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Mitarai, Osamu
JSPS Post Doctoral Fellowships (General)

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MACROSCOPIC MEASUREMENTS IN A TURBULENT HEATING EXPERIMENT

By Osamu MITARAI*

Turbulent heating experiment has been studied in the TRIAM-1 tokamak. The apparatus measuring macroscopic quantities such as current and voltage in the turbulent heating discharge is designed, constructed and has been used successfully.

Key words: Turbulent heating, Current, Voltage, Tokamak

1. Introduction

The turbulent heating experiment has been studied in the TRIAM-1 tokamak (25.4 cm major radius, 4 cm minor radius). The study of anomalous resistivity caused by plasma turbulence is one of the interesting subjects in the turbulent heating experiments. The resistivity of a plasma can be obtained from the ratio of a heating voltage to a heating current. The electron drift velocity is also important parameter which can be estimated from the heating current and averaged electron density. Therefore, the apparatus measuring independently the current and voltage of the turbulent heating is needed for the turbulent heating experiment. In addition, this apparatus enables us to evaluate an input power, monitor the operation and check the reproducibility of the experiment.

In most of the turbulent heating experiments, a short current pulse has been applied to preionized plasma with a short duration time which is comparable to the current pulse. However, in TRIAM-1 tokamak, a single short current pulse was superposed on the tokamak plasma with a long duration time ($\lesssim$10 ms). Therefore it will be necessary to design a Rogowski coil circuit with wide bandwith. To cover this wide bandwith, both the low and high frequency Rogowski coil circuits were prepared.

For heating sufficiently the plasma by the turbulent heating, a high one turn voltage ($\gtrsim$kV) must be applied to the plasma. On the other hand, the one turn voltage of the tokamak plasma is usually less than

* JSPS Post Doctoral Fellowships (General), Research Institute for Applied Mechanics, Kyushu University.
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10 V. In order to measure these widely different voltage in one shot, an output of the divider is split into two channels; one is for the turbulent heating, the other for the tokamak plasma. Since the divider output in this case is too small to observe, an amplifier is necessary to measure the one turn voltage of tokamak plasma.

To apply the turbulent heating to a tokamak plasma, two kind of methods have been carried out. One is to use a thin liner[1] which has a skin time shorter than the electric field pulse and the other to use a chamber with ceramic breaks insulating the conductivity in the toroidal direction. The TRIAM-1 tokamak has two ceramic breaks. In the case of the ceramic method, a high voltage pulse may be applied not uniformly along the torus but locally at the both ends of the break. The system measuring such a break voltage is also necessary to moniter the voltage for fear that the high voltage pulse breaks up the chamber. The turbulent heating voltage was produced by the four coils poloidally placed around the chamber. These coil currents are distributed such that they do not produce irregular magnetic fields.

In this paper we describe the method measuring the tokamak plasma current, turbulent heating current, tokamak one turn voltage, turbulent heating voltage, ceramic break voltage and turbulent heating coil currents.

In Section 2, the design and construction of the experimental apparatus are described. Experimental results are given in Section 3. Section 4 contains the discussion and conclusion.

2. Design and construction of the experimental apparatus.

2. 1. Rogowski coil systems measuring turbulent heating current.

Since we have reported the work on the low frequceny Rogowski coil system to measure the tokamak plasma current in the previous paper[2], here we restrict ourselves to describe a Rogowski coil system measuring the turbulent heating current. This coil was wound at regular intervals along a ring of Teflon of 1. 5 mm mainor radius and 70 mm major radius, where the return coil wound in order to compensate unwanted fields. The number of turns of the coil was 150 and the diameter of the wire was 0. 4 mm.

Figure 1 shows the Rogowski coil circuit measuring the turbulent heating current. The circuit parameters were determined from the frequency characteristic test. It was found from these tests that the impedance viewed from the signal source must be 100 Ω in order to avoid a circuit resonance and have a flat frequency response up to 10 MHz. And from the condition that the impedance viewed from the receiver side must be 50 Ω for a matching, the resistance $R_1=150\ \Omega$, $R_2=240\ \Omega$ and $R_3=62\ \Omega$ were chosen. The result of the frequency characteristic is shown

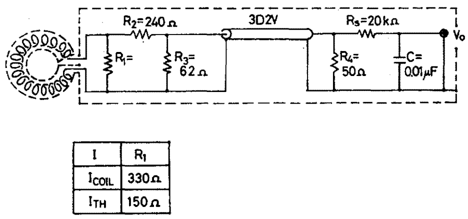


Fig. 1 The Rogowski coil circuit to measure the turbulent heating current.

