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Radiation-induced thermoelectric sensitivity in the mineral-insulated cable of magnetic diagnostic coils for ITER

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Abstract

Magnetic coils are indispensable for plasma position control in tokamaks. For ITER, non-inductive voltages generated under irradiation have to be reduced to well below 1 μV in order to support long pulse (3000 s) operation. In situ measurements of the differential voltage between the ends of two magnetic coils wound with mineral-insulated (MI) cable have been carried out at the JMTR fission reactor. The MI cables of the two magnetic coils had copper center conductor with diameter 0.5 and 0.8 mm, respectively, stainless steel outer sheath and MgO insulation. The measured differential voltage for the two MI cables increased with neutron fluence, reaching 4.5 and −0.7 μV in the two coils, at a fast neutron fluence of 1.26×10^{23} n/m^2. The magnitude of the measured voltage can be explained by thermoelectric potentials, enabled mainly by non-uniform transmutation and displacement damages of the copper core of the cable.

1. Introduction

Magnetic coils are indispensable for plasma position control in tokamaks. In ITER, coils will be installed inside the vacuum vessel, where a fast neutron flux of about 5×10^{23} n/m^2 s and an ionizing dose rate of about 100 Gy/s are expected. Magnetic coils wound with mineral insulated (MI) cable are proposed as the most reliable magnetic sensors in ITER [1]. However, radiation-induced EMF (RIEMF) of order 1V was observed between the center conductor and the outer sheath under fission reactor irradiation tests [2–5]. Should more than a small fraction (10^{-6}) of this RIEMF appear across the center conductor (as the signal voltage does), significant errors will be induced into the plasma position measurements.

In a previous experiment at the Japan Material Testing Reactor (JMTR) under the Japanese/US collaboration, a drift of 10–40 mV s for 1000 s integration time was observed by a prototype digital integrator connected across the center conductor of magnetic coils wound with MI cables [6]. However, it could not be confirmed whether the observed drift was caused by RIEMF, or some other effect such as noise of the integrator itself. As a preliminary test, direct measurement of the induced voltage across the center conductor of magnetic coils was carried out under ^{60}Co gamma-ray irradiation with a dose rate of about 4 Gy/s. There was no significant change in the voltage during and after irradiation [7]. Based on this, the RIEMF was estimated to be smaller than the measurement uncertainty of 100 nV. Since then, even lower limits have been reported in comparable conditions [8].

Here we present an interim report on the in situ measurement of the differential voltage across the same magnetic coils used in the ^{60}Co irradiation experiment using the same precision voltmeters but now under neutron irradiation in JMTR.

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2. Experimental Setup

Two magnetic coils were used in this test. Coils A and B are wound with MI cable with copper center conductor (core) diameters of 0.5 and 0.8 mm, respectively, in order to check for any core size effect. The outer sheath is stainless steel SS316L of diameter 1.6 mm. The insulation material is MgO. A schematic view of the coils is shown in Fig. 1. The MI-cable winding is 200 turns on an alumina bobbin. Both ends of the MI cable are used as lead wires with a length of 20 m each. These coils are similar though not identical, to those planned for ITER [1].

The coils were inserted into a SS316L irradiation rig with a diameter of 60 mm, in tandem, as shown in Fig. 2. The space between the magnetic coils and the rig was filled with aluminum spacers to remove the nuclear heat of the magnetic coils by conduction to the rig. The residual space inside the rig was filled with He gas for the same purpose. The outside of the irradiation rig was cooled with flowing water. The temperature of the magnetic coils was monitored with K-type thermocouples attached to the surface of the coil housing. No heaters, or other temperature controls were employed. The thermocouple temperature was 70–80 °C at 50 MW power in JMTR. The temperature of the coolant water was steady about 50 °C. We estimated the temperature of the core of the coils to be about 300 °C by a heat transport calculation. The gamma heating rate is about 1.25 W/g for stainless steel and has a distribution along the rig axis as shown in Fig. 2. This is about ten times higher than in ITER, but as the cooling in the rig is more effective, the temperature gradients are only slightly higher than expected in ITER.

