

Global Ion Heating during ST Merging Driven by High Guide Field Reconnection^{*)}

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The physical processes of ion heating during high guide field ($B_g/B_{rec} \sim 6$) reconnection is explored utilizing Doppler tomography measurement in the TS-6 ST (Spherical Tokamak) merging experiment. The newly developed 288CH extensive/high-resolution ($\Delta r \sim 1.5$ cm; $\Delta Z = 1.0$ cm) ion Doppler spectroscopy system has revealed the detailed characteristic of ion heating in the downstream region. In the high guide field regime, ion heating occurs not only around the diffusion region but also more globally in the downstream region. This was beyond the scope of the previous ion temperature measurement and hence we have confirmed a different heating mechanism which is attributed to strong in-plane electric field produced extensively in high guide field reconnection regime.

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1. Introduction

Magnetic reconnection is a fundamental plasma phenomenon that involves changing of magnetic topology via breaking and rejoining of magnetic field lines. Reconnection is an ubiquitous process that occurs across an extensive domain of plasma parameter space, including the collisionless plasma at the Earth's magnetosphere and the dense, hot plasmas deep in the solar convection zone such as solar flares. Particularly in solar flares, a significant energy is released during reconnection and transferred into energetic electrons and ions, with ions reaching temperatures of several GeV [1].

There has been a strong interest in reconnection heating by utilizing spherical tokamak merging over the past few decades in plasma fusion research. In ST merging experiments, through magnetic reconnection, two torus plasmas with low temperature are merged into a single torus plasma with higher temperature under high guide field. Since 1986, a number of plasma merging experiments: TS-3/4 [2], UTST [3] in University of Tokyo, START [4], MAST [5] in Culham research institute, MRX [6] in Princeton Plasma physics Laboratory, were conducted, showing that ions are mainly heated in the downstream region and electrons are heated around the X-point. It is reported that the presence of the guide field could have a qualitatively significant effect in reconnection physics, particle acceleration, and associated particle heating. Since charged particles are still magnetized even at the X-point, particles are accelerated along the guide field by the reconnection electric field, which is almost parallel to the guide

field, resulting in a quite different acceleration/heating mechanism as compared to the non-guide field case [7–9]. In particular, anomalous ion heating has been frequently observed to be much faster than conventional collisional heating in various astrophysical and laboratory guide field reconnection events.

Despite numerous reconnection research, there have been outstanding challenges that drive experimental/theoretical investigations of the high guide field reconnection physics, namely : 1) Which effect determines ion acceleration and heating? 2) How much energy is converted to particles? As for the first question, various candidates have been suggested such as stochastic heating for heavy ions, pickup, viscosity heating in shock waves, collisions in the downstream region [10], and fast reconnection driven by plasmoid ejection in the high- q region [11]. Regarding the second question, previously the experimental ion temperature diagnostics are focused mainly around diffusion region despite the fact that some ions get energy through extensive path. Our recent ion Doppler tomography measurement has enabled us to measure the global downstream region with higher resolution ($\Delta r \sim 1.5$ cm; $\Delta Z = 1.0$ cm) and comprehend the ion heating mechanism. Therefore, understanding how ions gain energy from guide field reconnection is of central importance in the present research of magnetic reconnection. This paper presents data from experiments carried out on a recently developed ST merging reconnection experiment, TS-6. An important feature of this experiment is that it allows us to study high guide field reconnection up to high value of guide field $B_g/B_{rec} \sim 10$. The detailed characteristics of the ion heating and magnetic fluxes can be captured using high res-

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olution 2-D plasma parameters diagnostic systems. This paper is organized as follows : Section 2 describes the setup of the ST merging experiment system, which produces two ST-like counter-streaming plasma flows. The elaborated configuration of plasma diagnostics, the novel Doppler spectroscopy system, high resolution 2-D magnetic probe array are also explained. Section 3 provides the results, showing the global characteristics of ion heating in high guide field reconnection. Section 4 summarizes these experimental results.