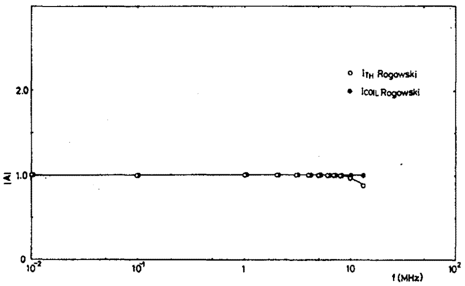


Fig. 2 The frequency characteristics of the Rogowski coil to measure the turbulent heating and coil current.

in Fig. 2 which suggests that this coil could be used up to about 20 MHz. We also measured the time delay of the coil, which was 40 ns. The Rogowski coil was shielded by the Al foil with a poloidal cut in order to reduce electrostatic noise. We used the passive integrator with a time constant 200 μs which was much longer than the turbulent heating current pulse 10 μs.

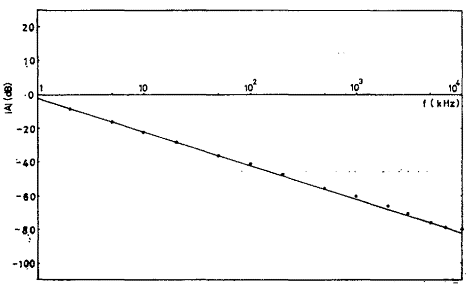


Fig. 3 The frequency characteristic of the passive integrator.

Figure 3 is the frequency characteristic of the integrator. This figure demonstrates that the entire Rogowski coil system can be used at least up to 10 MHz.

The Rogowski coil was placed on the chamber as shown in Fig. 4

because of the difficulty of the setting on the ceramic break. However, the Rogowski coil on the SUS chamber provided the correct value in measuring the current in the chamber. This fact was discussed in detail in Appendix.

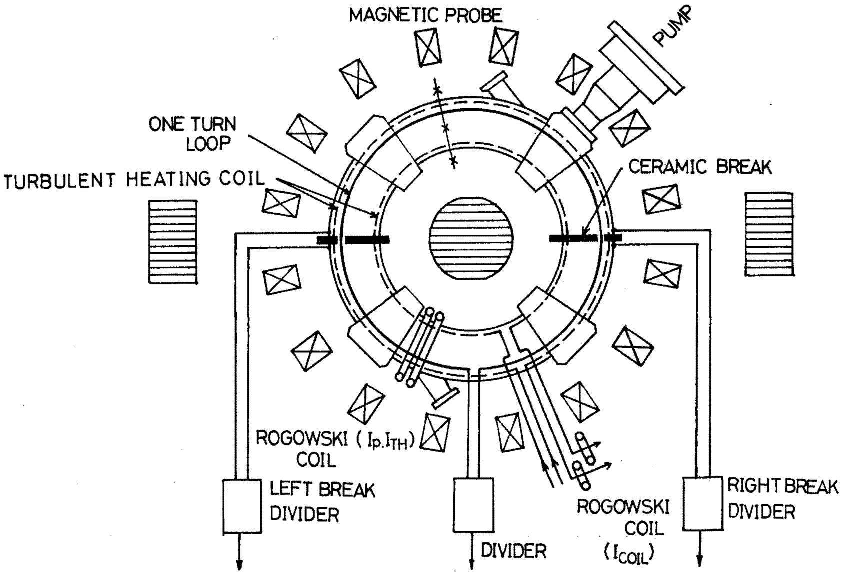


Fig. 4 The arrangement of the plasma monitor apparatus.

