Development of a Local Current Diagnostic using a Small Rogowski Coil for a Spherical Tokamak Plasma in TST-2*)

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A local current diagnostic using a small Rogowski coil was developed in the TST-2 spherical tokamak device (R = 0.38 m, a = 0.25 m, B_t = 0.3 T, I_p = 0.1 MA). A Rogowski coil is a cost effective tool for local current diagnostic that can detect the current signal directly. A new small Rogowski coil (outer diameter = 20 mm, inner diameter = 12 mm, number of turns = 360) with small sensitivity to external magnetic fields, such as B_t and B_p, was developed and successfully installed in the TST-2. The measured local current at the edge just inside the last closed flux surface for ohmic heating was about 15 A.

Keywords: Rogowski coil, external magnetic effect, local current diagnostic, local current density profile, spherical tokamak

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1. Introduction

In tokamak plasmas, the profile of the local toroidal current density is critical because it is affected by the current drive method and affects the equilibrium configuration. Therefore, a method to measure the local current density needs to be established. In TST-2@K, equilibrium analysis suggested large current near the outboard boundary [1]. Thus, measuring such current directly is critical. At present, current startup experiments using lower hybrid waves are being performed on TST-2 [2], and the direct measurements are needed to understand and optimize the current startup. Measurements of the Motional Starc effect (MSE) are typically used to derive the radial profile of current density [3]. This method is attractive for measuring current density; however, it is not suitable for small tokamak devices because the NBI system is large and expensive. Another attractive tool is the small Rogowski coil, which is an induction coil that can detect the time derivative of electrical current [4]. In the SINP tokamak device (R = 0.03 m, a = 0.007 m), local current near the center of the plasma was successfully measured using a Rogowski coil (outer diameter = 17 mm, inner diameter = 7 mm, number of turns 275) for a discharge with $I_p \sim$ 20 kA and a duration of ∼ 1 ms [5]. The measurement in TST-2 is, however, much more difficult. In a tokamak discharge, there are toroidal (B_t) and poloidal (B_p) magnetic fields that can be the main measurement error because the coils have finite fabrication accuracy and lead to undesired sensitivity to external fields. The typical current density at the edge of the ohmic discharge in TST-2, which is our target, is about 10 times smaller than that measured in the SINP tokamak and the discharge duration of TST-2 is 20 times longer than that in the SINP tokamak, leading to a small signal and time derivative. On the other hand, the values of the magnetic fields are almost the same. Therefore, the required signal to noise ratio (SN) is much higher than that in the SINP tokamak. In addition to SN, the Rogowski coil should be sufficiently small to not affect the macroscopic plasma behavior. A numerical simulation was performed to estimate and reduce the sensitivity to external fields. With the help of the simulation results, a new small Rogowski coil was designed and fabricated. The local current density for ohmic discharge plasma was measured using the Rogowski coil.

2. The Diagnostic Principle of the Rogowski Coil

A Rogowski coil is an induction coil that can detect the time derivative of the electrical current passing through the central hole. The relation between the current and output voltage of a Rogowski coil is given as follows:

$$V = \frac{\mu_0 NS}{l}\frac{\mathrm{d}I}{\mathrm{d}t}, \tag{1}$$

where μ_0 is the magnetic permeability in vacuum, N is a

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turn number, S is a cross-sectional area of the torus and l is a perimeter of the torus. The output voltage is proportional to N and S, and inversely proportional to l. An ideal and precisely fabricated Rogowski coil has a constant turn density (N/l) and a constant cross-sectional area (S). When these are not constant, the coil becomes sensitive to the external magnetic field are generated by external currents. When the Rogowski coil has a constant turn density and a cross-sectional area, its total magnetic flux is as follows: [6]

$$\Phi = \frac{SN}{l}\int_0^{2\pi r} B dl. \tag{2}$$

In a Rogowski coil with some nonuniformities, the flux deviates from Eq. 2, and it is sensitive to external magnetic fields.

