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High power heating of magnetic reconnection in merging tokamak experiments^{a)}

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Significant ion/electron heating of magnetic reconnection up to 1.2 keV was documented in two spherical tokamak plasma merging experiment on MAST with the significantly large Reynolds number $R \sim 10^5$. Measured 1D/2D contours of ion and electron temperatures reveal clearly energy-conversion mechanisms of magnetic reconnection: huge outflow heating of ions in the downstream and localized heating of electrons at the X-point. Ions are accelerated up to the order of poloidal Alfvén speed in the reconnection outflow region and are thermalized by fast shock-like density pileups formed in the downstreams, in agreement with recent solar satellite observations and PIC simulation results. The magnetic reconnection efficiently converts the reconnecting (poloidal) magnetic energy mostly into ion thermal energy through the outflow, causing the reconnection heating energy proportional to square of the reconnecting (poloidal) magnetic field $B_{\text{rec}}^2 \sim B_p^2$. The guide toroidal field B_t does not affect the bulk heating of ions and electrons, probably because the reconnection/outflow speeds are determined mostly by the external driven inflow by the help of another fast reconnection mechanism: intermittent sheet ejection. The localized electron heating at the X-point increases sharply with the guide toroidal field B_t , probably because the toroidal field increases electron confinement and acceleration length along the X-line. 2D measurements of magnetic field and temperatures in the TS-3 tokamak merging experiment also reveal the detailed reconnection heating mechanisms mentioned above. The high-power heating of tokamak merging is useful not only for laboratory study of reconnection but also for economical startup and heating of tokamak plasmas. The MAST/TS-3 tokamak merging with $B_p > 0.4$ T will enable us to heat the plasma to the alpha heating regime: $T_i > 5$ keV without using any additional heating facility. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4920944>]

I. INTRODUCTION

The high-power reconnection heating of torus plasmas has been studied in TS-3 (Tokyo University Spherical Torus No.3) merging experiment as their promising solenoid (CS)-less startup and heating.^{1–3} As shown in Fig. 1, two torus plasmas axially merge together, forming a current sheet around the X-point. We already observed that the reconnection heat mostly plasma ions up to 200 eV within short reconnection time, increasing the plasma beta of torus plasmas to 20–30%.^{1–3}

Since 1985, this idea has been developed by a series of torus plasma merging experiments of University of Tokyo: TS-3,^{1–7} TS-4,^{8,9} and UTST (University of Tokyo Spherical Tokamak).¹⁰

As shown in Figs. 2(a)–2(c), two toroidal plasmas (STs) with major radii ~ 0.2 m (TS-3), ~ 0.5 m (TS-4), and ~ 0.45 m (UTST) were merged together in the axial direction by magnetic compression provided by two PF and acceleration coils. The TS-3 and TS-4 experiments explored the

merging startup of ST plasmas and compact torus (CT) plasmas for high-power reconnection heating/ramp-up without using any center-solenoid (CS) coil.^{1–10} The TS-3 and TS-4 also produced an FRC (Field-Reversed Configuration) using two merging spheromak plasmas with opposing toroidal fields.^{2,8,9}

Since 1990, the merging compression of two ST plasmas has been demonstrated also in the START device.¹¹ Its successful experiment with neutral beam (NB) heating was up-scaled to the first Mega Ampere ST experiment: MAST¹² shown in Fig. 2. Its merging operation has been used to increase poloidal flux provided by the thin center solenoid coil, and is now the highest B-field reconnection experiment under the highest Reynolds number $> 10^4$. It is noted that the plasma merging operation in MAST has the highest plasma heating power among all laboratory reconnection experiments.

The counter-helicity merging of two spheromaks is now used widely in TS-3 and 4, MRX,^{13,14} SSX,¹⁵ Colorado FRC¹⁶ for slow formation of oblate FRC. Recently, high speed merging of two CT plasmas was used for formation and heating of largest-class FRC in the C-2 experiment.¹⁷

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FIG. 1. Two merging torus plasmas and their X-point region with current sheet, inflow and outflows.

In the solar satellite observations, the Ca XVII line width of coronal loop-top was measured by the Hinode satellite.¹⁸ The line-width image suggests a significant increase in ion temperature. This configuration directly causes high power plasma heating and its multiple accelerations are considered to produce high-energy non-thermal particles up to GeV.²⁰ The satellites for magnetosphere observation such as “Geotail,” “Cluster,” and “MMS” have measured directly the velocity distributions of ions and electrons caused by the reconnections. The ion temperatures tend to be higher than the electron temperatures, possibly due to the effect of reconnection.

