Investigation of fine structure formation of guide field reconnection during merging plasma startup of spherical tokamak in TS-3U

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Abstract
Ion heating/transport and its fine structure formation process through magnetic reconnection have been investigated by high guide field tokamak merging experiments in TS-3 and TS-3U. In addition to the previously reported demonstration of high-temperature plasma startup without center solenoid, the detailed fine structure formation process of reconnection heating has been revealed using new 96CH/320CH ultra-high-resolution 2D ion Doppler tomography diagnostics. By identifying the double-axis field configuration with the X-point on the midplane using in situ magnetic probe diagnostics, the detailed measurement successfully revealed that the ion temperature profile forms two types of characteristic heating structure, both around the X-point and downstream. The former is affected by the Hall effect to form a tilted heating profile, while the latter is affected by the transport process which forms a poloidal double-ring-like structure. The achieved ion heating mostly depends on the reconnecting component of the magnetic field, and the contribution of the guide field to decrease the heating efficiency tends to be saturated in the high guide field regime. Under the influence of better toroidal confinement with higher guide field, the downstream ion heating is transported vertically, mostly by parallel heat conduction, and finally forms a poloidal ring-like hollow distribution aligned with the closed flux surface at the end of merging.

Keywords: spherical tokamak, center-solenoid-free startup, guide field reconnection, ion heating

(Some figures may appear in colour only in the online journal)
VTF [8], TS-4 [9], UTST [10], C-2U [11] and MAST [12, 13]. For all of the laboratory experiments, the following common characteristics have been reported: (i) magnetic reconnection heats ions downstream and electrons around the X-point where magnetic field lines reconnect [13, 14]; (ii) ions are heated by the thermalization of flow energy of the reconnection outflow jet [15] while electrons gain energy mostly by Ohmic dissipation of the current sheet [14]; (iii) most of the heating energy goes to ions, and electron heating is small [16, 17] (ions are heated globally but electron heating is localized near the X-point); and (iv) the achieved maximum reconnection heating rate depends on the amplitude of the reconnecting component of the magnetic field: $B_{rec}$ ($B_p$ for tokamak) [18]. Based on these characteristics, significant plasma heating over 100 eV was demonstrated in TS-3 [3], START [19], C-2U [20] and MAST [21].

The high-field merging experiment in MAST documented ∼1 keV of global ion heating and bulk electron heating up to hundreds of eV through ion–electron energy relaxation [21–23], successfully exceeding the radiation barrier of low-Z impurities to achieve a duration time of over 100 ms in the solenoid-free startup [18, 23]. As a promising startup scenario for the spherical tokamak, the high-field merging experiment in MAST also achieved successful connection with additional heating by neutral beam injection and solenoid (hybrid startup scenario) to establish the H-mode and a longer flat-top plasma current (typically hundreds of milliseconds) [18, 23, 24]. In the MAST merging experiments, which are typically operated in the high guide field condition $B_t/ B_{rec} > 3$ with $B_t \sim 0.6$ T and $B_{rec} \sim 0.1$ T [25], better toroidal plasma confinement of ion heating after merging was key to connecting the high-temperature merging plasma startup to the long-pulse scenario.

However, in MAST, due to the absence of in-plane poloidal field measurements during reconnection, investigation of the detailed heating/transport mechanism was not possible. As post-MAST projects, further upgrade projects have now been started in ST40 ($B_t \sim 3$ T and $B_{rec} > 0.2$ T; higher than MAST) by Tokamak Energy Ltd. [26] and TS-U ($B_{rec} > 0.1$ T with MAST-like high-resolution diagnostics) at the University of Tokyo [27]. In order to investigate the further upgraded scenario of the tokamak merging with the high guide field ($B_t > 3B_{rec}$), detailed investigations of the ion heating/transport process have been done in TS-3 and TS-3U (TS-6). This paper addresses the highlights of the new findings in the laboratory merging experiments: the fine structure formation of the ion temperature profile by reconnection heating and the visualization of its global transport process, which also forms a characteristic profile using new 96CH/320CH ultra-high-resolution ion Doppler tomography diagnostics.