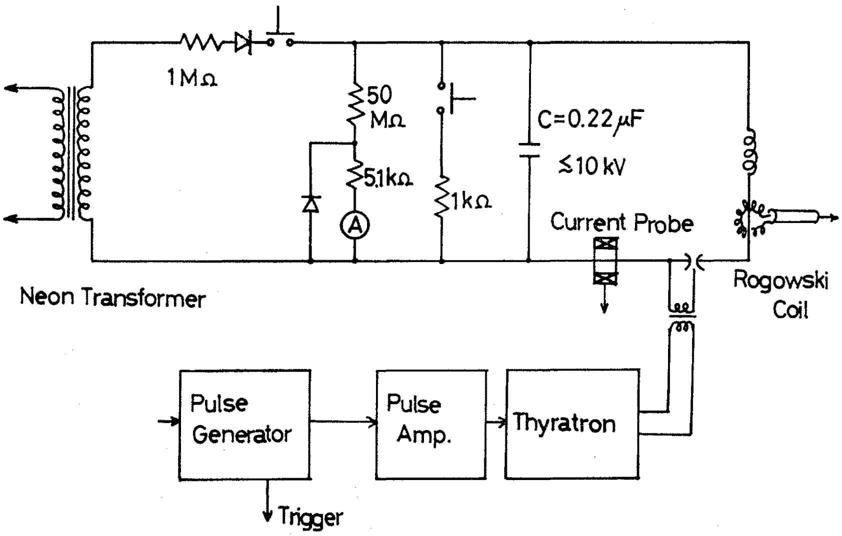


Fig. 5 The block diagram of the calibration circuit.

The calibration of the Rogowski coil was carried out using the circuit like Fig. 5. The coil output was calibrated by a current probe (Sony-Tectronix; CT-5, P 6021 and Termination). The peak time of this ringing current was 3 μs, as shown in Fig. 12(2). Thus, we had following calibrated value;

$$I_{TH} = (727 \pm 30) \times 10^3 V_0 \quad (\text{A, V})$$

where I_{TH} and V_0 is the turbulent heating current and output voltage of the Rogowski coil circuit, respectively.

2. 2. The system measuring the one turn voltage of the tokamak and turbulent heating plasma.

In order to measure the one turn voltage of the tokamak and turbulent heating plasma simultaneously, the circuit shown in Fig. 6 was adopted.

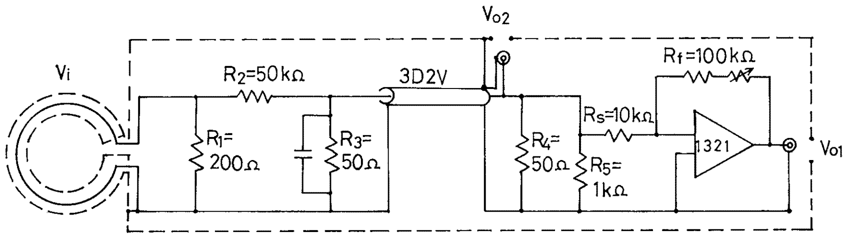


Fig. 6 The one turn loop circuit.

The one turn loop (34 cm major radius), which was placed inside the toroidal return coil, was made by the coaxial cable (RG142 B/U). The inner conducter was the one turn loop, while the outer one was for electrostatic shield.

The parameters of the divider were chosen so as to have a flat response curve, to match the output resistance to a 50 Ω coaxial cable and to be able to get an optimum output. From the frequency charac-

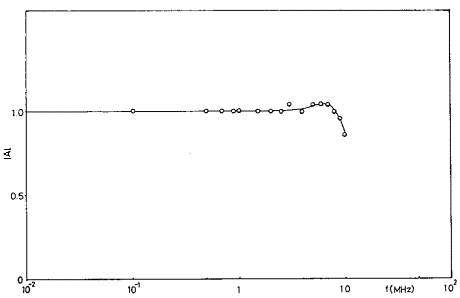


Fig. 7 The frequency characteristic of the one turn loop.

teristic test of the one turn loop, as shown in Fig. 7, the impedance viewed from the signal source must be 200 Ω. The parameters $R_1=200\ \Omega$, $R_2=50\ k\Omega$ and $R_3=50\ \Omega$ were chosen to satisfy above conditions. The power of the resistance made of the oxide metal film was 50 W. The high frequency insulation was painted on these resistances to prevent the break down.

The wave form of the pulse response of the divider is shown in Fig. 8(1). The square wave form of the divider output was adjust by the condenser which was connected in parallel with a resistance R_3 to prevent a ringing. This condenser was selected with trial and error. The time delay between two wave forms depended on the length of the coaxial cable (3D2V, 10 m long).