3. Numerical Evaluation of Finite Sensitivity to External Magnetic Fields

We have fabricated and tested two types of Rogowski coils. One has normal forward helical winding along the torus and backward toroidal winding without cross-sectional area, which is called return cable. The other has two layers of winding: one layer for forward helical winding and another for backward helical winding. Hereafter, these types are referred to as return winding and two-layer winding, respectively. We made 10 Rogowski coils of each type and found that the two-layer winding always performed better than the return winding. This is probably because of the difficulty in precisely adjusting the area of the return coil. Thus, we used the two-layer winding in our experiment. To estimate and minimize the sensitivity of the two-layer winding to external magnetic fields, we performed numerical simulations. The configuration of the Rogowski coil and external magnetic fields (B_z and B_y) are shown in Fig. 1. The direction of B_z and B_y are along the z-axis and y-axis, respectively, and the z and y directions correspond to the toroidal and the poloidal directions in the tokamak configuration. The wire of the Rogowski coil was represented by a set of points with three-dimensional coordinates (r, θ, z), and fabrication error was simulated by adding random errors to each coordinate of each point. In the rectangular cross-section case, we need four points per turn to define the wire. In uniform magnetic field, the effective projection areas (S_{x-y} and S_{x-z}) agree with the sensitivity to external magnetic fields. These areas are calculated by summing up the projected area of the triangles formed by two adjacent coordinates on the wire and a reference point. By adding random errors on the coordinates, we can estimate the effect of the fabrication error (i.e., S_{x-y} and S_{x-z}). The relation between the output voltage and S_{x-y} and S_{x-z} are given as follows:

$$V_{B_t} = S_{x-y}\frac{\partial B_t}{\partial t}. \tag{3}$$

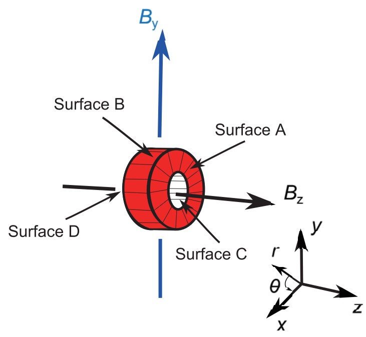

Fig. 1 A Rogowski coil in a tokamak discharge.

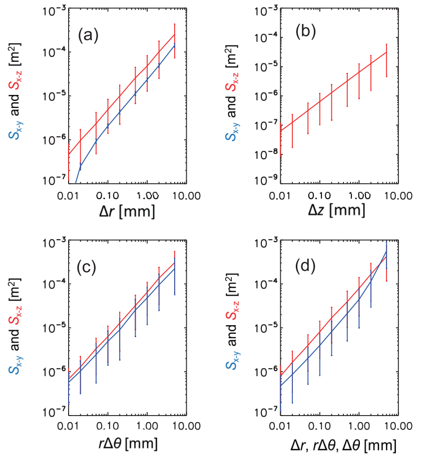

Fig. 2 S_{x-y} and S_{x-z} of the two layer winding, where, Δr, Δz and $r\Delta\theta$ are errors in each direction.

$$V_{B_p} = S_{x-z}\frac{\partial B_p}{\partial t}. \tag{4}$$

In the simulation, the outer diameter, inner diameter, thickness, and turn number of the Rogowski coil are set as 20 mm, 12 mm, 12 mm, and 240 turns, respectively. The calculation was repeated 500 times with different sets of random errors, and the results are shown in Fig. 2. The error bar is the standard deviation derived from the 500 trials. From Figs. 2 (a), (b) and (c), it is seen that the manufacturing errors in the θ direction tends to cause higher sensitivity than those in the r and the z directions.