### 2. Merging plasma startup of spherical tokamak

Figure 1 shows typical features of the merging plasma startup in TS-3 [14, 28]. Magnetic reconnection is driven by the poloidal field (PF) coil current $I_{PF}$ (kA · turn) and the two plasma rings at the top and bottom of the device ($t = 70$ µs) merge together and form a spherical tokamak after merging ($t = 90$ µs) as shown in the high-speed camera images and poloidal flux profile. The toroidal current density $j_t$ (MA m$^{-2}$) has the opposite polarity around the X-point (current sheet) during magnetic reconnection ($t = 76$ µs) and the fast camera detects a toroidal ring-like structure where the current sheet exists [29]. The ion temperature starts to increase around this

![Figure 1](image-url)
phase and forms a double peak structure at $r \sim 0.15$ m and $r \sim 0.25$ m where the reconnection outflow jets dissipate.

### 3. Fine structure formation of reconnection heating

Figure 2 shows the 2D ion temperature profile measured by new 96CH 2D ion Doppler tomography, which was upgraded from the previous 35CH system [30, 31] as a TS-U project (upgrade project for U-Tokyo spherical tokamak). As illustrated in figure 2(a), it spans 16CH radially and 6CH axially ($\Delta r \sim 35$ mm and $\Delta z \sim 20$ mm) to resolve the detailed structure around both the X-point and global profile downstream. In previous TS-3 experiments using the $7 \times 5$ or $8 \times 4$ chord system ($\Delta r \sim 35$ mm and $\Delta z \sim 20$ mm), its spatial resolution and the measurement range were not sufficient and the old tomography system could not resolve such a detailed
and ion skin depth of $T_i$ characteristic high: the toroidal guide field, the polarity of the downstream heating profile forms a poloidally tilted structure by the Hall effect, while the characteristic high-$T_i$ region propagates vertically after merging and forms a poloidal ring-like distribution.

distribution for more than a doubly peaked profile [14, 30]; however, the upgraded system can successfully resolve the micro/macro-scale fine structure formation process. During the characteristic three time frames within 10 $\mu$s at $t = 70, 75$ and 80 $\mu$s (before, during and after merging), the ion temperature starts to increase and forms the characteristic heating profile shown in figure 2(b). During reconnection at $t = 75 \mu$s, the ion temperature increases around the X-point as well as downstream from the outflow jet, while after merging at $t = 80 \mu$s, the high-$T_i$ region downstream propagates vertically, aligned with the closed flux surface of the tokamak configuration.

Figure 3 highlights these two characteristic time frames during reconnection (acceleration phase) and after merging (transport/confinement phase). During merging (phase 1), the ion temperature profile is affected by the accelerating effect of guide field reconnection (the coupling of the Hall effect with $B_t$ [32]) as the $T_i$ profile around the X-point changes. For the hydrogen merging experiment (ion gyro radius $\rho_i \sim 5$ mm and ion skin depth of $c/\omega_{pi} > 20$ mm), the $T_i$ profile forms a horizontally straight structure on the midplane, while for helium merging ($\rho_i \sim 10$ mm and $c/\omega_{pi} > 40$ mm), the ion temperature profile around the X-point forms a poloidally tilted structure in the anti-clockwise direction (highlighted by red arrows) because of the enhancement of the contribution of the Hall effect by the larger scale length with higher mass ratio [33]). After merging (transport/confinement phase), the reconnection heating profile forms another structure downstream. For the experimental condition of the tokamak merging with the high guide field ratio of $B_i/B_{rec} \sim 5$ ($B_{rec} \sim 0.02$ T and $B_t \sim 0.1$ T), the ratio of ion thermal diffusivity $\chi_i / \chi_{\perp} \sim 2(\omega_{ci}\tau_{ni})^2 > 10$ and the parallel heat transport term dominates the heat conduction, the high $T_i$ region propagates vertically and forms a poloidal ring-like hollow distribution.