Figure 8(2) shows the pulse response of the amplifier. From the circuit shown in Fig. 6, the following relations were obtained;

$$V_{TOK}=200\ V_{01}\quad (\text{V, V})$$
$$V_{TH}=2000\ V_{02}\quad (\text{V, V})$$

where V_{TOK}, V_{01}, V_{TH} and V_{02} is the tokamak one turn voltage, output voltage of the tokamak one turn loop circuit, turbulent heating voltage

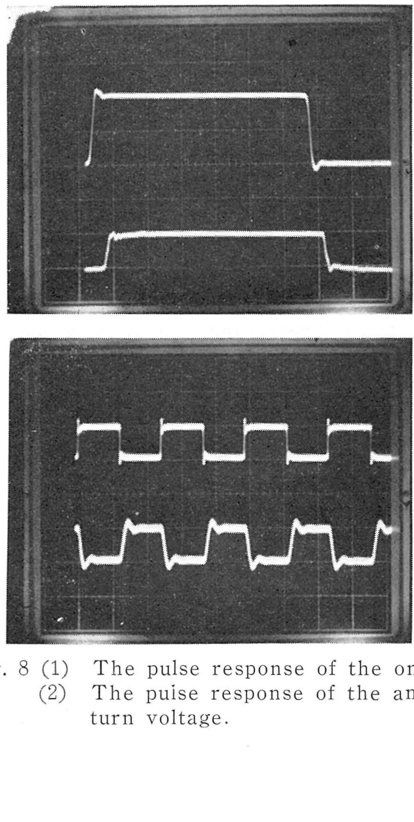


Fig. 8 (1) The pulse response of the one turn voltage divider.
(2) The puise response of the amplifier for the tokamak one turn voltage.

and output voltage of the turbulent heating one turn loop circuit, respectively.

2. 3. The system measuring the ceramic break voltages.

The schematic diagram is shown in Fig. 4. The chamber becomes the one turn loop when the breaks are connected with two dividers. In Fig. 9 we show the detail of the circuit, which consists of the senser, the divider and the pulse transformer. Since the chamber was floating from the ground, it was necessary to insulate the senser from the receiver side by the transformer. The parameters of the divider and pulse transformer were determined from the frequency characteristic test. The frequency characteristic of the pulse transformer is shown in Fig. 10, which indicates that this system could be used up to 10 MHz. The pulse response of this entire system is shown in Fig. 11.

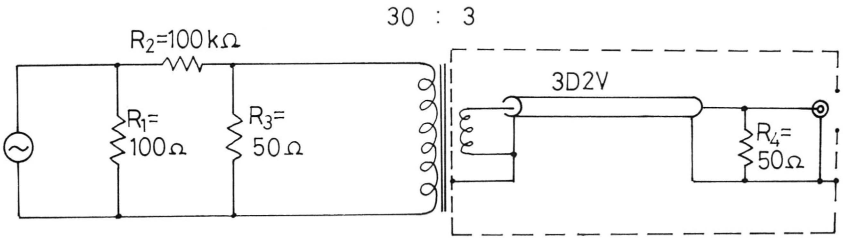


Fig. 9 The circuit to measure the ceramic break voltage.

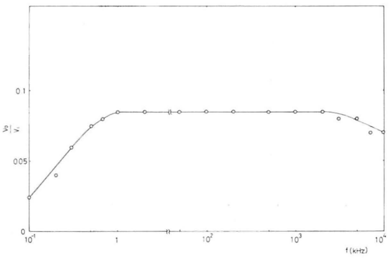


Fig. 10 The frequency characteristic of the pulse transformer.

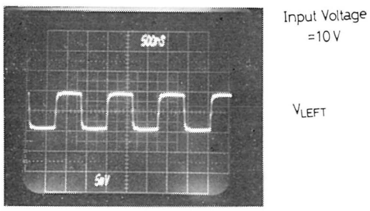


Fig. 11 The pulse response of the circuit to measure the ceramic break voltage.

