SCALING STUDY OF RECONNECTION/ MERGING HEATING OF SPHERICAL TOKAMAK PLASMAS FOR DIRECT ACCESS TO BURNING PLASMAS

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Abstract

The high-power reconnection heating of ST plasma has been developed in TS-3, TS-4 and MAST experiments, leading us to direct access to burning plasma. This unique method is caused by the promising scaling of ion heating energy that increases with square of reconnecting magnetic field $B_{\text{rec}}$. We studied mechanisms for this $B_{\text{rec}}^2$-scaling of reconnection (ion) heating mainly using TS-3U (TS-6) experiment and PIC simulations and found the following issues:

(i) the ion heating energy is as high as ~40-50% of poloidal magnetic energy of two merging ST plasmas, (ii) the ion heating energy is not affected by (guide) toroidal field $B_t$, in the region of $B_t/B_{\text{rec}}>1$ under two conditions: (a) compression of current sheet to ion gyroradius $\rho_i$ and (b) full-isolation of the merging ST plasmas from coils and walls. The sheet compression to $\rho_i$ was found to be a key condition to realize the fast reconnection as well as the high power ion heating consistent with the $B_{\text{rec}}^2$-scaling prediction. Under this condition, the ion heating energy is determined uniquely by $B_{\text{rec}}$, not by $B_t$ in the conventional tokamak operation region: $B_t/B_{\text{rec}}>1$. The merging ST plasmas need to be fully pinched off from the PF coils for the purpose of minimizing loss of the hot ions heated by the reconnection/merging. This promising scaling is expected to realize the burning plasma temperature $T_i > 10\text{keV}$ (under electron density $n_e \sim 1.5 \times 10^{19} \text{[m}^{-3}\text{]}$) just by increasing $B_{\text{rec}}$ over 0.6T, leading us to construction of new high-$B_{\text{rec}}$ field merging ST devices: TS-6 in U. Tokyo and ST-40 in Tokamak Energy Inc.

1. INTRODUCTION

We have been investigating toroidal plasma merging for high-power heating of spherical tokamak (ST) and field-reversed configuration (FRC) [1-14]. As shown in Fig. 1(a), we axially merge two STs, forming an X-point at their contacting point (Fig. 1(b)) and finally a new high-beta ST. The series of merging experiments: TS-3U (TS-6) (ST, FRC: R=0.2m), TS-4U (ST, FRC: R=0.5m), UTST (ST: R=0.45m) and MAST (ST: R=0.9m) made clear the promising scaling of reconnection heating: the ion temperature increment $\Delta T_i$ scales with square of the reconnecting magnetic field $B_{\text{rec}} \sim B_p$ (poloidal field), under constant density $n_e \sim 1.5 \times 10^{19} \text{[m}^{-3}\text{]}$ [1, 12]. This fact suggests that
the axial merging of two STs possibly obtain the burning plasma temperature $T_i \sim 10\text{keV}$ without using any additional heating like neutral beam injections (NBIs) [12, 13]. An important question then arises as to what are the necessary conditions for this $B_{rec}^2$-scaling of reconnection heating of ions. If plasma inflow is set low, the ion heating should be quite small.

Figure 2(a) shows dependence of ion temperature increment $\Delta T_i$ on the reconnecting magnetic field $B_{rec}$ for all merging STs under the constant electron density $n_e \sim 1.5 \times 10^{19} \text{m}^{-3}$ in TS-3, TS-4 and MAST. This $B_{rec}^2$-scaling was extended over 1.2keV in TS-6 and MAST experiments made by Culham-Univ. Tokyo collaboration[12-15]. The ion temperature increment $\Delta T_i$ was found to depend just on the reconnecting magnetic field $B_{rec}$ and not or little on the (guide) toroidal field $B_t$, if we turn on the fast reconnection by compressing thickness of the current sheet to the order of ion gyroradius $\rho_i$ [15].

![Figure 2](image-url)

**FIG. 2** Dependence of ion temperature increment $\Delta T_i$ on reconnecting magnetic field $B_{rec}$ of merging STs and spheromaks under constant electron density $n_e \sim 1.5 \times 10^{19} \text{m}^{-3}$[15].