4. The effect of guide field and reconnecting field on startup performance

For the application of reconnection heating, it has long been discussed that the toroidal field contributes to the confinement after merging, while the reconnection heating rate also decreases because of the suppression of the ion viscosity coefficient and acceleration efficiency in the high guide field regime. However, for the trade-off problem, recent laboratory experiments and particle-in-cell simulation demonstrated that sufficient acceleration efficiency could be arranged by triggering fast reconnection by the driving inflow even in high guide field conditions [34, 35]). Regarding the dissipation of flow energy by viscosity heating: $P = \int [\eta_D(\text{div}u)]^2 + \eta_R(\text{rotu})^2]dV$ (reduced form of Braginskii’s viscosity heating term [36] in $\omega_{ci}\tau_{ni} \gg 1$ [37]), figure 4(a) shows the guide field dependency of viscosity coefficients $\eta_D$ and $\eta_R$. The coefficient $\eta_R = 0.3nT_i/(\omega_{ci}^2\tau_{ni})$ is strongly suppressed by the guide field as it decreases with the square of ion gyro frequency. On the other side, another viscosity coefficient $\eta_D = (1 + (\omega_{ci}\tau_{ni})^2)\eta_R = 0.3nT_i/(\omega_{ci}^2\tau_{ni}) + 0.3nT_i\tau_{ni}$ has a DC term $0.3nT_i\tau_{ni}$ which is not affected in the high-guide-field regime. Figure 4(b) shows the experimental results of reconnection heating as a function of the guide field ratio. Ion heating is suppressed in the high guide field case compared with the low guide field case but such features are saturated in the higher guide field regime $B_i/B_{rec} \sim 3$: toroidal field $B_t \sim 0.1$ T (a higher reconnecting field $B_{rec}$ typically increases the amplitude of heating by increasing the inflow
speed \(B_t = 0.1 \, \text{T}\). A similar feature is also demonstrated in MAST with a higher guide field ratio \(B_t/B_{\text{rec}} \sim 5\) and \(B_t/B_{\text{rec}} \sim 10\) achieved the same bulk ion heating downstream [13, 18] and successfully achieved \(\sim 1.2 \, \text{keV at maximum [21].}\)

Figure 4(c) shows the scaling of ion heating as a function of reconnecting field \(B_{\text{rec}}\) (three different guide field conditions are plotted: counter-helicity spheromak merging [3] (no guide field: \(B_{\text{rec}}\) includes reconnecting component of \(B_p\) and \(B_t\)), co-helicity spheromak merging [39] (low guide field: \(B_{\text{rec}} \sim B_p\)) and tokamak merging (high guide field: \(B_{\text{rec}} \sim B_p\) [16, 25]. The heating efficiency is slightly higher in the low guide field condition but its contribution is mostly negligible for the practical performance of plasma startup.

5. Progress of the upgrade project TS-U: construction of TS-3U (TS-6)

As a post-TS-3/MAST project, the University of Tokyo started the upgrade project of the merging/reconnection startup experiment [27]. At the end of 2017, TS-3 finished its operation and its vacuum vessel was replaced by a new chamber TS-3U (\(\phi 750 \, \text{mm} \times 1440 \, \text{mm}\)). The new device radially keeps the same major radius as TS-3 but is vertically extended (\(\phi 750 \, \text{mm} \times 1440 \, \text{mm}\)). The heating efficiency is slightly higher in the low guide field condition but its contribution is mostly negligible for the practical performance of plasma startup.
Furthermore, the flexibility of diagnostic access is significantly improved in the new experiment and it is possible to perform both in situ probe measurement and optical diagnostics with \(-0.3 \text{ m} < z < 0.3 \text{ m}\) (in TS-3, optical access was limited to \(-0.075 \text{ m} < r < 0.025 \text{ m}\)).

Figure 5 shows the schematic view of the new experiment and the visible images of the first plasma produced in the spring 2018 plasma commissioning: both PF coils (φ0.44 m/4turns and φ0.62 m/3turns) and capacitor banks of TS-3 (40kV/18.75 µF) are reused in the initial campaign). As recorded in the fast camera images, two plasma rings are formed at the top and bottom of the device, which merge together around the mid-plane with a similar time scale as in TS-3 (τPF swing ∼ 100 µs).

