Measurement of the Local Current Density Inside a Current Sheet Using a Rogowski Coil Array on UTST Merging Plasmas

Hibiki YAMAZAKI, Hirokazu FURUI, Kotaro YAMASAKI[1)], Tomohiko USHIKI, Akira EJIRI, Michiaki INOMOTO, Yuichi TAKASE, Yasushi ONO, Naoto TSUJII, UTST group and TST-2 group

The University of Tokyo, Kashiwa 277-8561, Japan
[1)]Kyushu University, Fukuoka 819-0395, Japan

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Plasma merging is a unique method of plasma start-up, and magnetic reconnection is a key process for plasma heating in this method. On the University of Tokyo Spherical Tokamak (UTST), we use a pickup coil array to obtain the macroscopic behavior of magnetic reconnection, but direct measurement of the localized current is still necessary to study the details of the magnetic reconnection process. A small Rogowski coil is a useful tool for measuring small scale currents, and we used five such coils to measure the radial structure near the X-points of merging plasmas on UTST. As a result, we have found current densities up to 1.5 MA/m^2, with a typical time scale of several micro seconds. The current density increases with the plasma current, and the average radial width is about 30 mm.

Keywords: spherical tokamak, start-up, plasma merging, magnetic reconnection, Rogowski coil

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The tokamak magnetic configuration requires a plasma current to make a poloidal magnetic field, and in conventional tokamaks it is driven by a central solenoid coil. In spherical tokamak (ST) reactors [1], however, the plasma current needs to be driven without a central solenoid, because of the small aspect ratios of STs. Plasma merging is one method for plasma current start-up and heating for an ST, in which magnetic reconnection provides a high heating power leading to a high-beta plasma. Plasma merging experiments are being conducted on several devices, such as MAST [2], MRX [3], TS-3, TS-4 [4] and UTST [5]. UTST is a unique device in which external coils located outside the vacuum vessel are employed for plasma merging. Using these coils, initial ST plasmas are generated inductively in the upper and the lower regions of the vacuum vessel. Then, by flipping the current direction in the external coil, two plasmas, in which the plasma current directions are the same, are axially pushed toward the midplane. The two plasmas with opposite radial fields contact each other at the midplane, resulting in the formation of a radially elongated current sheet around the X-point. The details of plasma merging were described previously [5].

Measurements of the current inside the current sheet that is formed around the X-point are important for elucidating the underlying physics of the reconnection events. On UTST, the internal magnetic configuration and toroidal current density are derived from a two-dimensional pickup coil array with a spatial resolution of 70 mm [5]. The typical current sheet length and the reconnection duration obtained by this array are 200 mm and 50 µs, respectively. Although a pickup coil array is a powerful tool for obtaining the macroscopic behavior of plasma merging, a direct measurement of the localized current is necessary to study the details of the magnetic reconnection process. In order to reveal such details, we installed small Rogowski coils, which can directly measure the toroidal current with good spatial resolution [6–8].

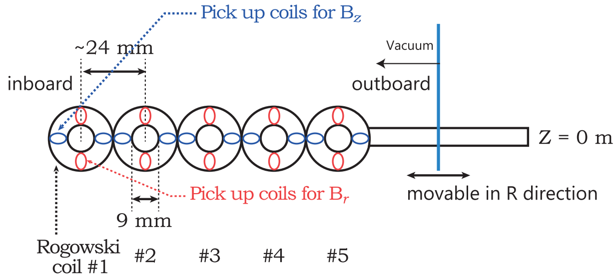

Fig. 1 A schematic drawing of the Rogowski probe, comprising five Rogowski coils and 10 pickup coils for the B_z and B_r components. The probe was inserted at the midplane (Z = 0 m) of UTST.

For this study, we fabricated a Rogowski probe, which contains five Rogowski coils and pickup coils for the measurement of the radial and axial magnetic field components B_r and B_z (Fig. 1) and installed it on UTST. The diameter r of the central hole of each Rogowski coil is 9 mm. The

author's e-mail: yamazaki@fusion.k.u-tokyo.ac.jp

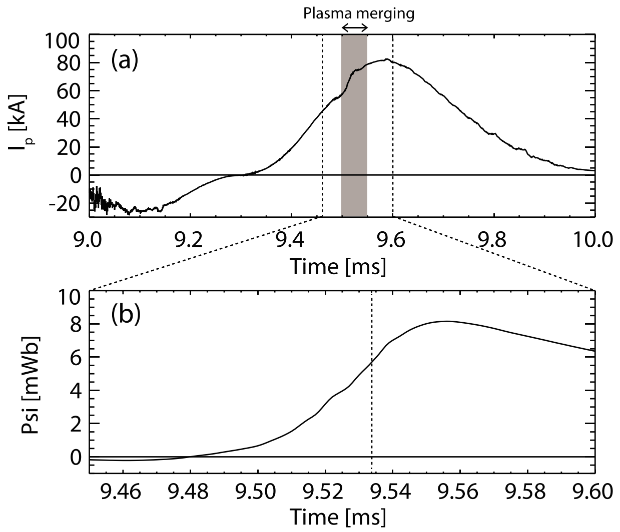

Fig. 2 Typical waveforms of (a) the plasma current I_p and (b) the magnetic flux Ψ at the X-point. The gray shaded area shows the time duration of plasma merging.

