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RIEMF in MgO and Al_2O_3 insulated MI cable ITER magnetic diagnostic coils

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Abstract

Radiation induced currents and voltages, generally termed RIEMF, have recently been the object of discussion due to inconsistent results. The problem is due to a possible RIEMF generated along the centre conductor of a coil in a radiation field. To address this, two representative ITER coils have been made from 1 mm diameter MI cable with copper and stainless steel inner conductors. Measurements were made of the radiation induced voltage and current between the centre and outer sheath, as well as the voltage across the two ends of the centre conductor during ^{60}Co gamma irradiation at 10 Gy/s. While putting an upper limit on the radiation-induced part, it has been demonstrated that, within the measurement capability, no significant RIEMF is produced along the central conductor. However, the measurements have highlighted other potential problems due to temperature and pressure gradients for the use of MI cable magnetic coils in ITER.

1. Introduction

It has become evident that the use of mineral insulated (MI) coaxial cables in the expected ITER radiation field must accommodate radiation induced currents and voltages, generally termed RIEMF (radiation induced electromotive force), which represent additional noise in the cables. The problem is of particular concern for the sensitive magnetic coil diagnostics, a prime candidate for plasma current and position control.

The existence of RIEMF between the central conductor and outer sheath which can generate potentials of the order of volts and microamps of current, has been known and employed for many years. However in recent experiments orientated towards ITER diagnostic needs, tentative evidence has been found for the possible generation of a small voltage along the central conductor itself. Such an RIEMF is of serious concern. Due to experimental difficulties in measuring small voltages and currents in a radiation environment at the end of long cables, no definite conclusions could be drawn [1,2].

The difficulty arises because at the 100 nV level, thermal voltage effects, as well as possibly temperature/pressure and movement induced polarization effects in the insulator itself become important.

2. Experimental procedure

2.1. Coils

To perform the task two separate coils were wound using different MI cables, see Table 1. The coil dimensions were calculated from the recommendations taken for ITER relevant conditions [3]. These may be summarized as follows:

The coil diameter including case should be less than 0.025 m to avoid large blanket cut-outs and large thermal gradients. Here to perform the gamma irradiations this size limitation is required in order to avoid large dose rate gradients due to the localized radiation field. The sizes relevant for ITER-FEAT of the MI cable should be about 1.6 mm (outer) and 0.75 mm (inner) diameter, and the coil should have an NA value of about

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Table 1
Physical data for the two cables and the two coils prepared for gamma irradiation

		#1	#2
Cable	Outer diameter (mm)	1	1
	Central conductor diameter	0.34 ± 0.03	0.34 ± 0.03
	Sheath material	Stainless steel	Stainless steel
	Conductor material	Zirconium–Copper	Stainless steel
	Insulator	Magnesia (>94%)	Alumina (99.6%)
	Total length (m)	25	25
	Code	1ZsAc10	1AcAc10
	Line resistance	0.25 Ω/m	8 Ω/m
Coil	Outer diameter (mm)	28	28
	Inner diameter (mm)	24	24
	Layers	2	2
	N (total turns)	112	112
	Rc (Ω)	5.4 ± 0.1	193 ± 0.6
	NA (turns m^2)	0.06	0.06

0.05 turn m^2. The coil should have a two-layer configuration with both cable ends being brought out on the same side. This is the configuration used here.

With these recommendations the cables were wound on two identical aluminium formers with an inner diameter of 20 mm, outer diameter 24 mm, and length 56 mm. The coil leads were about 7 m, and were terminated by crimping two sealed connectors in a dry nitrogen atmosphere to avoid moisture effects on the electrical conductivity of the mineral insulation. For each coil and leads a single 25 m length of MI cable was used hence avoiding any interconnections. Physical data are summarized in Table 1.

