Experimental Results of Ion Heating by Magnetic Reconnection Using External Coils[*)]

Shuji KAMIO, Takenori G WATANABE[1)], Kotaro YAMASAKI[1)], Qinghong CAO[1)],
Takuma YAMADA[2)], Michiaki INOMOTO[1)] and Yasushi ONO[1)]

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[1)]*The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8561, Japan*
[2)]*Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan*

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One of the purposes of the UTST device is to demonstrate of magnetic reconnection heating using external coils to conduct field line merging. In order to measure the ion heating, a Doppler spectroscopy system was developed. By increasing the reconnection magnetic field to 17 mT from 4 mT after the UTST upgrade, the ion heating was observed for the first time in the UTST reconnection experiments. The ion temperature increased to 50 eV from 15 eV due to reconnection during the plasma merging.

Keywords: magnetic reconnection, plasma merging method, Doppler spectroscopy

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1. Introduction

Laboratory experimental studies on magnetic reconnection have a long history. The quantitative evaluation of reconnection rate and energy conversion has been obtained by a series of torus plasma merging experiments which provided well-controlled reconnection condition with good energy confinement. Torus plasma merging experiments were carried out in the TS-3/4 (The University of Tokyo) [1,2], the MRX (Princeton University) [3,4] and the SSX (Swarthmore College) [5] devices, but most of these previous studies focused on the reconnection physics with no or small guide field which may not reflect the high guide field reconnection in the tokamak configuration.

The guide field effect on ion heating was studied in the TS-3 device. Doppler spectroscopy measurements showed that ions were heated from 10 eV to 40 - 60 eV in 10 µs, which corresponds to a heating power as large as 4 - 6 MW [6]. In the experiment, the guide field was found to reduce the efficiency of ion heating. Since the ion heating was most significant in the case without guide field, they proposed a new method to form an ultra-high-beta (up to 80%) ST [1] by transforming a high-beta field-reversed configuration plasma formed by magnetic reconnection without guide field. Nevertheless, recent ST merging startup experiments in the MAST device [7] (UKAEA) showed drastic ion and electron heating during reconnection even in the presence of very strong guide field [6]. Possible reasons for the discrepancy were (1) the energy confinement in the TS-3 experiment was not good enough, (2) the plasma was highly collisional in the TS-3 experiment, and (3) the guide field in the TS-3 was not high enough. Thus, it is important to investigate the details of energy conversion process during collisionless magnetic reconnection in the presence of a storong guide field.

The University of Tokyo Spherical Tokamak (UTST) [8] was constructed to investigate the feasibility of merging startup of high-beta STs under a more reactor-relevant condition with no internal poloidal field (PF) coils. In the UTST device, all the coils are located outside the vacuum vessel, whereas all the other existing merging devices use internal coils to form the initial plasmas. Thus, the UTST device is capable of producing low-density (collisionless) reconnection condition with very strong guide field (< 0.2 T) with good energy confinement property. In this paper, we report demonstration of the magnetic reconnection heating results for the first time using external coils.

Tokamak plasmas with extremely small aspect ratio are called the spherical tokamak (ST), which holds the promise of a high-beta alternative for the tokamak fusion reactor. The beta value is the ratio of plasma thermal pressure p to magnetic pressure $B^2/2\mu_0$ and is often used to evaluate the efficiency of a magnetically confined fusion plasma. High-beta confinement is strongly required to achieve economical fusion power plant, but the beta value of the magnetically confined plasma is limited mainly by the pressure driven instabilities such as ballooning mode. In the tokamak system, it is known that lower aspect ratio and non-circular cross section improve the beta limit significantly. However, due to the small aspect ratio of ST, there is small space in the center of the device to insert the Center Solenoid (CS) coil which is usually used to ramp up

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author's e-mail: kamio@nifs.ac.jp

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the plasma current in conventional tokamak devices. Development of non-inductive startup methods of ST plasma is one of the most important subjects in ST research field. The plasma merging is one of the ST startup methods to study the formation of high-beta equilibria without the CS coil. Plasma merging induces magnetic reconnection of two initial torus plasmas, which leads to a rapid conversion of magnetic energy to plasma kinetic or thermal energy [1]. When the magnetic field lines reconnect, the magnetic energy in the upstream region is mainly converted to the plasma kinetic energy in the downstream region. In a simple steady-state model with the assumption of incompressibility, the energy conversion is expressed as

$$\frac{B_{\mathrm{in}}^2}{2\mu_0} = \frac{\rho_{\mathrm{m}} V_{\mathrm{A}}^2}{2}, \tag{1}$$

where B_{in} is the reconnecting magnetic field in the upstream region, ρ_{m} is the mass density in the outflow region and V_{A} is the Alfvén velocity. Thus, plasma merging will provide a drastic increase of the beta value in the downstream.