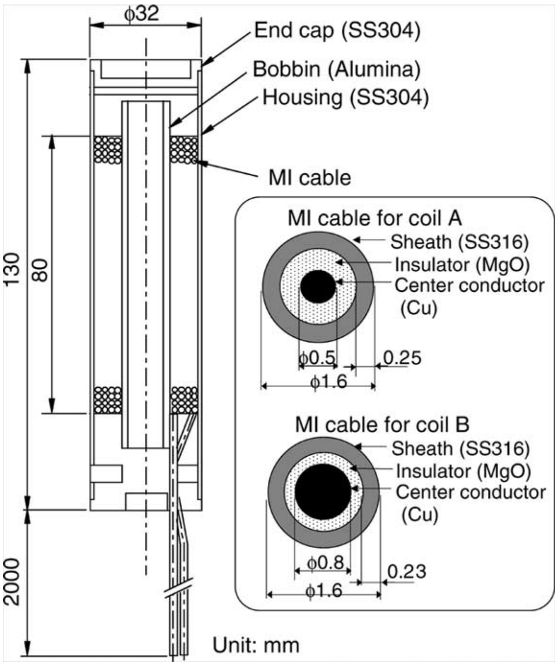

Fig. 1. Schematic view of the magnetic probe used in the irradiation test.

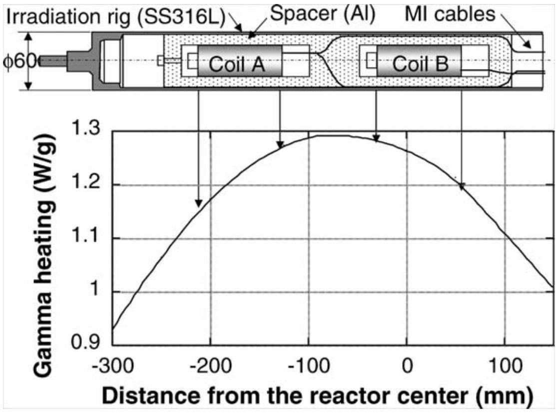

Fig. 2. Schematic view of the irradiation rig and the gamma heating rate distribution along the rig axis.

The fast neutron flux is 5.2×10^{16} n/m^2 s and the thermal neutron flux is 7.5×10^{17} n/m^2 s. Two runs are completed: 17 November to 10 December 2002 and 17 June to 20 June 2003. At the end of the second run, the fluence was 1.26×10^{23} n/m^2 (>1 MeV) or 3×10^{23} n/m^2 (>0.1 MeV), which is almost one third of the fast neutron fluence expected in ITER. The thermal neutron fluence is 1.8×10^{24} n/m^2 which is almost equivalent to that in ITER. (Fluence values at the end of the first run were approximately 13% lower.) More runs are planned.

Fig. 3 shows a block diagram of the instrument. Both ends of the MI cable were soldered to soft coaxial cable type RG-58U; these connections were potted within individual stainless steel capsules. The coaxial cables were connected to a junction box using BNC type connectors. In the junction box, the conductors were grounded by 511 Ω resistors to reject high impedance EMF. The differential voltage across the conductors was measured with a Keithley model 182 nano-voltometer. Simultaneously, current from the center conductor to the sheath was measured with a Keithley 486 pico-ammeter. The analog outputs of the nano-voltmeter and pico-ammeter were digitized and stored in a laptop computer. The signals of the thermocouples were stored in the main JMTR computer. For the second run: (1) the individual steel connection capsules containing the four potted MI to RG58U joints, exposed to air during the first run, were coated with thermal compound and clamped together inside a custom-built aluminum block heat-sink. (2) The junction box was replaced by a 10 mm thick aluminum base plate and all accessible cable connections were made by cold welding (Cu–Cu). The junction box connections were thermally grounded to

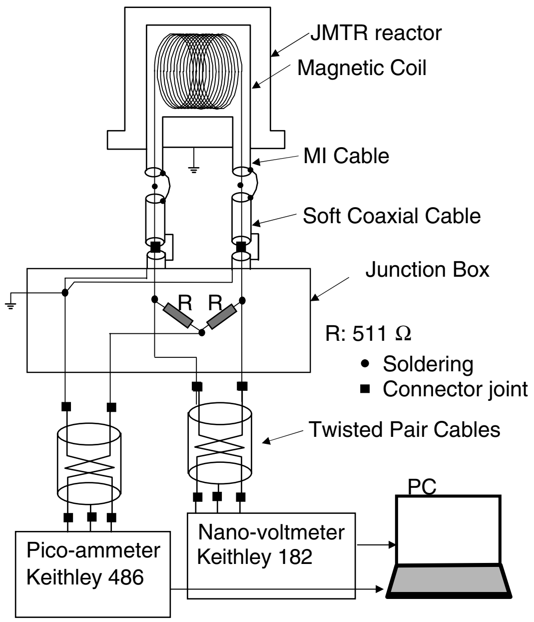

Fig. 3. Block diagram of the instrument for the in situ measurement of magnetic coils.

this base plate. These measures were taken to reduce the temperature gradients and eliminate any parasitic EMF.