### 2. EXPERIMENTAL SETUPS

The TS-3U (TS-6) device has been used to study the merging/ reconnection startup for high-beta torus plasma. As shown in Fig. 3, its cylindrical vacuum vessel with length of 1m and diameter of 0.8m has two

![Figure 3](image-url)

**FIG. 3** Photo and vertical cross-section of high magnetic-field merging device: TS-6 with 2D magnetic probe, 2D ion Doppler tomography and 2D Thomson scattering measurements.
poloidal field (PF) coils for poloidal flux injection in order to merge two torus plasmas with major radius \( R \approx 0.2 \text{m} \) and aspect ratio \( R/a \approx 1.5 \) together in the axial direction. Each merging toroid initially has the plasma parameters: \( T_i, T_e \approx 10 \text{eV}, n_e \approx 1-8 \times 10^{19} \text{m}^{-3} \) and magnetic field \( B \approx 1 \text{kG} \). The center toroidal coil is used to apply external toroidal field to the merging torus plasmas. Their merging/ reconnection process is caused mainly by attractive force between their parallel toroidal plasma currents. It is accelerated by magnetic pressures of the PF coil currents and decelerated by those of the separation coil currents on the midplane.

Nine thin arrays of magnetic pickup coils were inserted in the R-Z plane of the vessel for the purpose of measuring directly the 2D magnetic field profile. Their maximum spatial resolution is 5mm in the axial direction and 3cm in the radial direction. The poloidal flux contours, 2D profiles of current density and plasma pressure are calculated from the measured 2D magnetic field profiles. A 1m polychromator with an optical multi-channel analyser (OMA) was used to measure 2D profiles of ion temperature \( T_i \) by means of the Doppler widths of helium and carbon impurity lines. We used the Abel inversion to transform the measured line-integrated plasma emissivity of HeII line to local one at each wavelength, deducing 2D ion temperature profile in the R-Z plane [16]. We also used a Doppler probe to measure the local Doppler shift and broadening of HeII line for local ion velocity and temperature measurements. A 1-D Mach probe array and electrostatic probe array are scanned on the R-Z plane to measure 2D profiles of plasma flow vector \( \mathbf{v} = (\mathbf{v}_r, \mathbf{v}_z) \), electron density \( n_e \) and temperature \( T_e \) [1,11-15].

3. **EXPERIMENTAL RESULTS**

3.1. **Ion and electron heating mechanisms of magnetic reconnection**

The middle left panel of Fig. 4 shows 2D poloidal flux contours of two merging tokamak plasmas in TS-3...
3 merging experiment. Two ST plasmas with parallel toroidal currents were formed by induction of two poloidal field (PF) coils under uniform equilibrium field and collide together due to their attractive force. Their colliding speed is varied by use of reversed currents of the two PF coils for their acceleration and those of the separation coil current for their deceleration. Its guide toroidal field $B_g$ is about five times larger than the reconnection magnetic field $B_{rec}$. The magnetic reconnection occurs at the contacting point (or line) of two ST plasmas, transforming the reconnecting magnetic energy into plasma thermal and kinetic energy.

The top left panel of Fig. 4 shows 2D ion temperature profile inside the red square in the flux plot, which was measured by 2D Doppler tomography system developed. It clearly indicates that the reconnection heats plasma ions in the downstream. More detailed ion flow, temperature, density and magnetic field measurements indicates the plasma ions are heated in the two downstream areas by the reconnection outflow through some shock-like structures and ion viscosity [1].

The bottom left panel of Fig. 4 shows 2D electron temperature profile inside the blue square in the flux plot, which was measured by electrostatic probe array. It indicates that the reconnection heats plasma electrons inside the current sheet probably due to its Ohmic heating power. The ion heating energy is about five times larger than the electron heating energy probably because the dump of reconnection outflow in the downstream areas is global phenomenon while the Ohmic heating of current sheet is local one.

We made the corresponding 2D Particle-in-Cell: PIC simulations using the slab model that has driven-type boundary in the upstream and open boundary in the downstream [17-19]. The top right and the bottom right panels of Fig. 4 show 2D ion and electron temperature profiles during the reconnection with the guide field $B_g = 4B_{rec}$. It clearly indicates the ion heating in the downstream and electron heating inside the current sheet in qualitative agreement with our experimental results.