2. Experimental Setup

After the first plasma discharge was demonstrated in the UTST in 2007, the first plasma merging condition on the UTST was successfully achieved in 2008 [9]. However, the magnetic reconnection effect such as ion heating was not clearly observed due to the small magnetic energy of the initial plasmas. So as to observe the effect of the magnetic reconnection, it is important to increase the magnetic energy of the reconnection magnetic field by improving the initial STs. For the improvement of the plasma parameters in the UTST device, (1) upgrade of coils, (2) expansion of capacitor banks, (3) optimization of the operation and (4) improvement of vacuum have been made.

Figure 1 shows the cross-section view of the UTST device and Table 1 shows the device parameters of the UTST device. The UTST device has a cylindrical vacuum vessel with the maximal radius of 0.7 m and axial length of 2 m. The induced electric field by the ramping down of the external PF coil currents (PF#2 and PF#4 in Fig. 1) breaks down the puffed helium gas at the upper and lower regions of the device and form two ST plasmas at once, as shown in Figs. 2 (a) and 2 (b). These two initial plasmas merge together through magnetic reconnection [Fig. 2 (c)], which brings about the efficient conversion of the upstream magnetic energy to the downstream kinetic or thermal energy. This energy conversion increases the downstream plasma beta value within a short period of magnetic reconnection, leading to an attractive startup method of high-beta STs. During plasma merging, the $J \times B$ force of the reconnected magnetic field lines accelerates the plasma to the Alfvén velocity. The accelerated ions are thermalized in the downstream area by damping mechanisms such as viscosity or fast shock damping, resulting in the formation of a high-beta ST equilibrium.

Table 1 The UTST Parameters.

Chanber radius	0.7 m (midplane) 0.6 m (top & bottom)
Chanber height	2.0 m
Major radius	0.45 m
Minor radius	0.38 m
Aspect ratio	1.2
Plasma current	70 kA (w/o CS) 310 kA (with CS)
Electron density	$3 \times 10^{19}\mathrm{m}^{-3}$

The magnetic probe array has 128 channels in the upper section around the plasma formation region and 162 channels in the central section to measure the magnetic field B_{t} and B_z directly inside the vacuum vessel. The poloidal flux Ψ and toroidal current density j_{t} can be derived from the measured magnetic field. In Fig. 1 the left side shows the locations of the pickup coils which cover about two thirds of the UTST cross-section area. The magnetic probe array measures B_{t} and B_z components at 145 locations. Under the assumption of toroidal symmetry, the poloidal magnetic flux Ψ, the toroidal current density j_{t} are derived as follows;

$$\Psi(R,t,z) = 2\pi \int_{R_0}^{R} B_z(\rho,t,z)\rho \mathrm{d}\rho, \tag{2}$$

$$j_{\mathrm{t}}(R,t,z) = -\frac{1}{\mu_0}\left(\frac{1}{2\pi R}\frac{\partial^2 \Psi(R,t,z)}{\partial z^2} + \frac{\partial B_z(R,t,z)}{\partial R}\right). \tag{3}$$

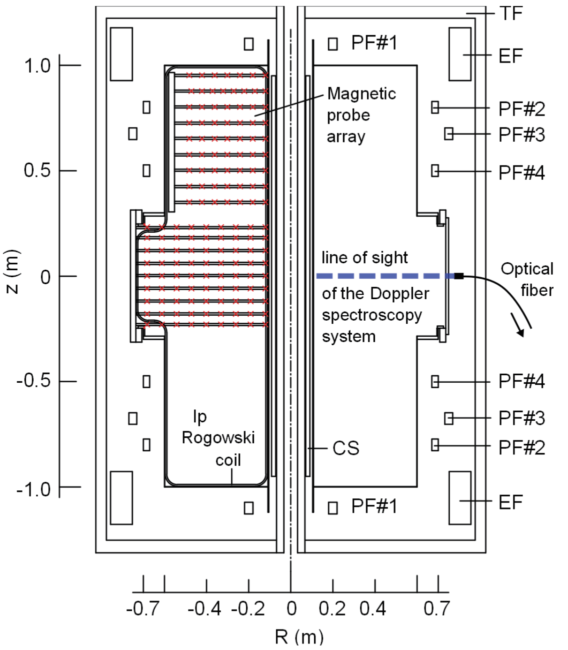

Fig. 1 Cross-section view of the UTST device shown together with the internal diagnostics of magnetic probe array and line of sight of the spectroscopic system.