3. Results

3.1. First run

Fig. 4(a) shows the induced voltage across the coil as a function of elapsed irradiation time. In the first day, the reactor power was ramped up step by step from 0 to 50 MW. During the ramp up, the temperature of the surface of the coil housing increased from 20 to about 80 °C. There was no consistent response in the voltage corresponding to the stepping-up of the reactor power. The voltage of coil A decreased to be about −0.4 μV in the first day of the irradiation and increased almost monotonically during the constant reactor power of 50 MW. In contrast, the voltage of coil B increased once and decreased almost monotonically towards about −0.5 μV. At the ramp down of the reactor power, both voltages returned to the initial values in minutes. The magnitude of the voltage of coil A is about six times larger than that of coil B just before the reactor ramp down.

Fig. 4(b) and (c) shows the current from the core to the sheath, and the voltage between the core and the sheath, respectively. These correspond to the RIEMF current and voltage as reported in Refs. [4–6]. The current increased with reactor power at the ramping-up phase, and gradually decreased during the flat-top of 50 MW. Of particular note is that the current and the voltage of coil A

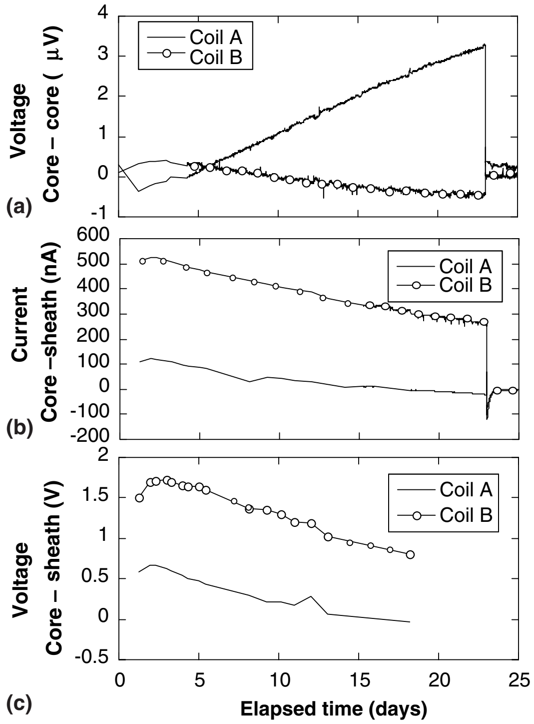

Fig. 4. First run: Time histories of (a) the voltage across the coil, (b) the current from the core to the sheath and (c) the voltage between the core and the sheath.

approached zero, indicating that the electron emission from the core and the sheath are balanced in coil A. At the reactor power ramp down, currents of coils A and B returned to zero via significant overshooting.

The behavior of the voltage across the coils, shown in Fig. 4(a) is very different from that of the core to sheath RIEMF shown in Fig. 4(c), suggesting that the differential voltage is not caused by RIEMF. A possible explanation is thermoelectric potential differences. Two elements must combine to form effective thermoelectric elements: temperature gradients and material property changes. Both transmutation, as well as displacement damage [9] can generate non-uniform thermoelectric properties (usually denoted as changes in the thermopower, μ) in the conductor. Transmutation is essentially permanent. Based on the data under 14 MeV neutron irradiation of Ref. [9], we can expect some relaxation for atomic displacement at 300 °C, the temperature of the coils during irradiation.

3.2. Heating test

In order to examine the temperature sensitivity of the coils, a Joule heating test was carried out after the first run of the irradiation. The center conductor of coil A was heated by AC power (50 Hz, 10 A, 30 V approximately).

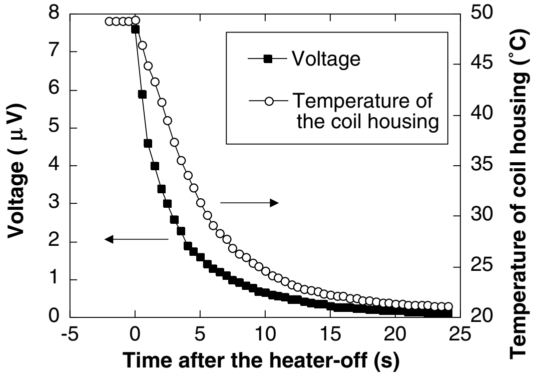

Fig. 5. Time histories of the voltage across the coil and the temperature of the coil housing during the heating test.

After turning off the heating, the differential voltage was measured. The induced voltage was observed to be 8 μV at switch-off and decreased exponentially with the temperature of the coil housing as shown in Fig. 5. The applied heating power was estimated to be almost same as that of the nuclear heating during irradiation and, as confirmation, resulted in approximately the same temperature rise with respect to the coolant. The measured voltage in the heating test is of a similar magnitude to that obtained during irradiation, which is what would be expected if the voltage were of thermoelectric origin.