An important question is how the magnetic reconnection transforms the magnetic energy of merging STs into the thermal energy of the produced ST. We measured for the first

time detailed profile of plasma velocity together with those of ion temperature T_i , electron density n_e , and magnetic field B in order to study the conversion mechanisms of reconnection from magnetic energy to ion and electron thermal energies.

II. EXPERIMENTAL SETUPS

The TS-3 device has been used to study the merging/reconnection startup for high-beta torus plasma.^{1–10} As shown in Fig. 2(a), its cylindrical vacuum vessel with length of 1 m and diameter of 0.8 m has two poloidal field (PF) coils for poloidal flux injection in order to merge two torus plasmas with $R \approx 0.2$ m and $R/a \approx 1.5$ together in the axial direction. Each merging toroid initially has the plasma parameters: $T_i \approx T_e \approx 10$ eV, $n_e \approx 1\text{--}8 \times 10^{19} \text{ m}^{-3}$ and $B \approx 0.05$ T. 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 5 mm in the axial direction and 3 cm 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. As shown in Fig. 3, a 1 m polychromator with an optical multi-channel analyzer

FIG. 2. (a) A photo and a cross-section of TS-3 merging devices with PF and separation coils, (b) those of TS-4 merging device with fluxcores, separation and acceleration coils and (c) those of UTST merging device with external PF, separation and acceleration coils. The 0.8 MW and 0.7 MW pulsed NBI systems are installed on TS-4 and UTST, respectively.

FIG. 3. 35 channel Doppler spectrometer system and its viewing lines for 2-D ion temperature measurement in the R-Z plane.

(OMA) was used to measure 2D profiles of ion temperature T_i by means of the Doppler widths of helium and carbon impurity lines.^{3,21} 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. 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 $\mathbf{v} = (v_r, v_z)$, electron density n_e and temperature T_e .

The upgraded reconnection heating experiment was made in one of the world-largest ST devices: MAST, based on UK-Japan collaboration of magnetic reconnection. As shown in Fig. 4, the MAST device has the major radius $R \sim 0.9$ m and the reconnecting magnetic field $\sim$ poloidal magnetic field ~ 0.15 T, which are four and three times large than those of TS-3. Two merging ST plasmas are produced by the induction of two or four internal poloidal field coil and are merged together under the high guide field. Since its plasma temperature is too high for probe insertion, its major plasma diagnostics are composed of the 130-channel YAG Thomson scattering system for 1D electron temperature T_e and density n_e measurements on the midplane, the 32-channel ion Doppler system for 1D T_i measurement, the neutral particle analyser (NPA) for bulk T_i measurement and the high-speed camera and Mirnov coils for plasma shape measurement. The Doppler ion temperature measurement system composed of optical fibers and polychromator with CCD camera was installed for this reconnection heating experiment based on the UK-Japan collaboration. The same Abel inversion technique was used to transform the line-integrated plasma emissivity—mainly CVI lines to local one at each wavelength for 1D T_i and n_e measurements.

III. EXPERIMENTAL RESULTS

A. High power heating of magnetic reconnection

When we merge two ST plasmas in TS-3 device (Fig. 5(a)), we observe significant ion heating in the downstream and electron heating around the X-point. Figure 5(b) shows R-Z

	MAST	TS-4	TS-3
R [m]	0.9	0.5	0.2
a [m]	0.7	0.4	0.15
I_p [MA]	<1	<0.1	<0.07
B_t [T]	<0.5	<0.1	<0.2
B_p [T]	<0.2	<0.03	<0.05

FIG. 4. A cross-section of MAST device with PF coils and T_i and T_e diagnostics (top) and machine parameters of MAST, TS-4 and TS-3 merging devices (bottom).

contours of poloidal magnetic flux during the merging of two high- q ST plasmas with $B_{rec} \sim 0.04$ T under center coil current $I_{tfc} = 35$ kA ($B_t \sim 5B_{rec}$). The magnetic reconnection occurs from $t = 45 \mu s$ to $t = 55 \mu s$. Figures 5(d) and 5(e) show 2D contours of ion and electron temperatures, which are measured inside the red and blue squares of Fig. 5(b), respectively. The ion temperature peaks around the two downstream positions, while the electron temperature peaks at the reconnection (X) point. The most probable interpretation of the ion heating is as follows: the reconnection outflow accelerates plasma ions to the order of the poloidal Alfvén speed and the accelerated ions collide with the reconnecting field lines, forming a fast-shock-like pileup and the ions thermalized by the pileup and ion viscosity, forms two hot ion spots in the downstreams. On the other hand, the electron temperature profile peaks at the X-point probably due to ohmic heating effect of sheet current. However, its peaking is sharper than that of ohmic heating power of sheet current, suggesting the non-thermal toroidal acceleration of electrons by the induced electric field of reconnection.