2.2. Irradiation set-up

The irradiations have been performed at the CIEMAT Nayade ^{60}Co gamma irradiation pool facility. In the high dose rate configuration, 12 rod-shaped sources approximately 100 mm long are positioned on concentric circles surrounding a 40 mm diameter stainless steel cylindrical irradiation capsule. This arrangement provides a sufficiently uniform central irradiation volume with a dose rate of about 10 Gy/s. The capsule is connected to the control room by means of flexible 6 m long, 50 mm diameter hose which terminates in an airtight interface provided with electrical and gas feedthroughs. Dosimetry was performed within the capsule both along the axis and radially using standard UKAEA Harwell Red Perspex Dosimeters (Type 4034 range 5–50 kGy). Each coil was placed in turn within the capsule with the leads passing out through the interface to the measuring equipment. Therefore no connectors are irradiated, only a small fraction of the cable coming out of the coil region. The possible irradiation effects of this irradiated cable portion would be then much lower than that of the coil. The resulting radiation field is shown in Fig. 1, where the position of half of the coil is shown with maximum radiation at the centre ($H = 0$ mm), reducing towards the ends of the coil ($H = \pm 30$ mm). In this central symmetric position the dose rate varies by about 8% between the centre and the ends of the coil. Additional vertical positions were used by raising the coil in 30 mm steps. In this case the dose rate variation along the coil was about 20% (maximum at the bottom end and minimum at the top of the coil). During immersion in the pool and irradiation, nitrogen gas at an over pressure of 0.2 bar is circulated to avoid water leaks and the build up of radiation produced gases such as

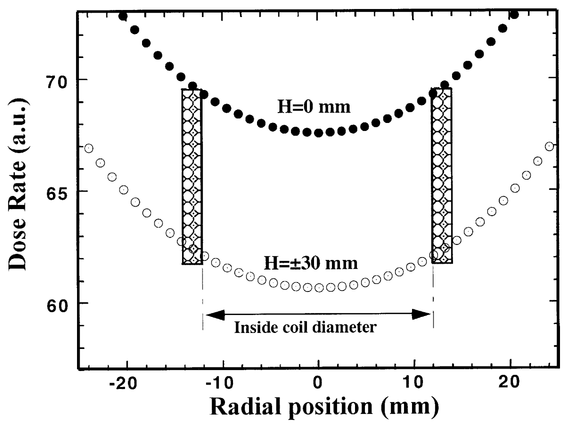

Fig. 1. Radial dependence of the dose rate for two different vertical positions: at the centre of the coil (closed circles) and near the ends (open circles). The rectangles show the position of the MI cables of the coil, where the dose rate at $H = 0$ mm is 10 Gy/s.

chlorine or fluorine from the hose and other organic materials.

2.3. Measuring instrument selection

For these measurements the exact configuration of the measuring system is crucial to obtain the maximum stability and sensitivity. Therefore a study of the required instruments and signal to noise ratios in the laboratory (without radiation) was made.

The current between the two ends of the central conductor was measured with three different ammeters. As expected, the very low value of the electrical resistance of the coil causes it to be always less than that of the measuring device input impedance. This produces unstable currents of the order of nA to μA to flow through the complete circuit (due to voltage burden).

The voltage across the two ends of the central conductor was then measured with two different voltmeters. This magnitude is easier to measure because it is an almost open circuit configuration. From the values of the correct current and voltage obtained with a test rotating magnet, it was found that under these conditions it is equivalent to measure voltage or current, the values being related by Ohm's Law. Finally a Keithley 148 nanovoltmeter with a resolution of less than 1 nV for the most sensitive range was selected to measure directly the voltage across the two centre conductor ends.

To ensure highest accuracy and lowest possible noise, the full maintenance routine for the Keithley 148 nanovoltmeter was carried out and all the internal circuits were checked and adjusted to fulfil the specifications. Finally a low thermal EMF shorting plug was used to measure noise and long term drift of the instrument alone. Under these ideal conditions noise was less than 1 nV and drift of the order of ±5 nV, well within the specifications.

Measurement of the normal RIEMF (radiation induced current and voltage between central conductor and sheath) proved to be far easier, with any standard picoammeter and voltmeter being suitable to provide reliable results. For all the measurements, data was recorded with a Yokogawa 2 channel paper chart recorder set with a 1 Hz Low Pass Filter to reduce the noise and record essentially the DC or slow component of any induced voltage or current.

The coil was then mounted in the irradiation capsule and connected to the nanovoltmeter for preliminary tests. In order to separate the effect of possible drift and off-set due to the nanovoltmeter itself from a real signal caused by RIEMF, a two-pole inverting 'make before break' wafer switch was mounted at the input of the nanovoltmeter in an electrically shielded box to enable the polarity of the cable ends to be changed. The 'make before break' switching sequence shorts the two conductor ends and instrument input when passing from one polarity to the other, thus avoiding large spurious voltages due to open circuits and charge build-up.

3. Results and discussion

3.1. Pre-irradiation tests

In order to separate and quantify the effect on the EMF of different physical processes, several tests were carried out before the irradiation itself. The main results are summarized below.