After the merging is over, the most of heated ions are confined inside the produce ST plasmas, because the reconnection (X-) point is surrounded by the thick reconnected flux. We often observed the sawtooth-type oscillation of ion temperature in RFP and tokamak plasmas, indicating that most of heated ions were lost through their X-point region close to the boundary. Also in the PIC simulation, the ion heating energy is confirmed to be two or three times larger than the electron heating energy. Since the PIC simulation used the small mass ratio of 100 and the slab model configuration, it is difficult to compare the simulation results quantitatively with TS-3 and TS-6 merging tokamak experiments.

### 3.2. Onset of fast reconnection in TS3U merging experiments and PIC simulations

Figure 5(a) shows time evolutions of reconnection electric field $E_{rec}$ at X-point, thickness of current sheet $\delta$ and ion gyroradius $\rho_i$, which are calculated from measured magnetic FIG. 5 Time evolutions of reconnection electric field $E_{rec}$, thickness of current sheet $\delta$ and ion-gyroradius $\rho_i$ at reconnection (X) point during two ST plasma merging ($\bigcirc \square \triangle$ represent those data points, respectively,) and (b) those of $E_{rec}$, $\delta$ and ion-meandering size $\rho_{im}$ in 2D PIC simulation with $B_g/B_{rec} = 4$ [18].
field $B$ (mainly toroidal magnetic field $B_t$) and ion temperature $T_i$ during the reconnection in TS-3U ST merging experiment with guide toroidal field $B_t$ is about five times larger than the reconnecting magnetic field $B_{rec}$. The magnetic field $B$ and ion temperature $T_i$ profiles were measured by 2D magnetic probe array and 2D ion Doppler tomography system, respectively. Figure 5(b) shows those of $E_{rec}$, $\delta$ and ion-meandering size $\rho_{im}$ in 2D PIC simulation of slab model reconnection with $B_t/B_{rec}=4$ [3]. We adopt an open boundary condition in the PIC simulation, where magnetic fields freely expand from the downstream region and plasmas cannot re-enter the diffusion region after they pass through the reconnection region. Plasmas encounter energy conversion events only once just like our merging experiments. The mass ratio 100 was used for this PIC simulation [18].

In both of the experiment and the PIC simulation, the reconnection electric field $E_{rec}$ increases significantly from the initial low levels to the higher levels (fast reconnection) when we compress the thickness of current sheets $\delta$ to the order of ion gyroradius $\rho_i$ in TS-3U experiment or to the order of ion meandering size $\rho_{im}$ in the PIC simulation. The large increase in reconnection electric field $E_{rec}$ at X-point is due to significant change in ion orbit and related negative potential well formation in the downstream [3]. Our experiments and simulations agree well that we can turn on the fast reconnection with large reconnection electric field $E_{rec}$ by compressing thickness of the current sheet $\delta$ to the order of ion gyromotion scale $\rho_i$ or $\rho_{im}$.

It is noted that high $B_t$ reconnection needs high compression force to compress the current sheet to $\rho_i$ or $\rho_{im}$. However, the ST plasmas with center $q=2-3$ have the balanced amount of poloidal and toroidal magnetic field $B_p$ and $B_t$, indicating the balanced amount of compression force by $B_p^2$ and toroidal magnetic field pressure $B_t^2$.

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**FIG 6** Dependences of growth rate $1/\tau_{rec}$ of ST merging/reconnection on toroidal (guide) field $B_t$ (normalized by $B_{rec}$-const.) and similar dependences of ion temperature increment $\Delta T_i$ before and after ST merging on $B_t/B_{rec}$ for three acceleration coils currents: (a) (a') $I_{acc}=13kA$, (b) (b') $I_{acc}=10kA$, (c) (c') $I_{acc}=6kA$. 
3.3. Mechanism for $B_{\text{rec}}^2$-scaling of reconnection heating

This onset of fast reconnection is directly connected to high-power ion heating. Figures 6 show dependences of reconnection rate $1/\tau_{\text{rec}}$ of ST merging/ reconnection on toroidal (guide) field $B_t$ (normalized by the reconnecting magnetic field $B_{\text{rec}}$) and similar dependences of $T_i$ (before and after ST merging) on $B_t$ (normalized by $B_{\text{rec}}$) for three acceleration coils currents: (a) (a’) $I_{\text{acc}}=13\text{kA}$, (b) (b’) $I_{\text{acc}}=10\text{kA}$, (c) (c’) $I_{\text{acc}}=6\text{kA}$. Since $B_t$ disturbs the sheet compression provided by $B_{\text{rec}}$, the high compression in (a)(a’) realizes $\delta \sim \rho_i$ at $B_t/B_{\text{rec}}\sim 2.5$ but the medium compression in (b)(b’) does at $B_t/B_{\text{rec}}\sim 1.5$ and the low compression in (c) (c’) cannot realizes $\delta \sim \rho_i$ for $B_t/B_{\text{rec}}\sim 1$.

