gun, two ST plasmas were formed by induction of four PF coils and were merged together in the axial direction. The merging process was observed to complete within 0.3msec. The initial experiment realized plasma current 40kA without CS and 120kA with CS. The mega-watt heating power of reconnection is expected to transform the initial low-beta merging STs to the high-beta ST (>30%).

5. Summary

We studied causes and mechanisms for ion and electron heating of magnetic reconnection in the merging ST experiment by use of 2-D ion and electron temperature measurements. The 2-D ion temperature (T_i) profile was measured by a new type 2-D Doppler tomography diagnostics composed of polychromators with ICCD cameras, optical fibers and lens system. The 2-D electron temperature profile was also measured by 2-D array of electrostatic probes. The magnetic reconnection is concluded to heat plasma ions around the downstream area by its own reconnection outflow whose speed is as high as Alfven speed. The fast shock structure was observed around the hot T_i area, indicating the most probable dumping mechanism for reconnection outflow. On the other hand, the reconnection heats electrons inside the current sheet, indicating that the ohmic heating of sheet current is the most probable cause for the electron heating. The ion heating power of reconnection is an order higher than the electron heating power, while the electron heating occurs earlier than the ion heating probably due to the outflow dumping process. In the present half kG (poloidal field) reconnection experiment, the reconnection heating power is about 4MW, which is as high as the largest-class neutral beam injection (NBI). The heating power was observed to increase with the external compression force for the merging STs and inversely with the toroidal magnetic field. It is noted that the reconnection transforms a part of poloidal magnetic energy into ion and electron energies within the short Sweet-Parker reconnection time. This energy conversion transforms the low-beta ST (beta~5%) into the high-beta ST (beta~40%). Based on those reconnection heating experiments of TS-3 and TS-4, we completed the new reactor-relevant upscaled experiment UTST and is now increasing the capacitor bank energy. In the initial experiment, the merging startup of ST plasma was demonstrated for the first time by the external PF coils. Two ST plasmas were produced by the external coils and completed their merging within 0.3msec. The mega-watt heating power of reconnection is expected to transform the initial low-beta merging STs to the high-beta ST (30-50%). A new high-power (0.5MW) NBI system was installed on the horizontal port of UTST, in order to maintain the high-beta state produced by the merging for several msec.

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