Fast magnetic reconnection with anomalous ion heating and its application

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Abstract

Magnetic reconnection of two toroidal plasmas with the third field component $B_x$ parallel to the X-lines revealed a clear dependence of sheet-current resistivity and ion heating energy on the sheet-width normalized by the ion gyroradius. Initially, the effective resistivity of sheet-current stayed constant, but it increased significantly when the sheet was compressed shorter than the ion-gyroradius. The anomalous current-sheet dissipation was followed by large increase in ion outflow velocity and ion temperature. This anomalous effect caused both the reconnection speed and the ion heating energy to increase with external compression force and inversely with the $B_y$ component. These properties of reconnection led us to a new controlled plasma heating for various fusion plasmas and other industrial plasmas. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Magnetic reconnection; Ion heating; Field component

1. Introduction

Magnetic reconnection is an efficient energy converter from the magnetic energy of the reconnecting magnetic field lines to the plasma kinetic and thermal energy. It is often observed during global restructuring of magnetized plasmas, such as solar coronas, magnetotails and fusion plasmas. The reconnection phenomena cannot be fully explained by magnetohydrodynamic (MHD) effects, but by some anomalous effects. The ’anomalous’ effects, possibly plasma particle effect and/or two fluid effect have been predicted to make reconnection much faster than the classical model. Recently, the solar satellite ’Yohkoh’ found high temperature spots on solar coronas using soft-X-ray and hard-X-ray cameras [1,2]. Anomalous dissipation of current sheet caused anomalous release of coronal magnetic energy into plasma kinetic and thermal energies. The fast outflow of reconnection was found to heat the top of coronal arcades preferentially, forming a fast shock structure [3]. The magnetosphere satellite ’Geotail’ has measured directly the anomalous dissipation and ion heating of reconnecting magnetotail [4]. In both cases, the measured reconnection speeds were much faster than that calculated from the Sweet Parker model [5,6], suggesting that their effective sheet-current resistivity were a few order higher than the classical resistivity. The reconnecting magnetotail lobe with anomalous dissipation of current-sheet had ion temperature about three times higher than electron temperature [4]. It is noted that reconnection of the southward interplanetary magnetic field (IMF) with the northward dipole field of the earth is faster than that of the northward IMF. The latter has much larger field component $B_y$ parallel to the ‘X-point’ line than the former [7]. As shown in Fig. 1, a generalized magnetic reconnection tends to contain the third magnetic field component $B_x$ together with the reconnecting component $B_y$. This so-called ’three-component’ reconnection with $B_x$ has a smaller merging angle ($\theta < 180^\circ$) of the reconnecting field lines than that of the two-component reconnection. Magnetic reconnection is also known to cause the periodic restructuring phenomenon: ’sawtooth oscillation’ in various fusion plasmas: tokamaks, spheromaks and reversed-field pinches (RFPs). It has been reported that plasma resistivity, magnetic fluctuation amplitude and temperature ratio of ions to electrons were significantly higher in the RFPs with small $B_y$ than in the tokamaks with large $B_y$. This dependence on the $B_x$ component has been reported both in fusion plasmas and in magnetosphere plasmas.

Three important questions then arise: (1) Why the reconnection speed and heating depend on the $B_x$ component? (2) Are they related with the non-MHD ’anomalous’ effect related with $B_y$? (3) How is the anomalous heating of reconnection related with anomalous dissipation of current sheet?

Recent macroparticle simulations studied several microscopic mechanisms for the anomalous dissipation of current-sheet and the ion heating [8–11]. Various MHD simulations made clear the effects of the current-sheet resistivity on magnetic field restructuring [12–14]. The RFP plasmas tend to have large magnetic fluctuations...
caused by those reconnections and their mode cascades up to ion-gyromode number causes the anomalous ion heating [15]. Stenzel performed a famous laboratory experiment of magnetic reconnection using a discharge current between electrodes as a current-sheet. The current-sheet width was always shorter than the ion-gyroradius [16,17]. They documented the non-MHD effect, such as the Whistler wave activities. However, the relation of anomalous resistivity/ion heating to sheet-compression process and its dependence on $B_x$ were left unsolved.