3.1.1. Temperature, pressure and bending effects

For voltage measurements in the nanovolt range, general electromagnetic noise and thermoelectric junction (contact) effects are of utmost importance. The sensitivity of the whole system (coil, cable and measuring system) was first checked without any radiation. With the coil connected to the nanovoltmeter the minimum noise level increased to 15 nV (peak to peak), compared with <1 nV for the low thermal EMF shorting plug, the instrument drift however remained of the order of 5 nV. During these tests it was observed that slight changes in room temperature produced a definite signal of tens of nanovolts. To examine this problem a hot air blower was used to simulate changes of air temperature. The effects were very different depending on the heating position. Heating in the region of the coil itself produced no effect up to about 60 °C. However, by about 2 m from the cable terminations, very large voltages (up to 700 nV) were generated due to temperature changes of less than 40 °C. To minimize this effect, a double-layered thermal shield was wound around the MI cables in this region, and the inverting connection box was also thermally insulated.

Also during these tests it was observed that bending of the MI cable or pressure on the cable could also induce relatively large voltages (100's of nV), which only decayed away slowly (minutes to hours). These effects, due to polarization of the insulator itself (microphonics), could be minimized by careful handling of the hose and cables, but unavoidably any movement produced a measurable voltage.

3.1.2. Gas pressure effects

When the irradiation capsule and hose were immersed into the 4 m deep pool, a voltage of about 200 nV was measured across the ends of the central conductor. The reason for this voltage is not clear, although it may be related to pressure or temperature differences. The pool temperature is quite constant at 25 °C, while the control room temperature varied from about 15 to 22 °C during the day. From the discussion above on temperature effects one would expect an induced voltage around 100 nV for a 10 °C temperature difference.

Furthermore it was observed that this voltage was affected by small changes in the nitrogen gas pressure. When the gas flow is switched on and off, the voltage changes by about 30 nV, taking several minutes to stabilize. Gas pressure variations will change the length of MI cable in close contact with the hose and outside water, thus causing temperature and pressure changes in the MI cable itself. In addition, it was observed that rapid or careless movements of the capsule and hose induced large voltages, which took many minutes to decay. This voltage is related to bending and pressure effects.

3.2. Gamma irradiation tests

3.2.1. Coil #1 (Cu conductor, magnesia insulation)

Following all the above tests, a first run was made in the pool but out of the radiation field, to provide a 'base-line' of the voltage, noise, and drift. The sign of this voltage (about 200 nV) changed when switching the polarity, indicating that it was a real voltage between the conductor ends. The coil was then introduced into the 10 Gy/s radiation field and the voltage measured again. The voltage increased within seconds to about 300 nV. It was also observed that the fast noise (>1 Hz) was much higher, but the drift was almost the same. The voltage then decreased with time, as may be seen in Fig. 2, and after about 5 h was about 150 nV, i.e. less than the value without radiation. Again the sign of the voltage changed when switching the polarity at the input box and the shorting position gave an effective zero to within 15 nV, about the same as the lower limit for signal (voltage) detection. Several runs were then made raising the position of the coil in 30 mm steps, to gradually produce lower dose rates. Although changes of the voltage were observed, they were neither reproducible nor consistent. From the earlier tests we conclude these voltage changes were related to changes of the pressure and/or temper-

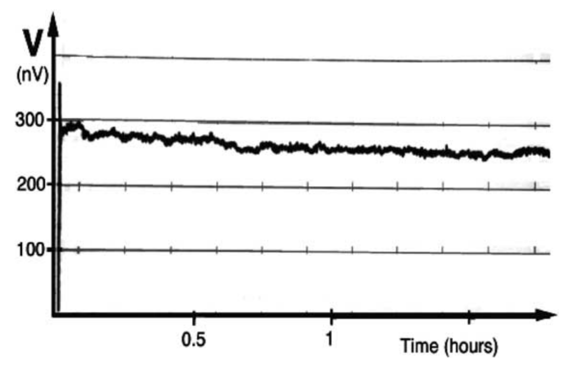

Fig. 2. Measurement of the EMF between the two ends of the central conductor as a function of time during gamma irradiation at 10 Gy/s.