Next question is how those ion and electron heating characteristics change, if we increase the poloidal magnetic field to 0.08 T in the MAST merging experiment. This 0.08 T operation was recently used for low mechanical stress on the old coils of MAST device. Figure 6 shows radial profiles of ion temperature T_i of two merging STs on the midplane, which were measured by the 32channel Doppler broadening measurement of CVI line. It clearly indicates the significant ion heating in two downstream areas, just like Fig. 5(d). The reconnection of $B_p \sim 0.08$ T increases ion temperature to

FIG. 5. (a) Schematic of ST plasma merging with high toroidal field ($B_t \sim 5B_{rec}$), (b) R-Z contours of poloidal magnetic flux, (c) radial profiles of toroidal magnetic field B_t , (d) R-Z contours of ion temperature T_i by 2D Doppler broadening measurement, (e) R-Z contours of electron temperature T_e by 2D electrostatic probe measurement and (f) R-Z vector plots of plasma flow measured by scan of 1-D Mach-probe array in TS-3 ST merging experiment.

0.25 keV during reconnection (around $t = 15.3$ ms) and starts decreasing after completion of merging/reconnection (around $t = 20.6$ ms). It is noted that another peak of T_i appears at around $R \sim 0.56$ m in the late reconnection phase. It is probably due to ion-electron energy relaxation around X-point. The electron temperature tends to peak at X-point during the reconnection. Figures 7 show radial profiles of electron temperature T_e and density n_e of two merging ST

plasmas in the $B_{rec} = 0.12$ T operation of MAST experiment. They were measured by the 130-channel YAG Thomson scattering system. It is noted that the electron temperature peaks very sharply at the X-point. The half width of T_e profile is as small as 2 cm at $t = 5.2$ ms. The peaking of T_e profile in TS-3 (Fig. 5(e)) is not so sharp as that in MAST, probably because the magnetic Reynolds number of MAST experiment $\sim 10^4$ – 10^5 is two order higher than that of

FIG. 6. Radial profiles of ion temperatures T_i at $t = 15.3$ ms and at $t = 20.6$ ms during magnetic reconnection of two high- q tokamak plasmas in the $B_{rec} \sim 0.08$ T merging experiment of MAST. They were measured by the 32 channel Doppler broadening measurement of CVI line.

FIG. 7. Radial profiles of electron temperature T_e and electron density n_e of merging high- q tokamak in the $B_{rec} \sim 0.12$ T merging experiment of MAST. Each color curve was measured at every 0.1 ms from 5.3 ms to 5.9 ms. They were measured by the 130-channel YAG Thomson scattering system.

TS-3 $\sim 10^3$. Radiation loss of low Z impurity tends to smooth out the T_e profile in the low T_e experiment of TS-3.

B. Formation of shock-like pileup

A new finding in both experiments is that the reconnection outflow decreases abruptly at shock-like plasma pileups in the down-stream of reconnection. In TS-3, the 2-D profile of velocity vector (v_r , v_z) was measured using two-component Mach probe array. Its spatial resolution is as small as 0.8–1 cm, which is 1/4 of thickness of the current sheet. Figure 5(f) show an R - Z vector plot of plasma velocity at $t = 50 \mu\text{s}$ during the reconnection/merging of two ST plasmas. It clearly indicates slow bi-directional inflow and fast bi-directional outflow around the current sheet, in agreement with the typical reconnection model like the Sweet-Parker. It is noted that the bi-directional outflow velocity abruptly decreases to 1/3 at $R = 12$ –13 cm and also at $R = 20$ –22 cm at about $t = 50 \mu\text{s}$. Its outflow speed $\sim 30 \text{ km/s}$ is close to the maximum measurable velocity—ion sound velocity by Mach probes. This sharp decrease in radial velocity is consistent with fast shock dumping of outflow reported in the Hinode observations of solar coronas.^{18,19}