We have been reporting that the counterhelicity merging of two spheromaks with the merging angle $\theta \approx 180^\circ$ was faster than the cohericity merging with $\theta \approx 90^\circ$, in the fast reconnection regime in the TS-3 [18,19] and the slow reconnection regimes in the magnetic reconnection experiment (MRX) devices [21]. Recently, we found that merging of two plasma toroids with wide range of $q$-value can vary the $B_x$ field component more accurately/continuously from 0 to 5 $B_o$, as shown in Fig. 2. If we fix poloidal fluxes of two merging toroids, this method enables us to vary $B_x$, keeping constant the reconnecting field component $B_z$. We found it important to keep the $B_z$ constant for comparing the three-component reconnections with different merging angles $\theta$.

Another control parameter in this experiment was an external force to compress the sheet-current. The acceleration-coil current $I_{acc}$ was used to vary the external force, enabling us to control the reconnection speed widely. This paper addresses three important issues of fast reconnection caused by anomalous resistivity: (1) how resistivity of current-sheet is determined by the external compressing force and the $B_x$ field component, (2) how the anomalous resistivity of the current-sheet is related to preferential ion-heating ($T_i > T_e$) of reconnection, (3) how the anomalous heating of reconnection is useful for fusion and other plasma researches. Our high-resolution measurements of current-sheet and ion temperature revealed a novel relationship between the effective sheet-current resistivity and the current-sheet width normalized by ion-gyroradius. This anomalous ion heating was found useful to heat a variety of plasmas quickly within short recombination time. Two major applications of the reconnection heating to fusion plasmas shall be introduced in the following discussions.

2. Experimental setup

The TS-3 merging device [18] was constructed in 1986 to study various merging phenomena of two compact toroids for fusion confinement and for basic research of reconnection. Its photograph and vertical cross-section are shown in Fig. 3. Its cylindrical vacuum vessel with length of 1 m and diameter of 0.6 m has two internal poloidal field (PF) coils and two sets of eight electrodes pairs to produce poloidal and toroidal fluxes of two toroids. After the plasma formation, the PF coil current was reversed and crowbered to push...
Fig. 4. 2-D contours of poloidal flux and toroidal field (red and blue colors) of two merging (a) RFPs, (b) spheromaks and (c) tokamaks and their axial profiles of reconnection field $B_T$ and $B_X$ field component parallel to the X-point line.

the two toroids together for the current-sheet compression. The reversed coil current shall be called an acceleration-coil current $I_{acc}$ in later. A center torus coil with diameter of 12 cm is located along the center geometric axis to produce the toroidal field $B_{ext}$. The third field component $B_X$ is the sum of the external toroidal field $B_{ext}$ and the internal toroidal field $B_{tor}$ produced by the poloidal plasma current. Right after their formations, the two plasma toroids had major and minor radii of 18 and 12 cm, respectively. Their initial ion and electron temperatures $(T_i, T_e)$ were as low as 10 and 5 eV. Their electron density $n_e$ was about $5 \times 10^{19}$ m$^{-3}$.