4. Optimum Winding of Two-Layer Winding

In the previous section, it was found that minimizing the errors in the θ direction effectively reduces of S_{x-y} and S_{x-z}. Several winding cores with small dips at the corners were made. By processing the dips on the core, we can precisely set the correct number of dips and turns. The dips are used to fix (hook) the cable, and we tested three dip arrangements. Their size and number of turns were the same. The winding patterns (i.e., dip patterns) are shown in Fig. 3. The red and the blue lines represent the forward and the backward windings, respectively. Surfaces A, B, C, and D are the same as that defined in Fig. 1. In pattern 1, the dips in all surfaces are made in the same phase (i.e., at the same θ). In pattern 2, the dips on both sides of surfaces B and D are in the same phase and the dips on both sides of surfaces A and D are in the opposite phase, i.e., the dips are shifted by a half period. In pattern 3, the dips on both sides of surfaces A and B are in the opposite phase and the dips on both sides of surfaces C and D are in the same phase. The sensitivity to external magnetic fields was measured using a Helmholtz coil. Table 1 lists the results of a particular day. For the test, we fabricated the winding cores and wound the Rogowski coils manually. The sensitivity to B_z (S_{x-y}) was always $\sim 10^{-5}$ in the patterns. On the other hand, the sensitivity of pattern 3 to B_y (S_{x-z}) was always about 10 times smaller than in pattern 1 and 2. The cable is wound with a certain tension that fixes the cable at each dip when it is hooked on the dips. Therefore, it is useful to have a zigzag pattern in addition to the uniform helical structure, which is necessary for the Rogowski coils. From this point of view, the cable traversing surfaces A, C, and D in pattern 1 has almost no zigzag structure. On the other hand, there are zigzag patterns in all surfaces of patterns 2 and 3; moreover, it can be assumed that the S_{x_y} of pattern 2 is as small as that of pattern 3. To explain the experimental results, we also simulated patterns 2 and 3. No obvious differences between the two simulated patterns were seen.

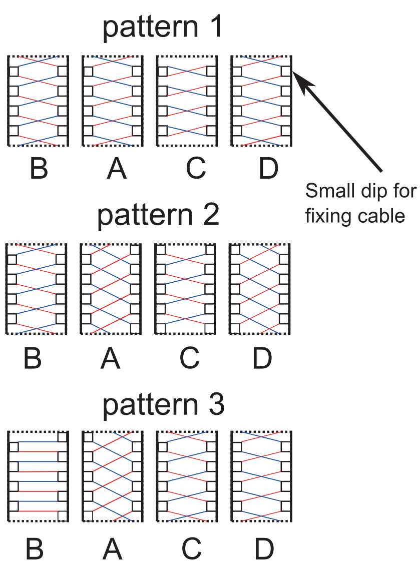

Fig. 3 The three fabricated patterns are shown. Surfaces A, B, C and D denote the four surfaces of the rectangular cross section (see Fig. 1). They are the top, inner, bottom, and outer sides, respectively.

Table 1 Sensitivity of the Rogowski coils.

pattern	S_{x-y} [m^2]	S_{x-z} [m^2]
pattern 1	1.8×10^{-5}	4×10^{-5}
pattern 2	1×10^{-5}	4×10^{-5}
pattern 3	1.8×10^{-5}	2×10^{-6}

We were unable to explain why S_{x_z} for pattern 3 is better (i.e., smaller) than that of pattern 2; thus, we adopted pattern 3.

5. Multi-Layer Rogowski Coil

To obtain large signal intensity, the cross sectional area S and turn number N should increase and the coil length l should decrease. For the local current diagnostic, the Rogowski coil must be sufficiently small. On the other hand, the size of the central hole of the Rogowski coil should be large enough to enable local current to pass through. Therefore, S and l must be determined considering these aspects. On the other hand, we can expect larger signal for larger N. Therefore, the turn number must increase to obtain sufficient signal intensity. To increase N, we used twisted wire. If we use a twisted wire in the two-layer winding, we can make a four-layer Rogowski coil. The twisted wire shortens the fabrication time and improves durability. A small Rogowski coil with large turn number is wound by a thin cable that requires careful winding and increases the fabrication time. Using twisted wires, we successfully fabricated an eight-layer Rogowski coil (Fig. 4). When we compare the one-layer winding (return type) and the eight-layer winding, the fabrication times per unit turn are about 20 times shorter than the latter. The eight-layer winding was better than the twelve-layer winding. In making the twelve-layer Rogowski coil, it was difficult to count the number of turns in a dip. Furthermore, it was rather difficult to keep the winding uniformity in the twelve-layer Rogowski coil. After winding the cable, it is necessary to adjust the position of the cable at the dip (dip width = 0.5 mm) using a small tool like a thin needle. We performed the adjustment by monitoring the sensitivity, and we achieved a good performance as shown in the next section. In the case of ohmic heating plasma, the dominant noises are the signals owing to B_z and B_y. We define the SN ratios as $SN(B_z)$, $SN(B_y)$, which are the ratios of the current signal to the noises in the B_z and B_y directions respectively. The SN ratios depends not only on S_{x-y} and S_{x-z}, but also on the dimensions. Using the method described in Sec. 3, we found that the $SN(B_z)$ increases with