2. Experimental Setup

We have used the TS-6 facility in order to experimentally study the ion heating mechanism in high guide field reconnection by the ST merging technique. Magnetic reconnection is provoked between poloidal magnetic fields of two torus plasmas, producing a single high-beta torus plasma in a very short time period (< 0.1 ms). Figure 1 shows the configuration of the TS-6 device, also providing its cross-sectional view. The TS-6 device consists of a cylindrical vacuum vessel, TF coils (12 turns), two pairs of PF coils, a pair of equilibrium coil, a CS coil. The dimension and winding number of these coils are also listed in Fig. 1. The blue solid line indicates the poloidal magnetic flux contour produced by poloidal field (PF) & equilibrium field (EF) coils. Typical major/minor radii of the merged ST plasma in the TS-6 are $R \sim 0.2$ m and $a \sim 0.1$ m, respectively. The radius of the vacuum vessel is 375 mm and its separatrix radius is around $R_{\text{sep}} \sim 335$ mm (which is controlled by EF coil current).

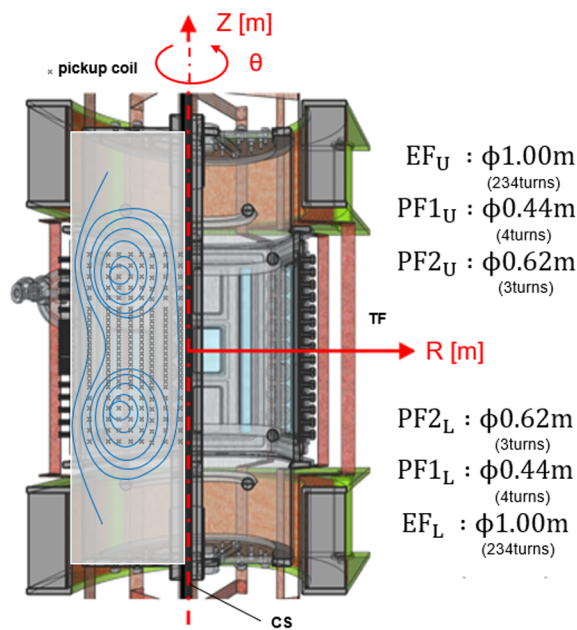


Fig. 1 Toroidal cross section of the TS-6 ST merging device. The blue solid lines indicate the poloidal magnetic flux contour. The red points denotes the position of magnetic probe pickup coils.

The main diagnostics for studying plasma formation and merging processes are a set of internal 2-D magnetic probe arrays and the ion Doppler spectroscopy system. The 2-D magnetic probe array with a spatial resolution of ($\Delta Z \sim 1.1$ cm) covers the poloidal cross-section (-0.23 m $\leq z \leq 0.25$ m, -0.075 m $\leq r \leq 0.335$ m).

The local ion temperature is measured by utilizing the novel ion Doppler tomography spectroscopic system, which consists of 288 measurement points with a high spatial resolution ($\Delta r \sim 1.5$ cm; $\Delta Z = 1.0$ cm). Figure 2(a) illustrates the recently developed ion temperature diagnostics installed in TS-6. The 288CH optical fibers (16CH radially, 18CH axially) are installed in collecting lenses system (focal length: $f = 30$ mm, 7.5 mm width, 25 mm diameter) which is attached on the vacuum window and transmits line integrated spectra to the fibers. This 2D projection of line-spectrum emission is transported to a spectrometer through each optical fiber (core width is 485 μ m, diameter of the clad is 500 μ m, NA = 0.5) relayed by glass fibers (core width is 200 μ m, diameter of the clad is 240 μ m, NA = 0.2). The spectrometer ($f = 1000$ mm, NA = 0.06, $F = 8.3$, $g = 1800$ L/mm) is equipped with the multi-slit (64×5 , slit width = 50 μ m) on its entrance which enables high resolution multi-channel diagnostics (Fig. 2(b)). Spectrally dispersed lights are detected by ICCD image sensors (1024×1024) after correction of the astigmatism through magnifying optics (meridional (λ): $\times 2$, sagittal: $\times 0.68$). The ICCD image in Fig. 2(a)