The 2-D array of magnetic probes was located on an $r-z$ plane of the vessel to measure their three-components magnetic field profiles. This 2-D magnetic field profile was used to calculate 2-D contours of poloidal flux $\Psi$ and toroidal current density $j_z$ on each single discharge, as shown in Ref. [18]. Its spatial resolution was as fine as 5 mm in the axial direction and 3 cm in the radial direction around current-sheet. Typical (axial) width 26 and length $L$ of the current-sheet were 3–10 and 15–25 cm, as shown in Fig. 4. Axial scan of the 2-D probe array allowed us to make the finer probe resolution to 2 mm, indicating that the measurement errors of $j_z$ and $\Psi$ were smaller than 10 and 2%, respectively. A 1 m polychromator with a 2-D CCD (584 × 386) detectors was used to measure Doppler width of $H_\beta$ line with wavelength resolution of 0.01 nm [23]. The Abel inversion was applied to the measured line-integrated signals of $H_\beta$ light emissivity to calculate the radial $T_e$ profile from 6 to 30 cm. The Doppler width of this neutral particle line followed quickly the fast (about 20 $\mu$s) increase in ion temperature during magnetic reconnection. The charge exchange time between H neutrals and H ions was around 0.1 $\mu$s, while equi-partition times between plasma impurities (C, O, etc.) and H ions were longer than the typical reconnection time: 20 $\mu$s time scale. An electrostatic probe was inserted axially at $r = 14$ cm and radially on the mid-plane to measure profiles of electron temperature $T_e$ and density $n_e$.

3. Experimental results

In this experiment, we merged two plasma toroids with varied $B_X$ keeping their poloidal fluxes constant. External toroidal field $B_{ext}$ was applied to two merging toroids with equal toroidal fields $B_{tor}$ to produce arbitrary $B_X = B_{ext} + B_{tor}$ along a toroidal X-point line. Fig. 4 shows the poloidal flux contours with toroidal field amplitude of two merging toroids, axial profiles of the reconnection field $B_T$ and the field component $B_X$ parallel to the X-point line under three different $B_T/B_{tor}$ conditions. The $B_X$ component was varied continuously from 0 (the low-$q$ RFP regime: $B_X \leq B_T$) to 3$B_T$ (the high-$q$ tokamak regime: $B_X \gg B_T$), as shown in Fig. 4(a)–(c). The X-point had the minimum toroidal field and two magnetic axes had the maximum ones because of paramagnetic poloidal plasma currents. Fig. 5 shows dependence of reconnection rate $\gamma$ on the field amplitude $B_X$, when current-sheets of the merging toroids were compressed by three acceleration-coil currents $I_{acc} = 13$, 10 and 6 kA. The $\gamma$ values are growth rates of $\alpha$ averaged.

Fig. 5. Averaged reconnection rates $\gamma$ of two merging toroids as a function of $B_X/B_{tor}$ for three different acceleration-coil currents: $I_{acc} = 13$, 10 and 6 kA.
over the reconnection time:
\[
\gamma = \frac{d\alpha}{dt} = \frac{1}{\alpha},
\]
(1)
where \(\alpha\) is the ratio of reconnected poloidal flux to total poloidal flux (common flux ratio) [18]. For this comparison, we kept equal the initial poloidal flux of each merging toroid, realizing an equal (within 10\%) initial \(B_0\) (= \(B_{00}\)) condition. The reconnection rate \(\gamma\) was observed to increase with the external compressing force provided by \(I_{acc}\). For \(B_{y}/B_{00} = 2\) the reconnection with \(I_{acc} = 13\) kA was about 2–3 times faster than that with \(I_{acc} = 6\) kA. The driven-type reconnection was concluded to prevail in our reconnection experiment. It was also observed in all three curves that \(\gamma\) increased inversely with \(B_X\). For \(I_{acc} = 13\) kA, the reconnection with \(B_X/B_{00} = 1\) was about 1.3 times faster than that with \(B_X/B_{00} = 3.5\). As shown in Fig. 6, it was concluded that the reconnection speed increased with external force \(I_{acc}\) and inversely with the third field component \(B_X\). It is noted that abrupt changes in \(\gamma\) were observed around \(B_{y}/B_{00} = 2.5\) in (a), 1.8 in (b) and 1 in (c). The speed reduction by \(B_X\) cannot be explained simply by the toroidal magnetic pressure of the current-sheet because the reconnection speed increases nonlinearly with \(B_X\). Some anomalous effect is considered to take place around those threshold values, as discussed later.