For the first campaign in 2018, several diagnostics were still under construction and the upgraded high field merging operation was not yet available. However, the installation of 150CH 2D magnetic probe arrays \((r−z: 6 \times 25\text{CH})\) and 2D ion Doppler tomography (96CH and 320CH) was completed and these were used for the measurement. The flexible diagnostic access in TS-3U enabled full 2D visualization of reconnection heating ranging from \(-0.25 \text{ m} < z < 0.25 \text{ m}\), which covered the full volume of the two merging flux tubes for the first time in the 30-year history of experimental reconnection studies.

Figure 6 shows the time evolution of the full 2D high-resolution imaging measurement of the ion temperature and magnetic flux profile in the new merging experiment TS-3U (TS-6).

As in the TS-3 experiment, ion heating by magnetic reconnection initially makes hot spots in the downstream region where the outflow jet dissipates [14]. The ion temperature continues to increase during the reconnection process, while the high-\(T_i\) region starts to propagate vertically under the influence of toroidal effect and forms a double-ring-like structure aligned with the closed flux surface of the two merging tokamaks as in the two-fluid modeling of the reconnection experiment in MAST [40].

Figure 7 shows the ion heat flux vector profile at the characteristic time frame of \(t = 85\mu\text{s}\) based on the full 2D \(T_i\) profile measurement: (a) ion temperature gradient vector \(-\nabla T_i\) with \(T_i\), (b) the ratio of parallel and perpendicular heat diffusivity \(\chi_i/\chi_i\) and (c) heat flux vector \(q\) [36] with \(T_i\). Ion temperature gradient vector \(-\nabla T_i\) itself has the strongest parallel components at the high-\(T_i\) region around \(r ∼ 0.1 \text{ m}\) at the midplane \((z ∼ 0 \text{ m})\) where reconnection heating forms a hot spot. The parallel heat transport coefficient has higher value at the inboard region (high-field side: \(B_t \propto r^{-1}\)) and perpendicular heat transport around the hot spot \((r ∼ 0.1 \text{ m})\) is strongly suppressed. Therefore, the heat flux vector \(q\) is strongly aligned with the closed flux surface and forms a poloidal double-ring-like structure.

In comparison with the no guide field operation \((\chi_i/\chi_i \sim 1\) in the null-helicity reconnection experiment in MRX), cross-field thermal transport is strongly suppressed in tokamak merging: \(\chi_i/\chi_i > 100\) in the high-field side and \(\chi_i/\chi_i \sim 10\) in the low-field side (in MAST, \(\chi_i/\chi_i > 100\) is satisfied both in the inboard and outboard region: such condition could be satisfied in TS-3U with a 3 times higher toroidal magnetic field when the high-field operation started in 2019). As a related post-MAST project, the ST40 experiment in tokamak energy proposes to have a further high guide
field regime with toroidal magnetic field $B_t \sim 3.0$ T at maximum [26, 41]. If the merging/reconnecting plasma startup scenario in such a high guide field condition successfully produces high-temperature plasma as suggested in figure 4, the improved confinement should lead to a further high-performance scenario and it is expected to exceed the records in MAST [21] in the near future [41].

6. Conclusion

In this study, ion heating profiles and their transport process during guide field reconnection have been investigated in TS-3 and TS-3U (TS-6). New 96CH/320CH ion Doppler tomography was installed for the upgrade project of TS-U and the ultra-high resolution 2D imaging diagnostics successfully resolved the fine structure formation process of guide field reconnection. The conclusions of the paper are summarized as follows: (i) Magnetic reconnection heats ions globally downstream of the outflow jet and forms a hollow temperature profile; (ii) the ion temperature increases around the $X$-point as well as downstream; (iii) ion heating around the $X$-point forms a poloidally tilted structure as the contribution of the Hall term is enhanced with higher mass ratio; (iv) global downstream ion heating is transported aligned with the closed flux surface of the tokamak configuration; (v) a higher guide field strongly suppresses cross-field thermal transport and the ion temperature profile finally forms a poloidal ring-like hollow distribution; and (vi) the achieved reconnection heating depends on the amplitude of the reconnecting component of the magnetic field $B_{rec}$ while the guide field ($B_t$) dependency is negligibly small for the high-field regime.