It is noted that these threshold values agree well with those where $T_i$ increases from low level to high level ~120eV together with $1/\tau_{\text{rec}}$. It is also important that the high-level ion heating ~120eV does not depend on $B_t$ but is uniquely on $B_{\text{rec}}$–$B_p$ once the sheet compression turns on the fast reconnection. Horiuchi et al. already reported that the sheet compression to $\rho_{\text{im}}$ causes the large anomalous resistivity by destabilizing Drift-Kink instabilities inside the current sheet [17].

![PIC simulation](image)

**FIG. 7** Dependence of ion kinetic/ thermal energy increment $\Delta K_i$ on reconnecting magnetic field $B_{\text{rec}}$ in 2D PIC simulation of slab model reconnection whose guide field is $B_t \sim 4B_{\text{rec}}$.

![Diagram](image)

**FIG. 8** Reconnection experiments with “closed current and closed flux” and their extension to reconnection heating applications for fusion plasmas: ST-40 and TS-6.
Due to this large anomalous resistivity, the reconnection is observed to accelerate ions to about 70% of the poloidal (reconnecting magnetic field) Alfvén speed \( B_{\text{rec}}/(\mu_0 m_i n_i)^{1/2} \), where \( \mu_0 \), \( m_i \) and \( n_i \) are permeability in vacuum, ion mass and ion density. Since the ion velocity scales with the reconnecting magnetic field \( B_{\text{rec}} \), the ion temperature increment \( \Delta T_i \), (and the reconnection heating energy) does with \( B_{\text{rec}}^2 \) under \( n_e \)-const. condition. Our PIC simulation by Inoue and Horiuchi [18] also verified the \( B_{\text{rec}}^2 \)-scaling of ion heating/acceleration as shown in Fig 7. This simulation adopted the driven-type boundary condition, the current sheets were always compressed to the size of ion meandering orbit, triggering the fast reconnection and high-power reconnection heating.

The reconnection heating does not depend on plasma size as long as the reconnection time is shorter than the energy confinement time. However, we confirmed that high \( T_i \) over 100eV were obtained only in low power-loss reconnection experiments with closed fluxes and sheet currents: TS-3, TS-4, UTST, TS-6, START, MAST, SSX, C2, not in the other open-type reconnection devices whose coil and/or wall intersects the plasmas. We confirmed that the pull type reconnection of two spherator plasmas around internal co boundary condition, the current sheets were always compressed to the size of ion meandering orbit, triggering the fast reconnection and high-power reconnection heating.

4. SUMMARY AND CONCLUSIONS

We studied mechanisms for the \( B_{\text{rec}}^2 \)-scaling of reconnection (ion) heating mainly using TS-3U experiment and PIC simulations. The sheet compression to ion gyroradius \( \rho_i \) was found to be a key to realize the fast reconnection as well as the high-power ion heating consistent with the \( B_{\text{rec}}^2 \)-scaling prediction. Under this condition, the ion heating energy is determined uniquely by \( B_{\text{rec}}-B_0 \) not by \( B_i \) in the conventional tokamak operation region: \( B_i > B_0 \). Another key is to use the merging configuration with fully closed flux/ current whose reconnection heating power is one order higher than the heat loss. After TS-3 in 1985 and MRX in 1995, we have now a variety of laboratory experiments of magnetic reconnection but a limited number of experiments satisfy these two conditions: TS-3, TS-4, UTST and TS-6, START [21], MAST [22], SSX [23], Colorado FRC [24], C2 in TriAlpha Energy [25] as shown in Fig. 8. This promising scaling law is expected to realize the burning plasma temperature \( T_i > 10 \text{keV} \) just by increasing \( B_{\text{rec}} \) over 0.6T (\( n_e = 1.5 \times 10^{19} \text{m}^{-3} \)). These facts lead us to construction of new high-\( B_{\text{rec}} \) merging ST devices: TS-3U (TS-6) in Univ. Tokyo and ST-40 in Tokamak Energy Inc., UK.

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