An important question is why the reconnection speed depends on \(B_X/B_{00}\) and \(I_{acc}\). Fig. 7(a) and (b) show the time evolutions of effective resistivity \(\eta_X\) at the X-point, current-sheet width \(2\delta\), and ion-gyroradius \(\times 2\) (diameter) \(2\rho_i\), at the X-point for two reconnections: (a) \(I_{acc} = 5\) kA, and (b) \(I_{acc} = 10\) kA. These two cases (a) and (b) correspond to those shown by the blue and red circles in Fig. 5, respectively. The cases (b) and (a) were obtained before and after the abrupt increase in \(\gamma\) in Fig. 5, respectively. The ion-gyroradius \(\rho_i\) was calculated from the magnetic field \(B_X\) and ion temperature \(T_{ix}\) measured at the X-point. After confirming null velocity \(v_z = 0\) at the X-point (by Mach probe measurement), the effective resistivity \(\eta_X\) was calculated based on the following equations:
\[
\eta_X = \frac{E_i + (\vec{v} \times \vec{B})_i}{2\pi r_e}\frac{1}{\frac{d\Psi_{com}}{dr}},
\]
(2)
where \(E_i, j, \vec{B}, \vec{v}, \Psi_{com}\) and \(r_e\) are toroidal electric field and toroidal current density at the X-point, magnetic field, plasma velocity, reconnected poloidal flux and radius of the X-point line, respectively [18]. In this comparison, \(B_X\) was set equal to \(1.0B_{00}\). In Fig. 7(a), the current-sheet width \(2\delta\) was longer than \(2\rho_i\) because of the weak external compressing force of \(I_{acc} = 5\) kA. During the slow and weak compression process, \(\eta_X\) was observed to be constant (=0.3 m\(\Omega\)m). However, \(\eta_X\) increased slightly when \(2\delta\) became as short as \(2\rho_i\). In Fig. 7(b), the larger external force of \(I_{acc} = 10\) kA compressed \(2\delta\) faster under the same \(B_X\) condition as (a). It is noted that \(\eta_X\) increased significantly right after \(2\delta\) was compressed shorter than \(2\rho_i\) = 5 cm \((t > 27.5\) \(\mu s))\). After \(t = 27.5\) \(\mu s\), \(2\delta\) was also observed to decrease faster than before.

Fig. 8(a) and (b) show time evolutions of \(\eta_X\) at the X-point, \(2\delta\) and \(2\rho_i\), for another two reconnections: (a) \(B_X = 2.5B_{00}\) and (b) \(B_X = 1.0B_{00}\). Both cases had equal external force \(I_{acc} = 10\) kA. These two cases (a) and (b) correspond
to those shown by yellow and red circles in Fig. 5, respectively. The cases (b) and (a) were obtained before and after the abrupt increase in \( \gamma \) in Fig. 5, respectively. In Fig. 8(a), the larger \( B_x \approx 2.7B_0 \) made \( 2\rho_i \) shorter than that of Fig. 8(b). It was observed that \( 2\delta \) was always longer than the small \( 2\rho_i \), and that \( \eta_x \) stayed as small as 0.2–0.3 m\( \Omega \)m. No change in \( 2\delta \) decaying speed occurred even if \( 2\delta \) was compressed shorter than \( 5 \) cm. On the other hand, large increase in \( \eta_x \) was observed in Fig. 8(b) when \( 2\delta \) was compressed shorter than \( 2\rho_i \approx 5 \) cm (\( t > 27.5 \) \( \mu \)s).