3.3. Second run

The second run was a short (four day) irradiation. Fig. 6 shows the measured voltages across the coils as a function of elapsed irradiation time. In the first day of the irradiation, approximately followed the reactor power, ramping up step by step from 0 to 50 MW. Immediately after ramp-up, voltages reached 4.5 and −0.7 μV in coils A and B, respectively. This indicates that the coils kept the enhanced sensitivity to reactor power they had acquired by the end of the first run and which we attribute to thermocouple circuits generated in the coils.

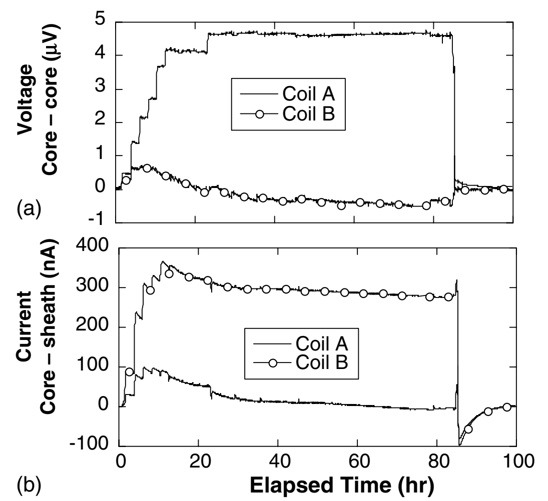

Fig. 6. Second run: Time histories of (a) the voltage between both cores and (b) the current from the core to the sheath.

4. Discussion

Under the JMTR irradiation conditions, the following transmutations are dominant for copper:

$$^{63}\mathrm{Cu}(\mathrm{n},\gamma)^{64}\mathrm{Cu}(t_{1/2}=12.9\ \mathrm{h}) \xrightarrow{\mathrm{EC}:41\%,\beta^{+}:19\%} {}^{64}\ \mathrm{Ni(stable)} \tag{1}$$

$$^{63}\mathrm{Cu}(\mathrm{n},\gamma)^{64}\mathrm{Cu}(t_{1/2}=12.9\ \mathrm{h}) \xrightarrow{\beta^{-}:40\%} {}^{64}\ \mathrm{Zn(stable)} \tag{2}$$

$$^{65}\mathrm{Cu}(\mathrm{n},\gamma)^{66}\mathrm{Cu}(t_{1/2}=5.09\ \mathrm{m}) \xrightarrow{\beta^{-}:100\%} {}^{66}\ \mathrm{Zn(stable)} \tag{3}$$

Based on the neutron spectrum in JMTR, transmutation rates were estimated. At the end of the first run, the densities of ^{64}Ni, ^{64}Zn and ^{66}Zn are, approximately, 0.03, 0.02 and 0.01 at.%, respectively. Although these are small changes, as an example, 0.1% of Au impurity in Ag is enough to change the thermopower of silver by 0.1 μV/K [10]. If the effect of Ni and Zn in Cu is comparable, the change in thermopower in the copper core due to these impurities would be ∼0.06 μV/K. For the available temperature differences of 50–200 K, voltages up to 12 μV could be expected and they encompass the full range observed in the reactor and Joule heating tests. Similar numbers can be derived based on the fast neutron fluence and the observations of change in thermopower by fast neutrons reported in Ref. [9].

Due to the complex construction of the coils and rig, a number of possible thermocouple circuits, some quite complex, can arise. Whether this, together with differences in construction details, can explain the large difference between coils A and B, is still under discussion. Points under consideration include: (a) The coils are wound the same way, but the radiation exposure gradient is reversed along the long axis (Fig. 2). This reverses a major thermoelectric term. (b) Coil A has an additional thermoelectric loop in its feeder cable (Fig. 2). This complicates its response. (c) The higher copper content of coil A (Fig. 1) means that the thermal gradients within coil B are smaller.

5. Conclusion

In situ measurements of the differential voltage between the two ends of the center conductors of magnetic coils wound from MI cable have been carried out at the JMTR fission reactor. In the first run of the irradiation the induced voltage increased with time during the reactor power flat top and returned to the initial value at the reactor shutdown, implying a large change in sensitivity to reactor power during the run. It was confirmed by heating tests that this voltage is likely of thermoelectric origin. A second short run showed that this change in sensitivity to reactor power was permanent. Two possible mechanisms able to generate thermoelectric circuits, lattice displacement damage and transmutation, were found, with the latter more likely to dominate in the temperature range of the experiments. The voltage generated is in the range of several μV, higher than that which can be tolerated for ITER long pulse operation. Minimizing this effect is therefore of high priority.

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