The calibration of this system was carried out by applying the square wave voltage (10 V) to the divider input. The following values were obtained;

$$V_{LEFT} = 1.25 \times 10^3 \, V_{O,L} \ \ (\mathrm{V},\ \mathrm{V})$$
$$V_{RIGHT} = 1.18 \times 10^3 \, V_{O,R} \ \ (\mathrm{V},\ \mathrm{V})$$

where V_{LEFT}, $V_{O,L}$, V_{RIGHT} and $V_{O,R}$ is the left ceramic break voltage, output voltage of the left ceramic break voltage circuit, right ceramic break voltage and output voltage of the right ceramic break voltage circuit, respectively.

2. 4. The system measuring the turbulent heating coil current.

The Rogowski coil was wound at regular intervals along a ring of vinyl of 2.5 mm mainor radius and 25 mm major radius. The number of the turns was 140. Figure 1 also shows the Rogowski coil circuit measuring the turbulent heating coil current. The circuit parameters were determined from the frequency characteristic test. Figure 2 shows the frequency characteristic of this Rogowski coil. The RC integrator was the same one as in the case of the circuit measuring the turbulent heating current. Therefore, this system could be used up to 10 MHz. These Rogowski coils were placed at the feeder portion of the turbulent heating coils.

The calibration was performed by the circuit previously mentioned. The results were as follows;

$$I_B = (100 \pm 5) \times 10^3 \, V_{O,B} \ \ (\mathrm{A},\ \mathrm{V})$$
$$I_A = (104 \pm 5) \times 10^3 \, V_{O,A} \ \ (\mathrm{A},\ \mathrm{V})$$
$$I_F = (98 \pm 5) \times 10^3 \, V_{O,F} \ \ (\mathrm{A},\ \mathrm{V})$$
$$I_E = (109 \pm 5) \times 10^3 \, V_{O,E} \ \ (\mathrm{A},\ \mathrm{V})$$

where I_B, I_A, I_F, I_E, $V_{O,B}$, $V_{O,A}$, $V_{O,F}$ and $V_{O,E}$ is the B-coil, A-coil, F-coil and E-coil current, the output voltage of the Rogowski coil circuit measuring the B-coil, A-coil, F-coil and E-coil current, respectively.

In Fig. 12 is shown an example of the wave form of the coil current.

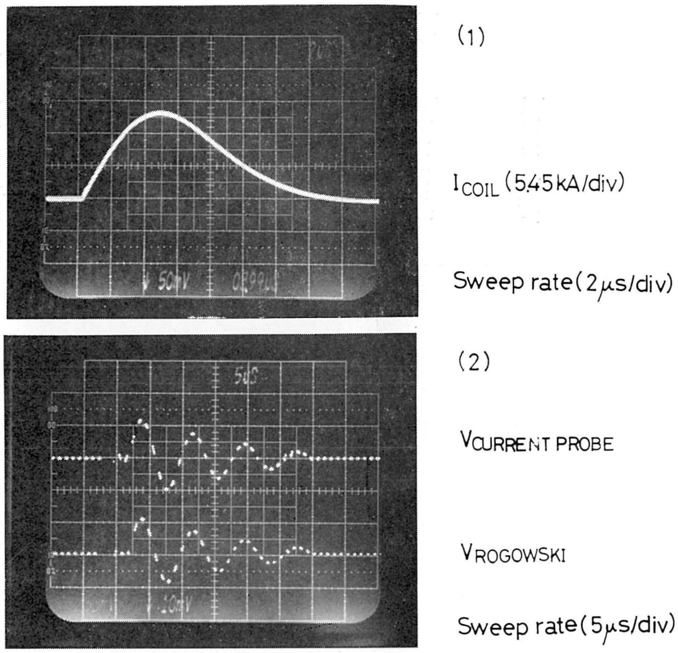
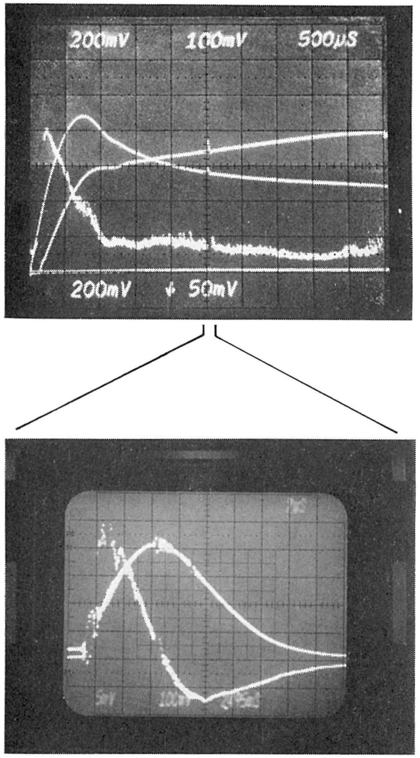


Fig. 12 (1) The E.-coil current.
(2) The current wave form of the calibration circuit.