Fig. 9(a) and (b) show more clearly the relationship between anomalous increase in \( \eta_x \) and the current sheet (2\( \delta \)) compression shorter than \( 2\rho_i \). In Fig. 9(a), fifteen time-evolutions of \( \eta_x \) under four different \( I_{\text{acc}} \) were superposed on the same plot, in terms of \( \delta \) normalized by \( \rho_i \). All curves agree that \( \eta_x \) stayed as small as the Spitzer resistivity \( \approx 0.2 \) m\( \Omega \)m calculated from the measured electron temperature = \( 5 \) eV, as long as \( 2\delta \) was longer than \( 2\rho_i \). However, \( \eta_x \) increased significantly, once large external force compressed \( 2\delta \) shorter than \( 2\rho_i \). The maximum \( \eta_x \approx 3–3.5 \) m\( \Omega \)m at \( \delta/\rho_i \approx 0.5 \) was almost 15 times larger than the Spitzer resistivity, leading to the fast reconnection observed in the large \( I_{\text{acc}} \). In Fig. 9(b), several evolutions of \( \eta_x \) under six different \( B_x \) field amplitudes were superposed to confirm the mentioned relationship. When \( B_x/B_0 \) was varied, \( \eta_x \) stayed constant (=0.2 m\( \Omega \)m) as long as \( 2\delta > 2\rho_i \) and became markedly large when \( 2\delta < 2\rho_i \). Both curves in Fig. 9(a) and (b) agree well with each other, indicating that the anomalous increase in \( \eta_x \) was caused by the compression of \( 2\delta \) shorter than \( 2\rho_i \).

Fig. 10(a)–(c) show the peak ion temperatures \( T_{ii} \) before and after reconnection (at \( t = 20 \mu \)s and at \( t = 35 \mu \)s, respectively) as a function of \( B_x/B_0 \). The ion temperature \( T_{ii} \) after reconnection was observed to increase with \( I_{\text{acc}} \) and inversely with \( B_x \). The large increase in \( \gamma \) was found to be correlated well with preferential ion-heating of reconnection. For \( B_x/B_0 \approx 2 \), the \( T_i \) increased from 20 to 105 eV, as \( I_{\text{acc}} \) was increased from 6 to 13 kA. For \( I_{\text{acc}} \approx 13 \) kA, it increased from 30 to 105 eV, as \( B_x/B_0 \) was decreased from 3.5 to 1. The electron temperature stayed around 10 eV during each reconnection, indicating the magnetic reconnection heated ions preferentially. It is noted that abrupt change in ion temperature \( T_i \) (after reconnection) occurred around \( B_x/B_0 \approx 2.5 \) (a), 1.8 in (b) and 1 in (c). These threshold values agree well with those in Fig. 5, respectively. It is concluded that abrupt increase in reconnection speed was closely correlated with the similar increase in ion temperature.

The large increase in ion temperature is further connected with another increase in ion outflow. The magnetic reconnection has an inflow roughly equal to reconnection speed and a fast outflow roughly equal to Alfvén speed, converting large portion of magnetic energy into plasma flow energy.

![Fig. 9](image-url)

**Fig. 9.** Time evolutions of effective current-sheet resistivities \( \eta_x \) as a function of \( \delta \) normalized by \( \rho_i \) when (a) four different acceleration-coil currents \( I_{\text{acc}} \) and (b) six different \( B_x \) fields were applied to the merging toroids.

![Fig. 10](image-url)

**Fig. 10.** Peak ion temperatures \( T_{ii} \) before and after the magnetic reconnection as a function of \( B_x/B_0 \) for three different acceleration-coil currents: (a) \( I_{\text{acc}} = 13 \) kA, (b) 10 kA, and (c) 6 kA.
Fig. 11. Dependence of averaged ion outflow velocity on $B_x/B_{|0|}$. The averaged outflow velocity was measured on the midplane ($z = 0$) by use of Doppler shift of carbon impurity line $C\alpha$. Since it was averaged over 3 and 10 cm in radial directions, it was probably smaller than the peak ion outflow velocity. It was observed that the outflow velocity stayed constant ($\approx 20$ km/s, as long as $B_x < 1.5B_{|0|}$. However, the velocity increased significantly up to 55 km/s once $B_x$ was set smaller than $1.5B_{|0|}$. This abrupt change in outflow speed agree well with those in reconnection speed $\gamma$ and the ion temperature $T_i$ after reconnection.