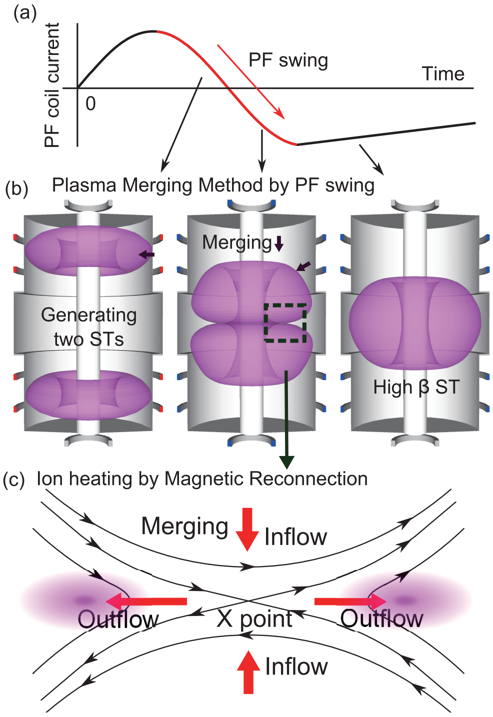

Fig. 2 Schematic view of high-beta ST startup by plasma merging in the UTST. (a) Typical wave form of the PF coil current which produces two ST plasmas at the top and bottom of the UTST device, (b) the schematic view of plasma merging method performed in UTST, and (c) the schematic view of magnetic reconnection.

To investigate the formation of a high-beta ST plasma in the UTST, ion-temperature measurement is required. Thus, a multi-channel Ion Doppler Spectroscopy (IDS) system was developed for the ion-temperature and flow measurement. The Doppler shift $\Delta\lambda$ of a spectral line emitted from a single traveling particle is defined in terms of the particle velocity as $\Delta\lambda = (\lambda_0 v)/c$, where v is the particle velocity, c is the speed of light, and λ_0 is the wavelength of the emitted wave. The Doppler spectroscopy measurement applies this principle to diagnose the collective behavior of ions in plasma. The velocity distribution determined by the particle thermal and collective motions yields the emission line intensity I in Gaussian form as

$$I(\Delta\lambda) = \frac{I_0}{\pi^{1/2}\Delta\lambda_{\mathrm{D}}} \exp\left\{-\left(\frac{\Delta\lambda}{\Delta\lambda_{\mathrm{D}}}\right)^2\right\}, \tag{4}$$

$$\Delta\lambda_{\mathrm{D}} = \frac{\lambda_0}{c}\sqrt{\frac{2kT_{\mathrm{i}}}{m_{\mathrm{i}}}}, \tag{5}$$

where T_{i} is the ion temperature and m_{i} is the ion mass. The ion temperature T_{i} is calculated by the full width at half maximum (FWHM) of the line broadening $\Delta\lambda_{\mathrm{FWHM}}$ as

$$\begin{aligned}\Delta\lambda_{\mathrm{FWHM}} &= 2(\ln 2)^{1/2}\Delta\lambda_{\mathrm{D}}\\ &= 7.69\times10^{-5}\lambda_0\left(\frac{T_{\mathrm{i}}}{A}\right)^{1/2},\end{aligned} \tag{6}$$

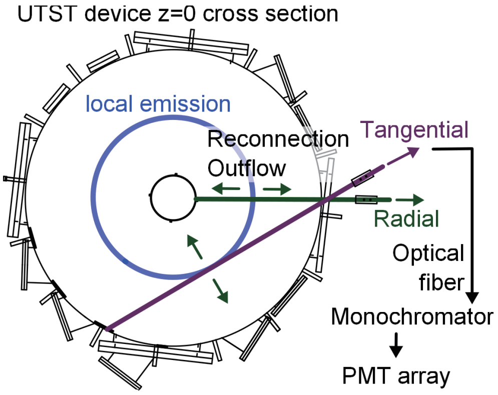

Fig. 3 Arrangement of lines of sight in the Doppler spectroscopy measurement, which has a radial view and a tangential view on the midplane ($z = 0$ cross section) of the UTST. The ion temperature was measured by the tangential line of sight.

$$T_{\mathrm{i}} = 1.7\times A\times10^8\left(\frac{\Delta\lambda_{\mathrm{FWHM}}}{\lambda_0}\right)^2, \tag{7}$$

where A is the ion mass number of the ion.

Figure 3 shows the arrangement of the measurement line of sight measurement. To measure the ion temperature, we used a tangential path, and thus did not to measure the ion acceleration by the magnetic reconnection outflow. Different from the radial view, which obtained the ion outflow velocity, the ion temperature from the tangential view is not affected by the broadening of the multi velocity components. After the optical fiber development, the Doppler spectroscopy measurement system was developed [10]. In the UTST magnetic reconnection experiments, the He II (468.58 nm) line was observed only during the plasma merging and the line emission was localized near the X-point [11]. This local He II line emission is employed to measure the ion temperature.