In addition to the detailed high-resolution measurement which supports the previously reported heating characteristics ((i) and (vi)), the new experiment successfully led to new findings such as microscopic heating around the $X$-point ((ii) and (iii)) and the global structure formation process ((iv) and (v)). Although the confinement/transport processes (iv) and (v) were proposed in many previous reports, it should be noted as an important milestone that such dynamic processes have successfully been demonstrated/resolved in a real tokamak merging experiment for the first time.

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References

[1] Zweibel E.G. and Yamada M. 2009 Magnetic reconstruction in astrophysical and laboratory plasmas *Ann. Rev. Astron. Astrophys.* 47 291

[2] Yamada M., Kulsrud R. and Ji H. 2010 Magnetic reconstruction *Rev. Mod. Phys.* 82 603

[3] Ono Y., Yamada M., Akao T., Tajima T. and Matsumoto R. 1996 Ion acceleration and direct ion heating in three-component magnetic reconnection *Phys. Rev. Lett.* 76 3328

[4] Gryaznevich M. *et al* 1998 Achievement of record $\beta$ in the START spherical tokamak *Phys. Rev. Lett.* 80 3972

[5] Ono Y., Kimura T., Kawamori E., Murata Y., Miyazaki S., Ueda Y., Inomoto M., Balandin A.L. and Katsurai M. 2003 High-beta characteristics of first and second-stable spherical tokamaks in reconnection heating experiments of TS-3 *Nucl. Fusion* 43 789

[6] Yamada M., Ji H., Hsu S., Carter T., Kulsrud R., Bretz N., Jobes F., Ono Y. and Perkins F. 1997 Study of driven magnetic reconnection in a laboratory plasma *Phys. Plasmas* 4 1936

[7] Brown M. 1999 Experimental studies of magnetic reconnection *Phys. Plasmas* 6 1717

[8] Egedal J., Fasoli A., Porkolab M. and Tarkowski D. 2000 Plasma generation and confinement in a toroidal magnetic cusps *Rev. Sci. Instrum.* 71 3351

[9] Tanabe H., Oka H., Annoura M., Kuwahata A., Kadowaki K., Kaminou Y., You S., Balandin A.L., Inomoto M. and Ono Y. 2013 Two dimensional imaging measurement of magnetic reconnection outflow in the TS-4 toroidal plasma merging experiment *Plasma Fusion Res.* 8 2405088

[10] Inomoto M. *et al* 2015 Centre-solenoid-free merging start-up of spherical tokamak plasmas in UTST *Nucl. Fusion* 55 033013

[11] Binderbauer M.W. *et al* 2016 Recent breakthroughs on C-2U: Norman’s legacy *AIP Conf. Proc.* 1721 030003

[12] Kirk A. *et al* 2017 Overview of recent physics results from *MAST Nucl. Fusion* 57 102007

[13] Tanabe H. *et al* 2015 Electron and ion heating characteristics during magnetic reconnection in the MAST spherical tokamak *Phys. Rev. Lett.* 115 215004

[14] Ono Y. *et al* 2011 Ion and electron heating characteristics of magnetic reconnection in a two flux loop merging experiment *Phys. Rev. Lett.* 107 185001

[15] Yoo J. *et al* 2013 Observation of ion acceleration and heating during collisionless magnetic reconnection in a laboratory plasma *Phys. Rev. Lett.* 110 215007

[16] Ono Y. *et al* 2015 High power heating of magnetic reconnection in merging tokamak experiments *Phys. Plasmas* 22 055708

[17] Yamada M. *et al* 2014 Conversion of magnetic energy in the magnetic reconnection layer of a laboratory plasma *Nat. Commun.* 5 4774