4. Discussions

These experiments, with varied $I_{cc}$ and $B_x$, consistently revealed the clear dependence of the effective resistivity of sheet-current on $\delta$ normalized by $\rho_i$. This fact clearly indicates that some particle effect caused the anomalous dissipation of the current-sheet when $2\delta$ was compressed shorter than $2\rho_i$. Thermal pressure of the current-sheet is considered to sustain the external compressing force of magnetic field, maintaining the current-sheet width. However, when the sheet width becomes shorter than the ion-gyroradius, ions no longer sustain the external force as a fluid, but start meandering inside and outside the current-sheet. The independent motion of ions may produce the thin electron sheet in the center or trigger two-fluid or particle instabilities. Horiuchi and Sato studied these processes using their macroparticle simulation and observed that the reconnection speed increases significantly when the sheet width is compressed shorter than the ion-gyroradius [10]. Their results agree qualitatively with our observation mentioned above. The ion-gyroradius $\rho_i$ increases with the ion temperature and inversely with the magnetic field. This is the most probable reason why the reconnection speed increases with the external force and inversely with $B_x$ in

Fig. 5. The ion-heating-suppression effect of $B_x$ agrees with the general tendency that the $T_i/T_e$ ratio is roughly equal to unity in the ohmic tokamak plasmas with $B_x \gg B_{|0|}$ and much larger than unity in the RFP/spheromak plasmas with $B_x \lesssim B_{|0|}$. In small $B_x$ reconnection, ion acceleration effect of magnetic field lines is considered to heat bulk ions selectively through large ion viscosity effect. The unmagnetized ions are easily mixed together and are thermalized after ion-acceleration phenomenon of reconnection. Since the ion-gyroradius is much larger than the electron-gyroradius, this anomalous heating of ions is considered to occur to that of electrons. However, the application of $B_x$ decreases the outflow speed of reconnection as well as the reconnection speed. It also decreases the ion-gyroradius and magnetizes ions like electrons, preventing the ion-thermalization process. The viscosity coefficient becomes smaller with increasing $B_x$ around the X-point. Decreases in the ion outflow speed and ion-gyroradius provide a possible explanation for the ion-heating-suppression effect of $B_x$. It is also noted that both of $T_i$ increments and reconnection rates $\gamma$ became markedly large, when $B_x/B_{|0|}$ was smaller than the threshold values: 2.5 in Fig. 5(a), 1.8 in Fig. 5(b) and 1 in Fig. 5(c). In each case, the compressed $2\delta$ was observed to reach $2\rho_i$ when $B_x/B_{|0|}$ was below each threshold value, indicating close relationship between the anomalous dissipation of current-sheet and the selective ion heating. Once $2\delta$ was compressed shorter than $2\rho_i$, the anomalous dissipation of current sheet increased significantly the plasma outflow speed as well as the reconnection speed as shown in Fig. 11. The anomalous increase in current sheet resistivity and that in ion temperature were related with each other probably because the high-speed outflow was thermalized through the large ion viscosity under small $B_x$ condition.

The ion heating effect of magnetic reconnection is promising heating method for various magnetized plasmas. We have been exploring several new applications of magnetic reconnection to high power heating of fusion plasmas. Two examples of plasma heating shall be described in this section.