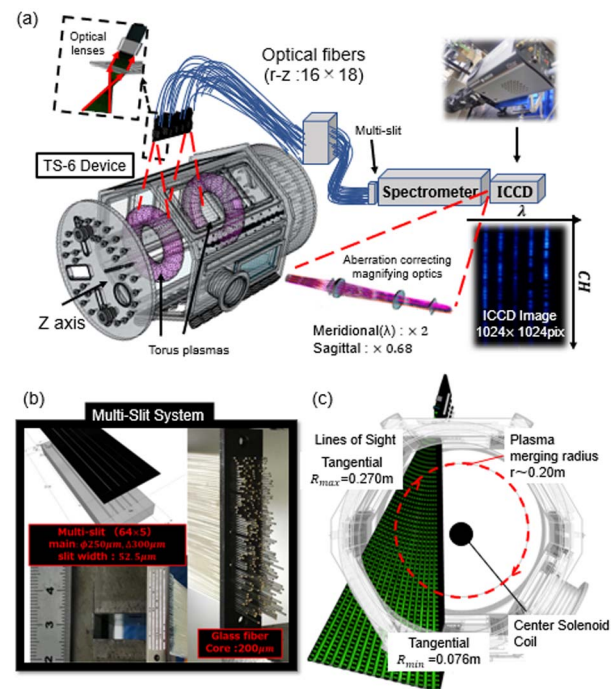


Fig. 2 (a) Schematics of ion Doppler tomography spectroscopic system installed on TS-6 device. (b) Details of multi-slit system. (c) Line-of-Sight (LOS) of ion Doppler spectroscopy in the cross section of TS-6. LOS has tangential view from R_{min} (0.076 m) \sim R_{max} (0.27 m).

shows the measured 288 line-integrated spectra of the H_α line which are collected with an exposure time $5 \mu\text{s}$. The dispersion of the instrument is 0.00332 nm/pixel . In this experiment, the 2D (16×18) chords are movable in axial direction according to the measurement area of interest: the system covers the axial range $-0.220 \text{ m} \leq z \leq 0.220 \text{ m}$ (we call it global mode), $-0.080 \text{ m} \leq z \leq 0.09 \text{ m}$ (local mode). The Line-of-sight has tangential view which covers from R_{\min} (0.076 m) $\sim R_{\max}$ (0.27 m) (Fig. 2 (c)).

3. Global Ion Heating in Guide Field Reconnection

In this experiment, we used hydrogen as the working gas. Typical plasma parameters are as follows; plasma current: $\sim 70 \text{ kA}$; toroidal magnetic field around the reconnection X point: $\sim 0.18 \text{ T}$ poloidal magnetic field: $\sim 0.03 \text{ T}$, plasma density: $\sim 1.0 \times 10^{20} \text{ m}^{-3}$.

Figure 3 shows time evolution of several characteristic parameters during the ramp-up phase of plasma current in the TS-6 ST merging experiment. Figure 3(b) shows time evolution of poloidal magnetic flux: private