[18] Tanabe H. *et al* 2017 Investigation of merging/reconnection heating during solenoid-free startup of plasmas in the MAST Spherical Tokamak *Nucl. Fusion* 57 056037

[19] Gryaznevich M. and Sykes A. 2017 Merging-compression formation of high temperature tokamak plasma *Nucl. Fusion* 57 072003

[20] Gota H. *et al* 2017 Achievement of field-reversed configuration sustainment via 10 MW neutral-beam injection on the C-2U device *Nucl. Fusion* 57 116021

[21] Ono Y. *et al* 2012 Ion and electron heating characteristics of magnetic reconnection in tokamak plasma merging experiments *Plasma Phys. Control. Fusion* 54 124039

[22] Yamada T. *et al* 2016 Localized electron heating during magnetic reconnection in MAST *Nucl. Fusion* 56 106019

[23] Gryaznevich M. 2005 Recent results from MAST *IEEJ Trans. Fund. Mater.* 125 881

[24] Sykes A. *et al* 2001 First results from MAST *Nucl. Fusion* 41 1423

[25] Tanabe H. *et al* 2017 Recent progress of magnetic reconnection research in the MAST spherical tokamak *Phys. Plasmas* 24 056108

[26] Gryaznevich M. and Asunta O. 2017 Overview and status construction of ST40 *Fusion Eng. Des.* 123 177

[27] Ono Y. *et al* 2018 Scaling study of reconnection/merging heating of spherical tokamak plasmas for direct access to burning plasma *Preprint: 2018 IAEA Fusion Energy Conf. (Ahmedabad) [EX/P3-24]*

[28] Kuwahata A. *et al* 2016 Energy flux due to electromagnetic fluctuations during guide field magnetic reconnection *Plasma Fusion Res.* 11 1301087

[29] Yamasaki K. *et al* 2015 Laboratory study of diffusion region with electron energization during high guide field reconnection *Phys. Plasmas* 22 101202

[30] Tanabe H. *et al* 2013 Two-dimensional ion temperature measurement by application of tomographic reconstruction to Doppler spectroscopy *Nucl. Fusion* 53 093027

[31] Tanabe H. *et al* 2016 Application of tomographic ion Doppler spectroscopy to merging plasma startup in the MAST spherical tokamak *Plasma Fusion Res.* 11 1302093

[32] Stanier A., Brownin P., Gordovskyy M., McClements K.G., Gryaznevich M.P. and Lukin V.S. 2013 Two-fluid simulations of driven reconnection in the mega-ampere spherical tokamak *Phys. Plasmas* 20 122302

[33] Fox W., Sciortino F., Stechow A.V., Jara-Almonte J., Yoo J., Ji H. and Yamada M. 2017 Experimental verification of the role of electron pressure in fast magnetic reconnection with a guide field *Phys. Rev. Lett.* 118 125002

[34] Ono Y. *et al* 2011 Intermittent magnetic reconnection in TS-3 merging experiment *Phys. Plasmas* 18 1113213

[35] Inoue S. *et al* 2015 Numerical study of energy conversion mechanism of magnetic reconnection in the presence of high guide field *Nucl. Fusion* 55 083014

[36] Braginskii S.I. 1965 Transport processes in plasma *Rev. Plasma Phys.* 1 205

[37] Yoshida Z. 1991 Direct ion heating through MHD relaxation *Nucl. Fusion* 31 386

[38] Ono Y. *et al* 2001 *Earth Planets Space* 53 521

[39] Horiouchi R., Moritaka T. and Usami S. 2018 PIC simulation study of merging processes of two spheromak-like plasmoids *Plasma Fusion Res.* 13 3403035

[40] Browning P.K. *et al* 2016 Two-fluid and magnetohydrodynamic modelling of magnetic reconnection in the MAST spherical tokamak and the solar corona *Plasma Phys. Control. Fusion* 58 014041

[41] Buxton P.F. *et al* 2017 Merging compression predictions for ST40 *Fusion Eng. Des.* 123 551