C. Mechanism for the reconnection heating

An important question is how the plasma ions are heated in the downstream. Figures 8(c)–8(g) show axial profile of radial ion flow v_r , radial profiles of ion temperature T_i , radial flow v_r , electron density n_e , and magnetic field amplitude $|B|$ of merging high- q STs ($I_{\text{fc}} = 35 \text{ kA}$) at $t = 50 \mu\text{s}$ during the

reconnection in TS-3. Figures 8(c)–8(e) were measured by the Doppler probe and (f) and (g) by electrostatic probe and magnetic probe, respectively. Figure 8(e) clearly indicates the bi-directional reconnection outflow whose maximum speed: 50 km/s is 80% of the poloidal Alfvén speed. This fact agrees well with the Sweet-Parker model.

Another question is whether the fast shock-like pileup is formed in the downstream in agreement with the abrupt decrease in plasma flow observed in Fig. 5. The merging starts at $t = 45 \mu\text{s}$ and completes at $t = 55 \mu\text{s}$. It is noted that both of n_e and $|B|$ change abruptly at two downstream positions where the outflow velocity v_r dumps. The outflow is observed to dump abruptly around two downstream points, where large increases in T_i , n_e , and $|B|$ are observed. The dumping ratios of v_r , T_i , n_e , and $|B|$ almost satisfy the following Rankine-Hugoniot equation for fast shock:

$$n_1/n_2 = |B_1|/|B_2| = v_2/v_1 \sim 2 - 3, \quad (1)$$

where the suffixes 1 and 2 indicate positions before and after the shock front. This fact indicates that the accelerated ions are thermalized at the two downstream areas probably through the fast shock-like pileup of plasma, maybe together with ion viscosity. As shown in the large error bars of n_e and $|B|$ (five shot average) around the two positions: $R \sim 13 \text{ cm}$ and $R \sim 22 \text{ cm}$, the fast shock position moves within 2 cm at each discharge. When we used pairs of triple probes whose separation length is as short as 5 mm, we successfully measured the sharp jump of electron density at around $R \sim 13 \text{ cm}$ and $R \sim 21 \text{ cm}$,²¹ in agreement with Figs. 5(d)–5(f). The shock-like pileup and ion viscosity are the most probable dumping mechanisms for accelerated ions in the two downstream regions. The positions of shock-like pileups agree well with the two hot T_i regions observed in Fig. 8(d). This sharp decrease in radial velocity is consistent with fast shock dumping of outflow reported in Hinode observations of solar coronas.¹⁸

A similar shock-like pileup is also observed in the MAST ST merging experiment. Figure 7(bottom) clearly shows the double peak profile of n_e around $t = 5.7 \text{ ms}$ during reconnection. The steep n_e jump is formed at $t = 5.4 \text{ ms}$ and propagates to the downstream. The n_e jump in the inner side is maintained longer than that in the outer side, probably due to the toroidal effect of density pileup. In the present MAST merging experiment, we need internal magnetic probe measurement to compare its reconnection with the Sweet-Parker model.

D. Energy flow during reconnection

After the merging is over, the heated ions are confined inside the produced new ST plasmas, because the heated ions in the downstream and the heated electrons in the current sheet are surrounded by the thick layer of closed (reconnected) magnetic flux. The energy loss during the merging formation is much lower than 10% of the heated ions. Figure 9 shows the energy flow during magnetic reconnection with guide field $B_t \sim 5B_{\text{rec}}$ and that during reconnection with $B_t \sim 0$ in TS-3. The former was obtained by merging of two high- q STs and the latter by merging of two

FIG. 8. (a) Schematic of ST plasma merging under high toroidal field ($B_t \sim 5B_{\text{rec}}$), (b) R - Z contours of poloidal magnetic flux, (c) axial profile of radial ion flow (d), (e) radial profiles of ion temperature T_i and radial flow v_r , measured by the Doppler probe and (f), (g) radial profiles of electron density n_e measured by 1D electrostatic probe and magnetic field amplitude $|B|$ of merging high- q tokamak ($I_{\text{fc}} = 35 \text{ kA}$) in TS-3. (b)–(g) are obtained at $t = 50 \mu\text{s}$ during the reconnection.