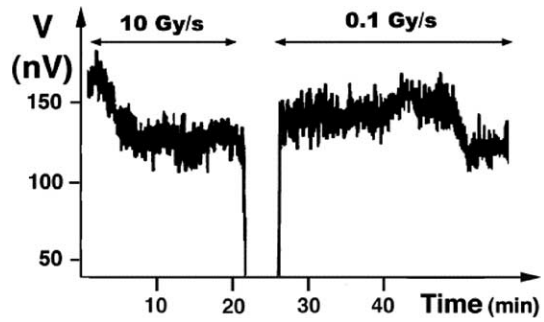

Fig. 3. Measurement of the coil EMF (between ends of central conductor) as a function of time. The arrows indicates the intervals of high (10 Gy/s) and low (0.1 Gy/s) radiation field.

ature (taking into account that there is an unavoidable change of pressure with depth), as well as movement and bending of the cable.

The test procedure was then changed. The coil was firstly placed in the maximum 10 Gy/s dose rate region, and the measured voltage allowed to settle (during several hours). Then the coil was carefully removed to a far corner of the pool at the same depth, where the dose rate was about 0.1 Gy/s. In this way only the radiation conditions changed. As can be seen in Fig. 3, there is no real change in the measured voltage. This operation was repeated several times, with the same result. We may therefore conclude that at 10 Gy/s and 25 °C, the RIEMF in the tested coil is <20 nV. From the initial calibration tests (Ohmic behaviour), one may also conclude that the current associated with any possible RIEMF under these conditions is <4 nA.

The measurement of the current flowing between the central conductor and the sheath was far easier, with the results being consistent and reproducible. Without radiation, a very low level of about 1 pA was observed. At the maximum dose rate of 10 Gy/s, the current was between 270 and 320 pA, depending on the exact position of the capsule. In the low dose rate corner (0.1 Gy/s) the current was 35 pA. Measurement of the current, voltage, and resistance between the central conductor and the outer sheath were also made at 10 Gy/s with a digital multimeter. The sequential values obtained were 270 pA, 135 mV, and 0.44 GΩ. This measured resistance value is very close to 0.50 GΩ, calculated from the current and voltage values, confirming that the process is Ohmic.

3.2.2. Coil #2 (stainless steel conductor, alumina insulation)

The same procedure was used for coil number 2. The results obtained are very similar to those obtained for coil #1. Probably due to its higher resistance value (193 Ω compared with 5.4 Ω for coil #1), the noise level was about 4 times higher, i.e. of the order of 80 nV. However within the limits imposed by the higher noise level, the stability of the measured voltage was observed to be the same as for coil #1, as were the effects of temperature, pressure, and bending.

Again, no evidence was found for a radiation-induced voltage between the two ends of the central conductor. In this case due to the higher noise level the limit is <80 nV, however several stable runs were consistent with a considerably lower upper limit. One may then conclude that the current associated with any possible RIEMF under these conditions in coil #2 is <0.4 nA.

The normal RIEMF (current between central conductor and sheath) was very similar to that observed for coil #1, i.e. about 320 pA at 10 Gy/s, a voltage of 300 mV and the resistance 1 GΩ, double that of coil #1. This difference between the coils is due to the different RIC in the coil insulating materials (magnesia and alumina, and different grain size and packing density). A difference of a factor 2 between the RIC in similar magnesia and alumina samples is reasonable. The calculated RIC values for the two insulating materials at 10 Gy/s and 25 °C are: magnesia 3×10^{-11} S/m, alumina 1.5×10^{-11} S/m. These values are consistent with RIC values measured for high impurity content ceramics (see [4] and references therein).

4. Conclusions

The results presented have demonstrated that, within measurement capability for the two coils examined, no significant RIEMF voltage is produced along the central conductor. For ^{60}Co gamma irradiation at 10 Gy/s, the RIEMF is less than 20 and 80 nV for MI coil #1 and #2 respectively, and the current associated with any possible RIEMF under these conditions is less than 4 and 0.4 nA respectively.

The normal RIEMF currents and voltages generated between inner conductor and outer sheath at 10 Gy/s and 25 °C, were 270 pA and 135 mV for coil #1, and 320 pA and 300 mV for coil #2.

It is important to point out that even under the well controlled conditions employed for these experiments, an unambiguous determination of the voltage induced along the centre conductor of a coil was extremely difficult. At the 100 nV level, induced voltages related to temperature gradients, as well as pressure and movement (bending) induced polarization effects in the insulator itself are of paramount importance. Such effects have undoubtedly led to many of the unexplained results reported earlier. Although the radiation-induced part has been found to be negligible, the results reported here clearly show that these other effects are serious potential problems for the use of MI cable magnetic coils in ITER.

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