3. Experimental results of the tokamak plasma current, turbulent heating current, tokamak one turn voltage and turbulent heating voltage.

The examples of the results of the tokamak plasma current and the turbulent heating current are shown in Fig. 13. The symbol I_p in Fig. 13(1) is the tokamak plasma current, on which the short pulse is superimposed. However, this pulse does not correctly represent the turbulent heating current, since as mentioned in the previous paper, this Rogowski coil circuit has a frequency response less than 100 kHz, while the turbulent heating current has the one above 100 kHz. The symbol I_{TH} in Fig. 13(2) shows the turbulent heating current. The lift of the zero line is seen in Fig. 13(2). This is considered to be due to the toroidal magnetic field and the tokamak plasma current. The small amplitude noise is seen on the current. This noise was able to be removed by complete electrostatic shield.

The symbol V_L in Fig. 13(1) shows the one turn voltage in the tokamak discharge. The symbol V_{TH} in Fig. 13(2) and Fig. 14(1) shows the turbulent heating voltage. These photographs show that a ringing wave form appears in the starting up. This phenomenon may not come from the measuring system. However, the noise at the time of about



(1)

I_p (5.84 kA/div)

I_{BV}

V_L (10V/div)

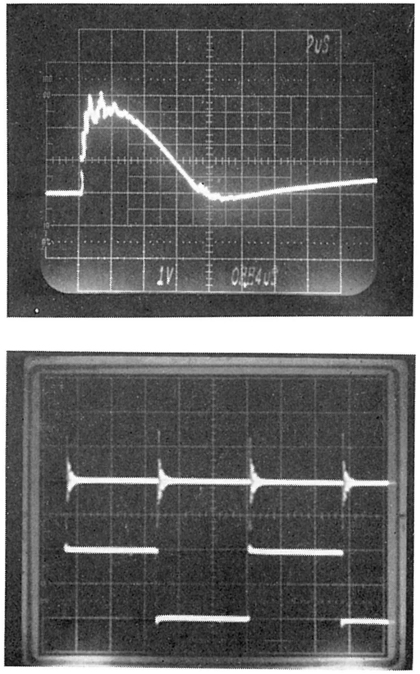
(2)

I_{TH} (3.64kA/div)

V_{TH} (200V/div)

Sweep rate (2µs/div)

Fig. 13 (1) The plasma current and one turn voltage in the tokamak discharge.
(2) The turbulent heating current and voltage.



(1)

V_{TH} (2kV/div)

Sweep rate(2µs/div)

(2)

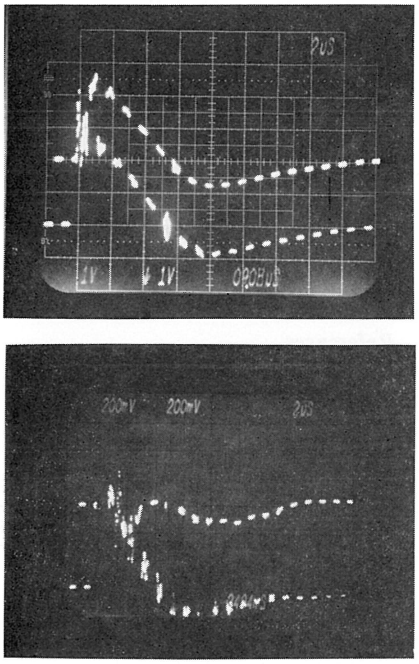
One Turn Loop Noise

Sweep rate(2µs/div)

Fig. 14 (1) The turbulent heating voltage without plasma.
(2) The electrostatic noise on the one turn loop.