Fig. 4 Eight-layer Rogowski coil: Outer diameter = 20 mm; inner diameter = 12 mm; thickness = 12 mm; number of turn 360; sensitivity = 5.0×10^{-7} Vs/A; and thickness of the cable = 0.12 mm.

the inner radius and thickness, whereas it decreases with increasing outer radius. $SN(B_y)$ increases with outer radius and it is constant with increasing thickness. On the other hand, $SN(B_y)$ is optimized by controlling the inner radius. The outer radius and the thickness were determined from the viewpoints of plasma disturbance and the fabrication.

6. Experimental Results

The sensitivities to external magnetic fields were measured using a Helmholtz coil. The Rogowski coil was placed on the central position of the Helmholtz coil and a function generator was employed to produce sinusoidal current. The typical frequency for the calibration was 500 Hz, which is far from the characteristic frequency (300 kHz) of the Rogowski coil. Because the output signal of the Rogowski coil was very small, an amplifier with a gain of 100 was used. The S_{x-y} and S_{x-z} were 1.37×10^{-6} m^2 and 5.20×10^{-6} m^2, respectively. We also simulated S_{x-y} and S_{x-z} for the eight-layer Rogowski coil like Fig. 2. Comparing the calibration and simulation results, the fabrication accuracy of the eight-layer Rogowski coil is smaller than ±0.1 mm. Furthermore, the sensitivity of the eight-layer Rogowski coil is about 100 times smaller than that of the return Rogowski coil (see Sec. 5). Using the eight-layer Rogowski coil, the ohmic heating of the discharge plasma was measured. In the experiment, the Rogowski coil was connected to an integrator circuit with cutoff frequency of about 0.03 Hz and gain of about 1100 s^{-1}. The Rogowski coil was located just inside the last closed flux surface (R = 551 mm) and the vertical position of the Rogowski coil was also $z = 0$. Figure 5 (b) shows the time evolution of the local current measured by the Rogowski coil. The observed local current was about 15 A when the plasma current reached its maximum. On the other hand, the expected current for the parabolic current density profile is 10 A. In the discharge, an abrupt current drop was seen at 23 ms. This seems to be caused by an internal reconnection event that redistributes the current [7].

Lastly, we estimated $SN(B_z)$ and $SN(B_y)$ of the Rogowski coil. Using the typical values of B_z = 0.2 T, B_y = 40 mT and the current density 100 kA/m^2, $SN(B_z)$ and $SN(B_y)$ were 12 and 15 respectively. These ratios are sufficient to measure the local current density because we have no other tools for direct measurements. Rogowski coils are sensitive to electrostatic noise and the signal can be affected by the plasma floating potential (e.g., 50 V). Thus, we performed the following test. Two copper plates, to which sinusoidal voltage with a frequency of 2 - 50 kHz was applied, were attached on a Rogowski coil with an aluminum shield and a Teflon sheet. The SN ratio was about 20000 for the same parameters described above. As a result, the effect of electrostatic noise is negligible.

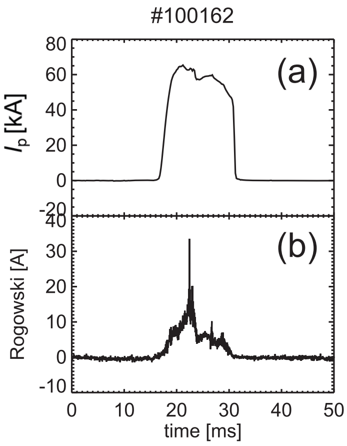

Fig. 5 The time evolution of the plasma current (a) and the local current measured by the Rogowski coil (b).

7. Summary

A new multilayer Rogowski coil was developed. Numerical simulations were performed to estimate the effect of fabrication accuracy on the performance (i.e., noise) of the measurements. Comparing the experimental and simulation results, the Rogowski coil was successfully fabricated with an accuracy of smaller than ±0.1 mm. The Rogowski coil has a large number of turns and small sensitivity to external magnetic fields. Using the Rogowski coil, the local current in ohmic heating of plasma was measured and the current value was about 15 A.

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