FIG. 9. Energy flows from magnetic energy to ion and electron thermal energies during magnetic reconnection with and without guide (toroidal) magnetic field in TS-3 merging tokamak and spheromak experiments.

spheromaks with opposing toroidal field.^{2,3} In both cases, about 90% of the dissipated magnetic energies are converted to ion thermal energy probably through the reconnection outflow. The current sheet dissipation, whose 70% is converted into electron thermal energy is as small as 10% of the total magnetic energy dissipation in both cases. The guide field does not affect the energy flow during magnetic reconnection in our present merging/ reconnection experiments. In TS-3, the guide field reconnection transforms about 90% and 10% of the dissipated magnetic energy into ion and electron thermal/kinetic energies, respectively.

Figure 10 shows the time evolutions of bulk ion and electron temperatures $T_{i,bulk}$, $T_{e,bulk}$, and peak electron temperature $T_{e,peak}$, of merging ST plasma in the $B_{rec} = 0.15$ T (high poloidal field) merging experiment of MAST. It is noted that the reconnection heat bulk ions to 1.2 keV within short reconnection time $\tau_{rec} \sim 10$ ms. On the other hand, the reconnection heats bulk electrons to ~ 0.1 keV, which is one order smaller than $T_{i,bulk}$. The reconnection is observed to

FIG. 10. Time evolutions of bulk ion temperature $T_{i,bulk}$ measured by NPA, bulk and peak electron temperatures $T_{e,bulk}$ and $T_{e,peak}$ measured by Thomson scattering in the $B_{rec} = 0.15$ T merging experiment of MAST.

heat electron temperature to 0.4 keV locally around X-point probably due to ohmic heating/acceleration of electrons by reconnection electric field, but its energy is quite small due to small volume of the X-point area. If we assume effect of ion and electron transport effect is not large due to the high magnetic Reynolds number, the guide field reconnection in MAST transforms about 90% and 10% of the dissipated magnetic energy into ion and electron thermal/kinetic energies, in rough agreement with the TS-3 result mentioned above.

E. Effect of guide field for the reconnection heating

Next question is how the guide field B_t —unreconnected magnetic field component affects the reconnection heating of ions and electrons. Figure 11 shows time evolutions of ion temperatures of merging ST plasmas with three different guide field (toroidal magnetic field) $B_t = 0.38$ T, 0.44 T, and 0.5 T during the $B_{rec} = 0.15$ T merging operation of two ST plasmas. They are measured by the neutral particle analyser (NPA) on the midplane. It indicates that all three cases of ion temperatures increase to 1 keV within short reconnection time of 10 ms. We cannot find any dependence of the ion heating on the guide field B_t .

On the other hand, we found strong dependence of peak electron temperature $T_{e,peak}$ at X-point on the guide field B_t , but the bulk electron temperature $T_{e,bulk}$ does not depend on B_t . Figure 12 shows radial profiles of electron temperatures of merging ST plasmas with three guide field $B_t = 0.38$ T, 0.44 T, and 0.5 T during the $B_{rec} = 0.15$ T merging operation of two ST plasmas. It clearly indicates the strong dependence of peak electron temperature on the guide field. It is probably because the toroidal field increases electron energy confinement as well as electron acceleration length along the X-line by toroidal reconnection electric field.

The B_t dependence of heating in MAST is qualitatively constant with that observed in recent TS-3 reconnection experiment with varied guide field B_t . Figures 13(a) and 13(b) show reconnection rate and ion temperatures before and after the reconnection as a function of the guide field B_t . Before the current sheet is ejected from the X-point region, the black curve represents their dependences on B_t . Anomalous resistivity of the current sheet or fast reconnection is turned on when the current sheet is compressed thinner than ion gyroradius. Since the ion gyroradius increases

FIG. 11. Time evolutions of line-averaged ion temperatures T_i of merging high- q tokamak plasmas with three guide field $B_t = 0.38$, 0.44, and 0.50 T in the $B_{rec} = 0.15$ T merging experiment of MAST.