3. Experimental Results

In the UTST device, the duration of plasma merging (magnetic reconnection) is approximately 50 µs. Figure 4 shows the evolution of the two-dimensional (axial: z and radial: R) magnetic field structure measured by the magnetic probe array. The inflow comes from the top and bottom, and the outflow exhausts toward the left and right in these figures. A clear merging structure is identified in the UTST merging experiments. The color code shows the toroidal current density j_{t} and the current sheet is obtained between two STs. Typical reconnecting magnetic field (poloidal field in the upstream region) is 17 mT, while the guide field (toroidal field) at the X-point is 180 mT, which is much larger than the reconnecting field. Hence, in the UTST device, magnetic reconnection with significant guide field takes place during the ST merging period.

From the tangential view in Fig. 3, an increase in the ion temperature T_{i} by magnetic reconnection heating was

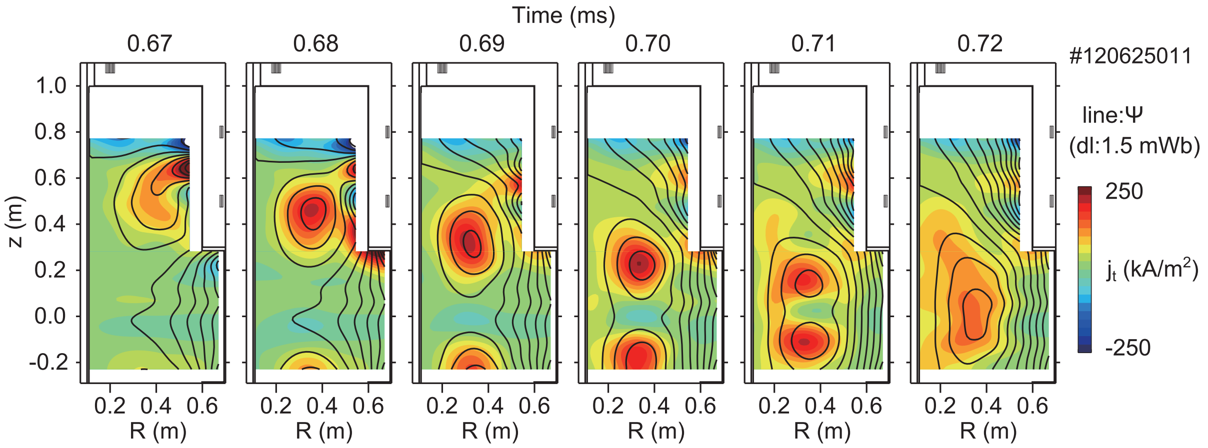

Fig. 4 Evolution of poloidal flux surfaces (contour lines) and troidal current density (color coded) during the plasma merging experiment.

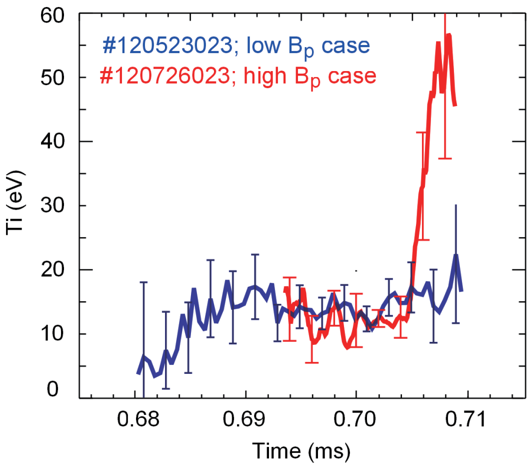

Fig. 5 The ion temperature of high B_p case (B_p = 17 mT) and low B_p case (B_p = 4 mT) measured by the tangential view. The ion temperature T_i increase due to magnetic reconnection heating was observed in the high B_p case.

observed. Figure 5 shows 50 eV ion temperature achieved by the magnetic reconnection heating. In these experiments, the CS coil is used for the current drive in the initial STs. However, the ion temperature is maintained at approximately 10-20 eV by the CS coil in the low B_p case as shown in Fig. 5 when the reconnection heating is very weak. The ion temperature cannot achieve more than 20 eV in the current UTST plasma even when the plasma current reaches 310 kA. One of the reasons for this is the radiation barrier of the impurity such as Fe. The magnetic reconnection is the only way to achieve ion heating to $T_i = 50$ eV.

4. Conclusion

Using the tangential line of sight IDS measurement, increase of the ion temperature T_i by magnetic reconnection heating was observed. In these experiments, the ion temperature is maintained at approximately 10 - 20 eV in the low B_p reconnection case. The ion temperature was increased to 50 eV in a short period in the high B_p case. The reconnecting magnetic field B_p is critical for increasing the ion temperature. In summary, the magnetic reconnection heating is verified in the UTST device in which the poloidal field coils are outside of the vacuum vessel.

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