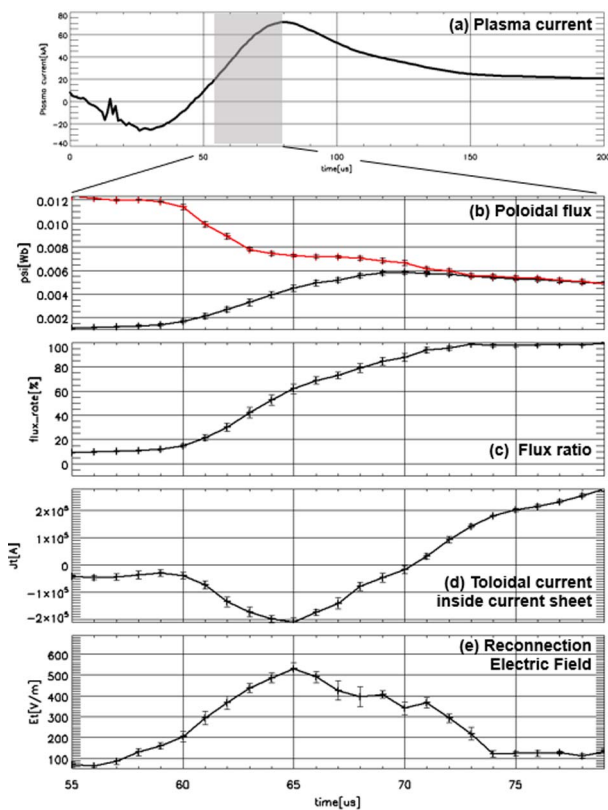


Fig. 3 Time evolutions of (a) Plasma current I_p , (b) Poloidal magnetic flux of private flux ψ_{private} (red) and common flux ψ_{common} (black), (c) Flux ratio, (d) toroidal current J_t inside the current sheet, (e) Reconnection Electric field inside the current sheet E_t . Drastic change of (b)-(e) occurs during the ramp-up phase of plasma current ($55 \mu\text{s} \sim 80 \mu\text{s}$). The error bar means standard deviation from several shot in same experimental condition.

flux ψ_{private} (which refers to magnetic flux that has not reconnected yet) and common flux at the X-point ψ_{common} (which refers to the magnetic flux already reconnected). Note that we evaluate the private flux as the maximum poloidal flux at the magnetic axis in approaching initial ST plasma. Figure 3(c) shows time evolution of the ratio of common flux at the X-point to private flux defined as $\psi_{\text{common}}/\psi_{\text{private}}$. Around the X-point, common flux gradually increases whereas the private flux decreases, and both values converge after the merging process is completed ($\psi_{\text{common}}/\psi_{\text{private}} \sim 100\%$). Figure 3(d) shows the time evolution of the current density J_t inside the current sheet. The local structure of magnetic reconnection is generally characterized by the ion gyroradius or ion skin depth and in this experiment, the current sheet length ($\sim 60 \text{ mm}$) and ion skin depth ($d_i = c/\omega_{pi}$) are of the same scale, which results in the two-fluid effect inside the current sheet. During the pile up of the magnetic field, an oppositely polarized current sheet is formed between the 2 initial ST plasmas. The magnitude of J_t increases from $t = 60 \mu\text{s} \sim 65 \mu\text{s}$, and subsequently reduces as the flux_rate begins to saturate. The reconnection toroidal Electric field around the X-point also has a similar tendency (Fig. 3(e)). The magnitude of E_t gradually increases in the early phase of merging, and then, declines from its peak ($\sim 500 \text{ V/m}$) in synchrony with the J_t profile.

Recently many observations of ion heating during guide field reconnection in laboratory experiments have revealed the mechanisms of ion acceleration/heating [10, 12]. However, those observations were strictly limited to the region around the current sheet, along with a part of the downstream region. On the other hand, it has been demonstrated that in the high guide field regime, electrons and ions experience different acceleration along the magnetic field, so an electrostatic potential develops due to two-fluid effects, having a quadrupole structure in a large area of the downstream beyond the diffusion region [11, 13, 14]. This electrostatic potential E_{st} generates an in-plane electrostatic field which produces the bulk ion acceleration whose speed is close to the Alfvén velocity $V_A \equiv B_{\text{rec}}/\sqrt{\mu m_i n_i}$, where m_i is the ion mass and n_i is the ion density. On top of that, the other mechanism, “pick-up” model demonstrates that non adiabatic ions crossing the separatrix without passing the X-point are suddenly accelerated by the in-plane electric field and effectively heated as they are re-magnetized downstream [15]. Therefore, the in-plane electrostatic potential structure is responsible for ion acceleration/heating and due to its widespread structure, extensive ion temperature measurement was crucial in order to clarify ion acceleration/heating characteristics in guide field reconnection comprehensively.