FIG. 12. Radial profiles of electron temperatures, electron density and electron pressure for three guide fields $B_t = 0.38, 0.44$, and 0.50 T in the $B_{\text{rec}} = 0.15$ T merging experiment of MAST.

inversely with the guide field, low B_t reconnection and heating are faster and higher than those of high B_t reconnection. However, if we keep driving the constant inflow flux larger than the outflow flux, the plasma and flux tend to pile up inside the current sheet, increasing the size of current sheet, as shown in Fig. 13(c). When the sheet size exceeds the threshold value, the whole current sheet is ejected from the X-point area. The sheet ejection is observed to increase significantly and transiently the reconnection speed as well as

ion temperature in the downstream. Finally, dependence of reconnection speed and ion heating depend weakly on B_t , as shown in the red curve in Figs. 13(a) and 13(b). The mentioned mechanism for the sheet ejection is shown in Fig. 13(d). Both of MAST and TS-3 results agree that the major reconnection heating: outflow heating of ions does not or little depends on the guide field B_t .

F. Scaling for the reconnection heating

Finally, Fig. 14 shows dependence of ion temperature increment ΔT_i on the reconnecting magnetic field amplitude $B_{\text{rec}} \sim B_p$. Since the plasma density is set approximately constant (with constant density $n_i \approx 2 \times 10^{19} \text{ m}^{-3}$), the ion temperature increment ΔT_i ($\gg \Delta T_e$) is almost proportional to the heating energy of reconnection. Since dependence of the guide field on the bulk heating is quite weak, the TS-3 data in Fig. 14 clearly indicate that ΔT_i and the reconnection heating energy scale with the square of reconnecting (poloidal) magnetic field B_{rec}^2 . Recently, the new MAST reconnection experiment documented the highest ion and electron temperatures 1.2 keV. It is noted that their data agree well with the same scaling line, as shown in Fig. 14.²¹ The observed B_{rec}^2 -scaling can be explained by ions accelerated to Alfvén speed $B_{\text{rec}}/(m_i n_i)^{1/2}$. Since the ion velocity increases with $B_{\text{rec}} \sim B_p$, the reconnection heating energy should scale with B_{rec}^2 . The reconnection outflow and shock-like dumping quickly produce MW-class (4–10 MW and 8–15 MW in TS-3 and MAST tokamak merging experiments, respectively) of ion heating power based on the B_p^2 -scaling. If we increase the poloidal field over 0.5 T, we have a good possibility to increase ion temperature over 10 keV, realizing the burning plasma without using any additional heating facility like neutral beam injection.

FIG. 13. (a) and (b) Reconnection rate and ion temperature before and after reconnection as a function of guide field B_t in TS-3 ST merging experiment. The dependence changes from the black curve to the red curve after current sheet ejection. (c) R-Z contour of poloidal flux and toroidal current density (by red and blue color) during the sheet ejection and (d) a possible mechanism for the sheet ejection.

FIG. 14. Ion temperature increments ΔT_i of the two merging tokamak and spheromak plasmas as a function of reconnecting (poloidal) magnetic field B_p . The data points were obtained from TS-3 and MAST merging experiments with various guide fields.

IV. CONCLUSIONS

We studied ion and electron heating characteristics of magnetic reconnection under high toroidal guide field, mainly using the TS-3 and MAST merging experiments. Both experiments agree that the reconnection heats ions in the downstream and electrons at the X-point. Their electron density measurements clearly indicate formation of shock-like plasma pileup in the downstream as a thermalization process of reconnection outflow. The internal probe measurements of TS-3 confirmed that the reconnection outflow accelerates plasma ions to the order of the poloidal Alfvén speed and dumps at the shock-like plasma pileup. At the shock front positions, the jump of magnetic field, electron density and plasma velocity almost satisfy the Rankine-Hugoniot relation. Both of TS-3 and MAST results agree that the ion heating energy scales with square of the reconnecting magnetic field B_{rec} due to the outflow acceleration of ions to the order of the poloidal Alfvén speed. On the other hand, the electron temperature peaks at X-point probably due to the ohmic heating effect of the sheet current. The bulk heating of ions and electrons do not depend on the guide field, while the electron heating localized at the X-point increases with the guide field. Both experiments agree that the magnetic reconnection transforms 90% of the dissipated magnetic energy into ion thermal energy and 10% into electron thermal energy. The promising B_{rec}^2 scaling of reconnection heating lead us to the present UK-Japan joint reconnection heating experiment of MAST in order to document a new ST startup with ion heating over 1 keV. We, Japan-UK merging team are now planning to produce two merging STs with $B_{rec} > 0.4$ T to heat ions over 5 keV (alpha-heating region) without using any additional heating facility.