5 μs came from the electrostatic noise pickup by the measuring system. This fact was confirmed by electrostatic noise tests. The result of the test is shown in Fig. 14(2).

The examples of the ceramic break voltage measurements are shown in Fig. 15. The zero crossing time of the break voltage in Fig. 15(1) is different from that of the turbulent heating voltage in Fig. 14(1). This may be due to the fact that the measuring system has a bad low frequency characteristic in comparison with the one turn loop system.



(1)

V_{LEFT} (1.25kV/div)

V_{RIGHT} (1.18 kV/div)

Sweep rate(2μs/div)

(2)

V_{LEFT} (250 V/div)

V_{RIGHT} (236V/div)

Sweep rate(2μs/div)

Fig. 15 (1) Ceramic break voltages without piasma.
(2) Ceramic break voltages with plasma.

4. Discussion and conclusion.

It is important to measure correctly the phase relation of the current and voltage in evaluating the input power in the turbulent heating experiment. From the results in Section 2, the time delay of the Rogowski coil and one turn loop circuit is about 40 ns and 30 ns, respectively. Since the time difference of these systems is about 10 ns, this problem is not very serious.

As shown Fig. 15(1) the output voltage of the left and right break in the case without the plasma is nearly equal. However, the output voltage of the left break with the plasma is nearly zero from Fig. 15(2). This fact seems to demonstrate that the left break portion is not insulated.

In this turbulent heating experiment the plasma position is only measured during the tokamak discharge, but is not measured during the turbulent heating discharge. Although the access of the probe to the ceramic break is reduced, the plasma position may be able to be measured by the smaller and higher frequency magnetic probes.

In conclusion, the apparatus measuring the macroscopic quantities such as the current and voltage in the turbulent heating experiment is designed, constructed and has been used successfully.

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Appendix

The chamber effect on the Rogowski coil output.

The Rogowski coil measuring the turbulent heating current was placed on the SUS chamber because of the difficulty of setting on the ceramic break. The problem was whether or not the SUS chamber had the effects on the gain and phase shift of the coil output. It was found by the following experiment that the SUS chamber had no effect in the frequency range required. The experimental method is shown in Fig. 16. Instead of the torus SUS chamber (25.4 cm major radius, 6 cm minor radius and 5 mm thick), the straight SUS pipe of 1.3 m long, 90 mm outer diameter and 4 mm thick was used. The current probe previously described was placed outside the SUS pipe and the one Rogowski coil was placed outside and on the SUS pipe alternately. The current required was produced by the calibration circuit previouly described. The rise time of the current was faster than that of the turbulent heating current. The results were obtained by the comparison of the coil outputs outside with on the SUS pipe. Figure 17 shows the result. Both outputs show that the SUS pipe has no effect on the gain of the Rogowski coil. Furthermore, the wave form of the current probe output and the coil output are shown in Fig. 18. It is found from these photographs

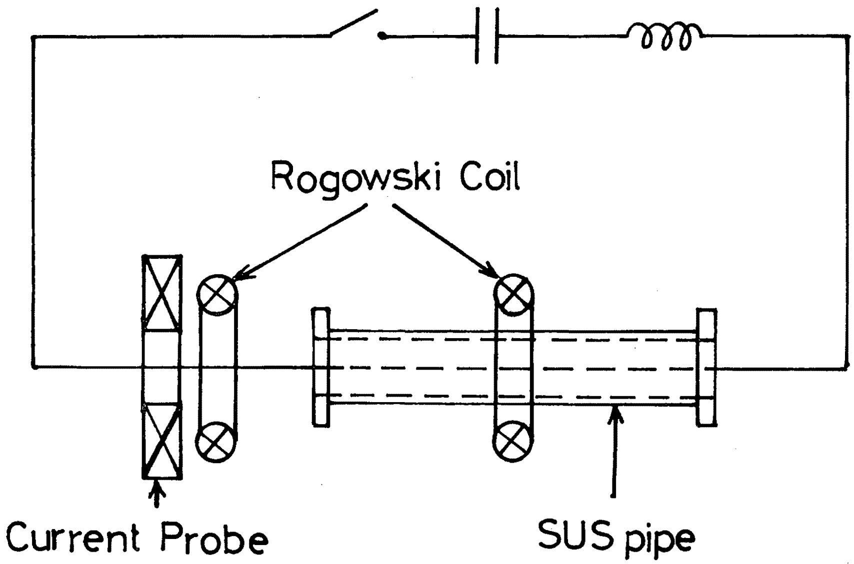

Fig. 16 The method measuring the chamber effect on the Rogowski coil output.