Figure 4 shows the characteristic time of the 2D ion temperature profile measured by 288CH ion Doppler tomography spectroscopic system in the TS-6 ST merging experiment. Here, we use the H_α ($\lambda = 656.27 \text{ nm}$) spectrum because the charge exchange time τ_{ch} is suf-

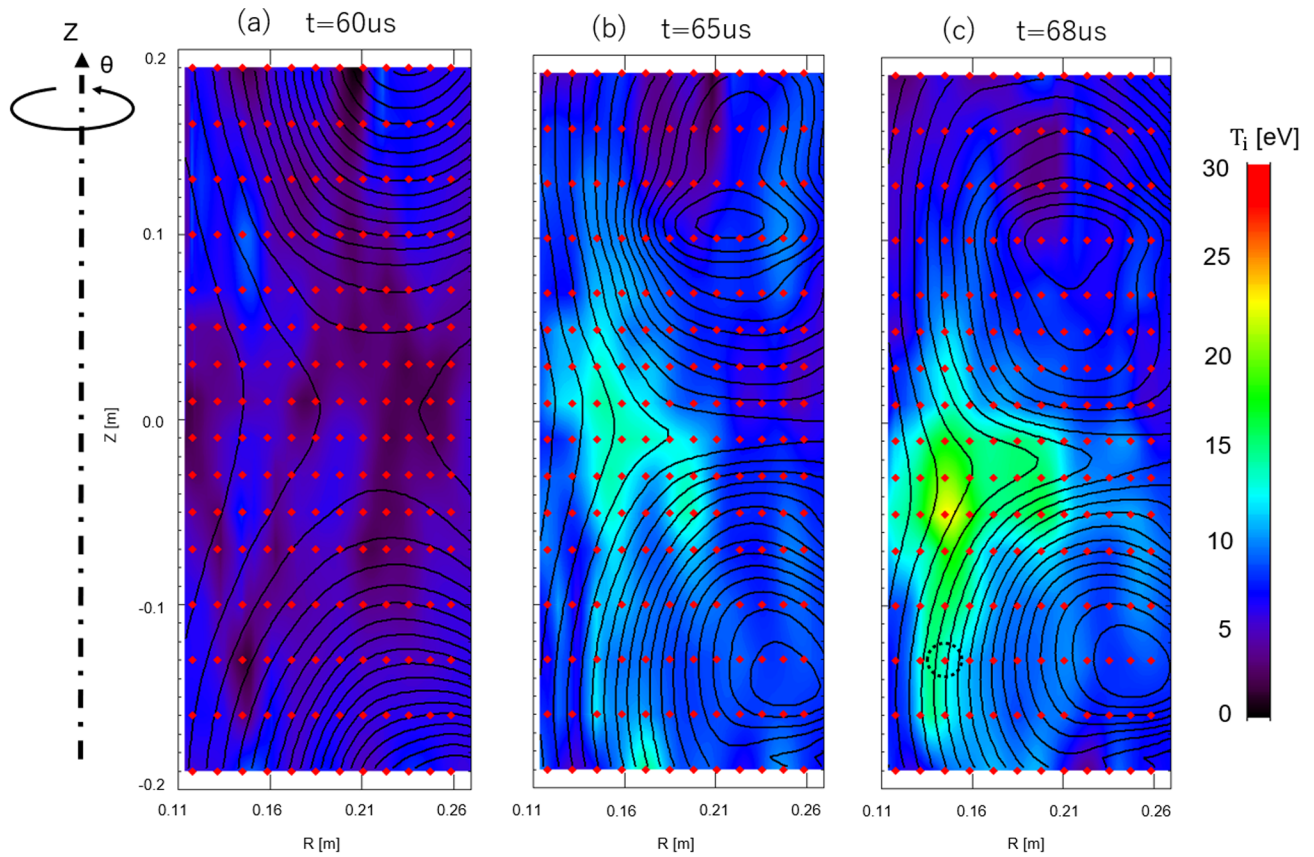


Fig. 4 Detailed 2D profile of Ion temperature (a) $60 \mu\text{s}$, (b) $65 \mu\text{s}$, and (c) $68 \mu\text{s}$ measured by 288CH Doppler tomography installed on TS-6. The novel ion temperature measurement system detect the global ion heating process downstream and along separatrix. The red marker shows the measurement point of the optic fiber. The black contour line depicts the poloidal magnetic field measured by 2D magnetic probe array.