The field-reversed configuration (FRC) merging formation with significant ion heating was documented during magnetic reconnection of two spheromaks with opposing
toroidal magnetic field. As shown in Fig. 12, two spheromaks with opposing toroidal field were collided in the axial direction and their merging/reconnection converted the toroidal magnetic energy of the initial spheromaks into ion thermal energy of the produced FRC. In this case, merging angle of reconnecting field lines were 180° ($B_\parallel = 0$), indicating that the strongest ion heating was expected during the reconnection. A spheromak and an FRC are both compact toroids whose simply connected topologies allow their axial translations and mergings. The spheromak with toroidal and poloidal magnetic fields $B_r$, $B_p$ is in the Taylor minimum-energy states, which are widely known to be stable force-free states without plasma thermal pressure. On the other hand, the FRC solely with poloidal magnetic field $B_p$ has the high-beta (>70%) equilibrium whose equilibrium is sustained by self-expanding force of thermal pressure and self-shrinking force of PF. Fig. 13 shows the 2-D contours of poloidal flux surface and toroidal field amplitude, measured by 2-D magnetic probes array. Two spheromaks with opposite $B_r$ were observed to merge together from $t = 10$ to 17.5 $\mu$s. The reconnected field lines offered an overshoot or oscillation: initially, the polarity of $B_r$ was positive on the left-hand side and negative on the right-hand side and then after $t = 20$ $\mu$s, it became negative on the left-hand side and positive on the right-hand side. From $t = 12.5$ to 22.5 $\mu$s magnetic field lines were observed to move oppositely in the both edge regions: positive for $R > 18$ cm and negative for $R < 18$ cm. The inner-halves and the outer-halves of the reconnected field-lines accelerated plasma ions oppositely in the toroidal direction, as illustrated in the upper-left. The ion acceleration was followed by a large increase in $T_e$. Fig. 13 also shows the radial profiles of ion temperature $T_e$ measured on the midplane. As shown in Fig. 13, ions were selectively heated by magnetic reconnection from 10 up to 200 eV within 10 $\mu$s, while $T_e$ stayed around 10–20 eV. The total increase in the ion thermal energy $W_{th}$ was estimated to be 180 J, which was as large as 80% of the dissipated magnetic energy $W_m \approx 230$ J. Since the neutral current sheet dissipation was as small as 20 J, $W_m$ was considered to be converted directly to $W_{th}$ through the reconnection outflow. This direct energy-conversion was probably due to the ion viscosity heating in the process of velocity shear formation. Ion viscosity force against the overshoot motion was significantly large because ions were unmagnetized widely around the field annihilated X- and O-points. This high-efficiency energy-conversion is the main mechanism for this high-β equilibrium transition and is useful for the initial heating of FRCs, leading us to a new scenario of FRC slow-formation, heating and flux(current)-amplification proposed in Ref. [19].

Fig. 13. Poloidal flux contours with toroidal field amplitude and radial ion temperature profile during the merging formation of FRC. Its reconnection process is illustrated in the upper left.

![Graph showing toroidal flux contours and reconnection process in FRC.](image)

Fig. 14. Initial high-power heating of STs by use of their axial merging/magnetic reconnection.
Another fusion application of magnetic reconnection is high-power heating of spherical tokamak (ST) plasmas by use of their axial merging [20]. The ST has a potential to be a high-beta fusion confinement ($B_X$) because of the Troyon scaling $\beta = 1/A$ (aspect ratio). Recently, it has been reported that ST has a large direct window to the second stability regime for ballooning instability. As shown in Fig. 14, one ST was collided into another target ST and their merging/magnetic reconnection was expected to inject heating energy into the target STs within short reconnection time. Since the STs have the $B_X$ field component parallel to the X-point line, the heating power of merging mostly depends on $B_X$ amplitude. Fig. 15 shows time evolutions of thermal energies of the merging STs and a single ST when $B_X/B_{00} = 1$ (a) and $B_X/B_{00} = 2.5$ (b) under an equal poloidal poloidal flux condition. Each thermal energy was calculated from measurements of $T_e$, $T_i$ and $n_e$. In both cases, the thermal energies of the merging STs were observed to increase significantly as soon as they started merging. The maximum heating power of 10 MW was obtained when $B_X/B_{00} = 1$. The thermal energies of the merged STs were much larger than those of the single STs in both cases. It is also noted that the heating energy increased with decreasing $B_X/B_{00} = 1$ ($q$-value) of the merging STs. The heating of target ST was mostly caused by the ion heating effect of magnetic reconnection mentioned in Fig. 10. The ion temperature $T_i$ increased inversely with $B_X/B_{00}$, in agreement with Fig. 10. After the large increase in $T_i$, the electron temperature $T_e$ increased slowly up to 40 eV, but its increment was much smaller than in $T_i$ probably because the present small-scale (major radius $R \approx 0.2$ m) plasmas had large electron loss channel such as radiation losses in our TS-3 device.