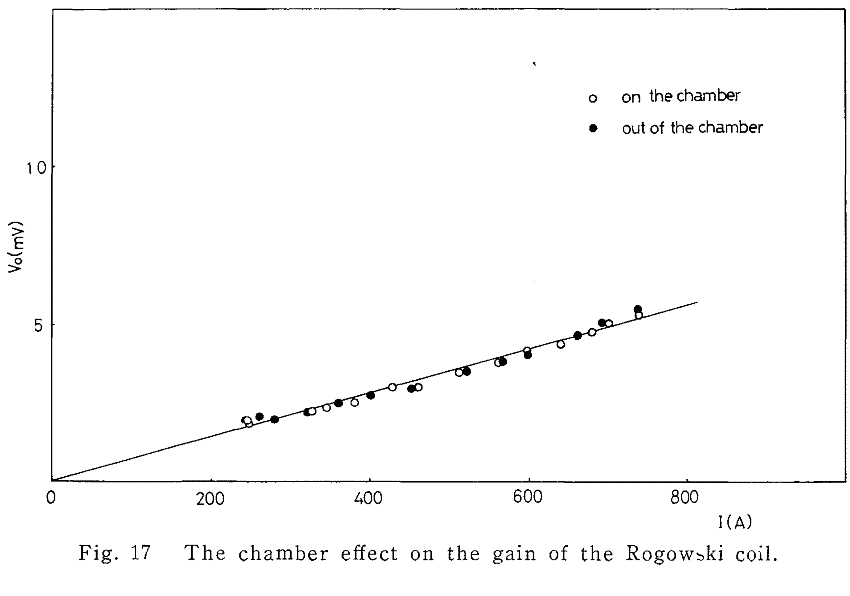

Fig. 17 The chamber effect on the gain of the Rogowski coil.

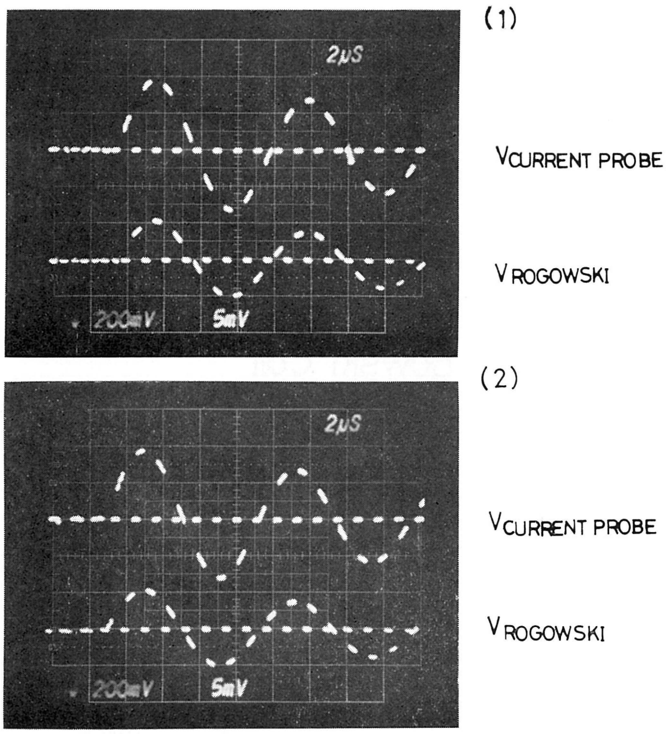

Fig. 18 (1) Outputs of the current probe and Rogowski coil when the coil is placed on the SUS pipe.
(2) Outputs of the current probe and Rogowski coil when the coil is placed outside the SUS pipe.

that there is no time delay in the output of the coil placed outside and on the SUS pipe. This may be explained by the surface loop current streaming inner and outer surface in the axial direction. Thus, we can measure correctly the turbulent heating current with the Rogowski coil on the SUS chamber.