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- ¹Y. Ono, T. Kimura, E. Kawamori, Y. Murata, S. Miyazaki, Y. Ueda, M. Inomoto, A. L. Balandin, and M. Katsurai, *Nucl. Fusion* **43**, 789 (2003).
- ²Y. Ono, M. Yamada, T. Akao, T. Tajima, and R. Matsumoto, *Phys. Rev. Lett.* **76**, 3328 (1996).
- ³Y. Ono, H. Tanabe, Y. Hayashi, T. Ii, Y. Narushima, T. Yamada, M. Inomoto, and C. Z. Cheng, *Phys. Rev. Lett.* **107**, 185001 (2011).
- ⁴Y. Ono, A. Yumoto, and M. Katsurai, in *Proceedings of the IEEE International Conference Plasma Sci.* (Saskatoon, 1988), p. 77; Y. Ono, K. Katayama, A. Yumoto, and M. Katsurai, *J. Plasma Fus. Res.* **56**, 214 (1986) (in Japanese).
- ⁵Y. Ono, M. Yamada, and M. Katsurai, *Phys. Fluids B* **5**, 3691 (1993).
- ⁶Y. Ono, Y. Hayashi, T. Ii, H. Tanabe, S. Inoue, A. Kuwahata, T. Ito, Y. Kamino, T. Yamada, M. Inomoto, and TS-Group, *Phys. Plasmas* **18**, 111213 (2011).
- ⁷Y. Ono, M. Inomoto, T. Okazaki, and Y. Ueda, *Phys. Plasmas* **4**, 1953 (1997).
- ⁸Y. Ono, T. Matsuyama, K. Umeda, and E. Kawamori, *Nucl. Fusion* **43**, 649 (2003).
- ⁹E. Kawamori and Y. Ono, *Phys. Rev. Lett.* **95**, 085003 (2005).
- ¹⁰Y. Ono, R. Imazawa, H. Imanaka, Y. Hayashi, S. Ito, M. Nakagawa, T. Yamada, M. Inomoto, A. Ejiri, Y. Takase et al., *Proc. Fusion Energy* **2008**, EXP/P9-4 (2008), available at http://www-pub.iaea.org/mtcd/meetings/fec2008/ex_p9-4.pdf.
- ¹¹M. Gyaznevich, A. Bondeson, P. G. Carolan, G. Cunningham, R. Duck, T. Edlington, S. K. Ereints, J. Ferreira, S. J. Fielding, K. Gibson et al., in *Proceedings of the 14th International Conference on Plasma Phys. Cont. Nuc. Fusion Res.*, Wuerzburg, Germany (IAEA, Vienna, 1992), Vol. 2, p. 575.
- ¹²M. Gryaznevich, V. Shevchenko, and A. Sykes, *Nucl. Fusion* **46**, S573 (2006).
- ¹³M. Yamada, H. Ji, S. Hsu, T. Carter, R. Kulsrud, N. Bretz, F. Jobes, Y. Ono, and F. Perkins, *Phys. Plasmas* **4**, 1936 (1997).
- ¹⁴S. P. Gerhardt, E. V. Belova, M. Yamada, H. Ji, M. Inomoto, Y. Ren, and B. McGeehan, *Phys. Rev. Lett.* **99**, 245003 (2007).
- ¹⁵M. Brown, *Phys. Plasmas* **6**, 1717 (1999).
- ¹⁶T. Munsat, C. L. Ellison, A. Light, J. Nuger, W. Willcockson, and S. Wurzel, *J. Fusion Energy* **27**, 82 (2008).
- ¹⁷M. W. Binderbauer, H. Y. Guo, M. Tuszewski, S. Putvinski, L. Sevier, D. Barnes, N. Rostoker, M. G. Anderson, R. Andow, L. Bonelli et al., *Phys. Rev. Lett.* **105**, 045003 (2010).
- ¹⁸H. Hara, T. Watanabe, L. K. Harra, J. L. Culhane, and P. R. Young, *Astrophys. J.* **741**, 107 (2011).
- ¹⁹K. Shibata and S. Tanuma, *Earth Planets Space* **53**, 473 (2001).
- ²⁰M. Hoshino, *Phys. Rev. Lett.* **108**, 135003 (2012).
- ²¹Y. Ono, H. Tanabe, T. Yamada, M. Inomoto, T. Ii, S. Inoue, K. Gi, T. Watanabe, M. Gryaznevich, R. Scannell et al., *Plasma Phys. Controlled Fusion* **54**, 124039 (2012).