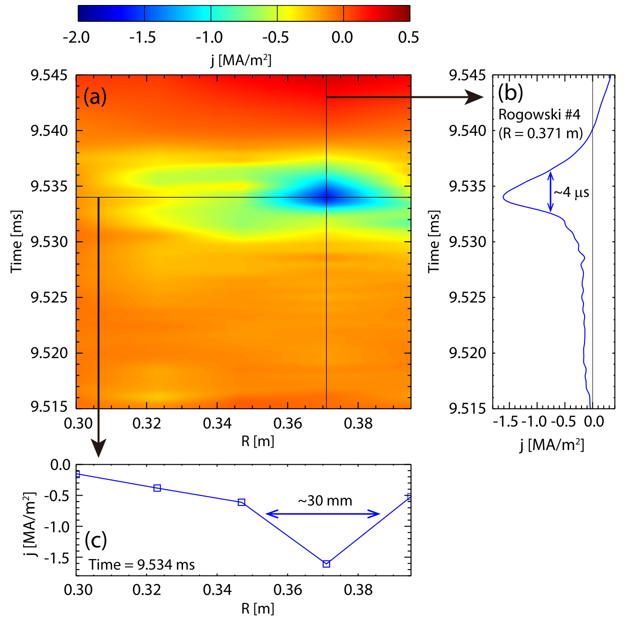

Fig. 3 (a) Color contour plot of the toroidal current density measured by the five Rogowski coils as functions of time and radial location R. (b) Time evolution of the current density at R = 0.371 m. (c) Profile of the current density at t = 9.534 ms.

cross section is 4 mm × 12 mm, each coil contains 60 turns and the toroidal thickness is 50 mm. The theoretical sensitivity of the Rogowski coil is 7.2×10^{-8} Vs/A, whereas the calibrated sensitivities of the five Rogowski coils are $\approx 7.5 \times 10^{-8}$ Vs/A at 10 kHz. Each Rogowski coil is connected to an active analog integrator, enabling measurement of the toroidal current $I(t)$ passing through the central hole. Since the frequency response (i.e., the gain and phase) shows a large variation above 1.5 MHz, a 1 MHz low-pass digital filter is applied in the analysis to suppress the high frequency components.

Figure 2 shows typical waveforms of the plasma current I_p and the poloidal magnetic flux Ψ at the X-point. The typical duration of plasma merging is 50 µs and a single ST is formed after that. During plasma merging, the poloidal magnetic flux at the X-point increases by magnetic reconnection, and a negative toroidal electric field and a negative toroidal current are generated.

The radial profile of the toroidal current density during reconnection events was measured by using the Rogowski coils located at R = 0.300, 0.323, 0.347, 0.371 and 0.395 m, while the typical major and minor radii of the plasma were 0.35 m and 0.24 m, respectively. We found a large toroidal current density $|j_t|$ localized near the X-point, and the maximum current density we measured in about 120 discharges was about 1.5 MA/m^2 (Fig. 3). Note that the negative polarity represents the direction of the toroidal current induced around the X-point in the reconnection events. The current density exhibits a pulse-shaped time evolution with a width of 4 µs. We cross-checked the magnitude of the current measured by the Rogowski coil using signals from the pickup coils located beside the holes of the Rogowski coils. These results suggest that the current density near the X-point has a spatiotemporally localized structure. The pulse occurred at t = 9.534 ms, and about 70% of the poloidal magnetic flux was already reconnected at this time (Fig. 2 (b)). The current density profile measured at t = 9.534 ms (Fig. 3 (c)) indicates that the full width at half maximum (FWHM) of the radial length of the high current density region was about 30 mm.

In order to determine the statistics between j_t, I_p and the radial length of the high current density region, we have analyzed discharges with a clear current pulse ($|j_t(t)| > 0.15$ MA/m^2). The quantity $|j_t|$ tends to increase with the total plasma current I_p at the time when $|j_t(t)|$ is a maximum, and the ratio can be represented as $|j_t|/I_p = (6.4 \pm 0.4)$ [1/m^2], with a correlation coefficient of ∼ 0.6. The average radial length (FWHM) and pulse width (FWHM) are about 30 mm and 10 µs, respectively. The radial length tends to decrease with $|j_t|/I_p$, but the correlation coefficient (−0.15) is small. Note that the measurable FWHM length is limited by the spacing of the Rogowski coils (∼ 24 mm), and the average radial length could be overestimated.

To determine the axial width of the high current density region, we evaluated the axial distance ΔZ between the Rogowski probe and the X-point. The statistics indicate that large current densities are observed only when the distance ΔZ is smaller than 10 - 20 mm. Thus, the axial width is estimated to be around 20 mm. This estimate agrees well with the current sheet thickness obtained from a one-dimensional pickup coil array with a spacing of 10 mm [9].

In summary, we have successfully measured the localized current inside a current sheet and have found that the current structure is spatiotemporally localized. We observed current densities up to $1.5\,\mathrm{MA/m^2}$. This large current density was formed in a time span that is a few times shorter than the merging duration ($\sim 50\,\mu\mathrm{s}$). We assessed the effect of the probe insertion by measuring the plasma current I_p and the poloidal flux at the X-point. The plasma current perturbation due to the insertion of the Rogowski probe is less than the shot-by-shot standard deviation of I_p, which is typically $\sim 9\%$. Therefore, we conclude that the insertion of the Rogowski probe does not significantly affect the macroscopic features of the plasma. However, the standard deviation of the poloidal magnetic flux at the X-point increases from about $\sim 9\%$ to about $\sim 19\%$, so probe insertion appears to affect the microscopic behavior near the X-point. Thus, we must take this ambiguity into account in future analyses.

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