ficiently short compared with the typical camera exposure time ($\sim 3 \mu\text{s}$) in this experiment. In the previous ion Doppler system, which had 7×5 or 8×4 chords ($\Delta r \sim 35 \text{ mm}$, $-0.05 \text{ m} < z < 0.05 \text{ m}$) [16], spatial resolution and measurement range were insufficient; on the other hand, the newly developed ion Doppler system covers extensive measurement range including the two merging ST. As the breakdown occurs and plasma rings formed on the upside and downside of vessel approach each other due to mutual attraction (Fig. 4(a)), a current sheet is formed around the X-point and magnetic reconnection takes place at the middle plane ($z = 0$). In this period, the ion temperature profile is flat and no significant difference in T_i is observed, however, during reconnection ($t \sim 65 \mu\text{s}$), ion temperature increases around the downstream region of the X-point ($-0.05 \text{ m} < z < 0.05 \text{ m}$, $0.13 \text{ m} < R < 0.22 \text{ m}$) up to over 20 eV, probably due to viscous damping of reconnection outflow and collision because of higher plasma density in the downstream region than the upstream region [10, 17]. According to a previous ST merging experiment [17], the ion flow diagnostic measured that the reconnection outflow from the X-point is damped downstream, where a fast shock-like structure is formed as electron density n_e and magnetic field strength change. Around

this fast shock point, thermalization of ions accelerated in the diffusion region takes place.

Besides, despite the relatively small amplitude of heating compared with the downstream, clear ion heating is also shown in the global region along a magnetic surface (the small black dashed area in Fig. 4(c)) which was beyond the scope of previous research. In this experiment, the strong in-plane electrostatic field is observed around the separatrix as well as around the marked area in Fig. 4(c). A typical magnitude of E_{st} around the dashed area is 2000 V/m which is much larger than out-of-plane reconnection electric field $E_t \sim 400 \text{ V/m}$. The corresponding $E \times B$ drift velocity is about 11 km/s which is equivalent to 0.63 eV per hydrogen ion - much smaller than energy required to compensate for the increment of thermal energy ($\sim 10 \text{ eV}$). The most probable interpretation of this global ion heating profile is that upstream non-adiabatic ions move across the separatrix and are accelerated by a large in-plane electric field near it (potential drop across separatrix is more than 10 V) [18]. The ions accelerated through this in-plane electric field are significantly heated by viscous damping and affected by the magnetic field further in the downstream, increasing the chance to get thermalized by collisions with the plasma inside the

thick closed (reconnected) field lines surrounding the hot spot [10]. Since in the high guide field merging operation ($B_g/B_{\text{rec}} \sim 6$) the ratio of ion thermal diffusivity $\kappa_{\parallel}^i/\kappa_{\perp}^i \sim 2(\omega_{ci}\tau_{ii})^2 > 10$ and heat transport perpendicular to the magnetic field is suppressed so that the accelerated ions across separatrix are re-magnetized and collide which leads to the high T_i region prevailing downstream and along magnetic surface (Fig. 4 (b)). In the ST merging operation, due to the higher toroidal field around the in-board side, downstream heating and efficient confinement of thermalized ion are achieved, which is advantageous for the application of reconnection heating to fusion plasma start-up.

4. Summary

Ion heating characteristics during high guide field reconnection has been investigated experimentally in the TS-6 ST merging experiment by utilizing the 2D magnetic probe array and ion Doppler tomography diagnostics. During ST merging, ion heating is classified into two groups. One is ions entering downstream through diffusion region and thermalized by viscous damping and collision. The second group is ions moving across the separatrix - this heating occurs in a rather global area that was inaccessible to conventional diagnostic systems. Although the detailed ion acceleration mechanism for this second group remains unsolved, it is found that a high ion temperature region prevails along the magnetic surface inside the tokamak. This indicates the region where ions gain energy is not limited

around the diffusion region but exists globally in regions having an in-plane electric field. The scaling of ion heating and in-plane electric field with the guide field will be explored in future work. Furthermore, different diagnostics such as IDSP or NPA which are under installation, are required to reveal the ion acceleration mechanism around these areas and understand it from a kinetic point of view.

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