A scale up experiment is needed to study the electron channel of magnetic reconnection, and also to explore various applications of magnetic reconnection to fusion plasmas such as high-beta STs and FRCs. This motivation leads us to the construction of the TS-4 FRC/ST merging device. Fig. 16 shows the photograph and the vertical cross-section of the TS-4 FRC/ST merging device. It has
two flux-cores for production of two spherical torus plasmas in its cylindrical vacuum vessel with length of 1.8 m and diameter of 1.8 m. Currents of separation coils will be used to control the merging of two plasma toroids, for the purpose of MRX in high Reynolds number over 3000. After merging/reconnection, the produced plasma toroids: STs or FRCs will have a major radius \( R = 0.5 \) m, an aspect ratio \( A \approx 1.25 \) and a toroidal magnetic field \( B_t < 3 \) kG at the magnetic axis. They will be sustained for 5 ms by the center OH coil to investigate their stability and confinement properties. Those fusion applications of reconnection heating also lead us to the initial operation for plasma processing at the TS group. The strong dependence of reconnection heating on \( B_x \) is being used to control independently ion and electron temperatures of processing plasmas.

Based on our various experiments of plasma merging and reconnection since 1986, the merging experiment has been recently adopted by several universities and national laboratories in the USA to study magnetic reconnection and its fusion application such as the FRC merging formation. As shown in Fig. 17(a), the MRX was constructed in 1995 for magnetic reconnection and FRC formation [21]. Then, the Swarthmore spheromak experiment (SSX) [22] shown in Fig. 17(b) started operation in 1997 using two plasma guns and a flux conserver. The Swift-FRC and the self-organized plasma with induction, reconnection and injection techniques (SPIRIT) were proposed in NASA [23] and in Princeton University [21] for merging formation of FRCs.

5. Summary

In summary, the CT merging experiments in TS-3 device made clear a mechanism for anomalous dissipation and ion heating effects of magnetic reconnection. The resistivity of the sheet-current was observed to increase significantly, when the current-sheet was compressed shorter than the local ion-gyro-radius. This effect caused the reconnection speed, ion outflow speed and its ion heating energy to increase with the external compressing force and inversely with \( B_x \). Especially, the application of \( B_x \) to the X-point was found to suppress the anomalous increase in the sheet-current resistivity and the ion temperature. This \( B_x \) effect is the most probable cause for the high magnetic fluctuations and \( T_i \gg T_e \) characteristics of the RFPs with small \( B_x \approx B_y \) reconnection and the low magnetic fluctuation and \( T_i \approx T_e \) characteristics of tokamaks with large \( B_x \gg B_y \) reconnection. The ion heating effect of magnetic reconnection was successfully applied to the high-power heating of several fusion plasmas. The merging/reconnection of two spheromaks with opposing toroidal magnetic field transformed the low-beta spheromak equilibrium into the FRC equilibrium with beta as high as 1 within a short reconnection time of 10 \( \mu \)s. The dissipated toroidal magnetic energy of two spheromaks was mostly (about 80%) converted into ion thermal energy of the produced FRC through the magnetic reconnection without \( B_x \). The reconnection with finite \( B_x \) was used for an initial high-power heating of STs. The ion heating power as high as 10 MW was documented in the present small size experiment. The ion heating energy was varied between 0 and 10 MW depending on the \( B_x \) component and the sheet-current compression force.

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