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TIEMF effect in ceramic coated cables

R. Vila *, E.R. Hodgson

Euratom/CIEMAT Fusion Association, Avenida Complutense 22, Madrid 28040, Spain

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ABSTRACT

Our previous work on mineral insulated cables demonstrated the important voltages that can appear in some of the coils used in ITER magnetic diagnostics simply due to thermal gradients present from the beginning of operation. To explore alternative cables, a new type of ceramic coated wire has being studied. The two wires examined consist of Cu–Ni and SS 304 conductors covered with a thin ceramic coating. This should reduce cold working during fabrication. An improved technique has been used to measure TIEMF with a rather narrow thermal gradient and highly reduced noise, able to examine the fine structure due to inhomogeneities. For both cables, marked TIEMF effects still exist. Although their absolute magnitude is relatively similar there are important differences in structure. The implications for ITER cables and coils are discussed. The coated cables are compared with MI cables taking also into account insulation and mechanical reliability.

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1. Introduction

At an early stage RIEMF (radiation induced electromotive force) in MI (mineral insulated) cables was recognized as a potential problem for ITER diagnostics [1–8]. Known for many years, RIEMF between the central conductor and outer sheath can generate potentials of the order of volts and microamps of current, producing additional noise in the cables. During these initial experiments evidence was found for the possible generation of a small voltage along the central conductor itself [7,8]. This is of serious concern for the sensitive magnetic coil diagnostics, a prime candidate for plasma current and position control, as it will introduce an error signal impossible to differentiate from the required information. Recent experiments have shown that this voltage, now known as TIEMF (thermally induced electromotive force), is due to temperature gradients (inherent to reactor operation) which can generate signals along the central conductor of the order of μV's even without radiation [9–12].

To date TIEMF has been found in all the MI cables studied. Taking into account that cold-working induces changes in the thermoelectric power of metals, and MI cables are subjected to high strain/stress during manufacturing damaging the inner conductor [12], TIEMF is probably inherent in such cables. To try to avoid this problem we have examined the possibility of using other cable types. Ceramic coated Ni–Cu and SS (stainless steel) cored cables have been examined and compared with MI cables also using Cu and SS conductors. A new experimental system with a miniature oven and well controlled displacement has been used to study the TIEMF.

2. Experimental details

2.1. Ceramic coated cables

Two different metals were selected for the central conductor wire: One configuration uses a copper–nickel alloy (Kulgrid 28) wire and the other a Stainless Steel AISI 304 (see details in Table 1).

The NiCu cable (#1) was manufactured by California Fine Wire and purchased by Consorzio RFX (Padua) in the framework of the EFDA Task TW5-TPDS-DIADEV.

Tests were performed to verify the electrical characteristics of the ceramic insulation and in particular the dielectric rating. The SS cable (#2) was also purchased by RFX from Ceramawire.

Samples of about 7 m were made available to study the TIEMF effect at CIEMAT and fully characterize the cables for magnetic diagnostics.

A calibrated 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. Further details can be found in [7], while improvements are commented below.

3. Experimental results

3.1. Tests description

Two basic experiments have been performed as follow.

* Corresponding author.
E-mail address: rafael.vila@ciemat.es (R. Vila).

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Table 1
Physical data for the two cables investigated.

Cable	#1	#2
Name	Ceramawire	California Fine Wire
Outer diam. (mm)	24 AWG ≅0.52 mm	24 AWG ≅0.55 mm
Central conductor diam.	0.511 Nominal	0.511 Nominal
Conductor material	27% Ni Clad Cu (Kulgrid28)	Stainless Steel AISI 304
Insulator	Vitreous enamel film[a]	Alcal insulation
Total length (m)	7.2	5
Wire resistivity (typ)	2.24 ∗ E−08 Ω m (at 20 °C)	7.2 ∗ E−07 Ω m (at 20 °C)
Measured resistance	0.9 ± 0.1 Ω	18.9 ± 0.1 Ω

[a] Proprietary formulation.

3.1.1. Type 1. Air flow scan technique

In the first set-up, a small portion of the cables (2–4 cm) was heated by airflow at a selected temperature (from 70 to 550 °C) using the same procedure as in the previous MI cable studies [10], allowing an easy rapid comparison. The position of this heated section was moved continuously at an almost constant velocity (20–25 mm/s) from the coil position (or cable turn) to close to the connection box along the total cable length and TIEMF is measured.

3.1.2. Type 2. Mini oven measurements

A new TIEMF measuring set-up has been designed, with three objectives:

(1) To reduce the noise generated by both the air flow itself (cable vibrations) and the electrical noise of the hot air gun motor.
(2) To increases resolution reducing the cable heated length.
(3) Finally to improve the reproducibility of the heated section during a scan.

To achieve these a very small circular oven was constructed winding 1 mm diameter Thermocoax heating cable on a former, 7 mm inner diameter, width 4 mm, enclosed by two ceramic discs to confine the heat. This oven was mounted on a carriage that slides on a linear guide driven by a small DC motor with controlled speed and monitored by measuring the voltage at a multi-turn potentiometer (*helipot*) coupled to the motor. Fig. 1 shows a close up view of the oven and cable.

The oven was heated using a DC power supply without active temperature stabilization to avoid oscillations (At constant current it reaches a stable temperature). Typical values were between 90 and 160 °C (measured on the cable).

The studied cable was centred in the oven and maintained straight by slight mechanical tension.

Tests of heating and cooling dynamics as the oven moves along the cable were performed by making measurements with a thermocouple located less than 1 mm from the cable. Fig. 1 also shows this thermocouple in the position used for monitoring the temperature profile.

Scanning the oven along the cable, the variation of the Seebeck coefficient can be investigated. This allows us to check the behaviour of the TIEMF as a function of temperature and position. As before, in order to minimize connection effects, heating was performed at >1 m from the connection box.

These two experiments will be referred as Type 1 (air flow) and Type 2 (mini oven), respectively.

3.2. Type 1 test results (air flow thermal scan)

Important characteristics observed and previously reported are:

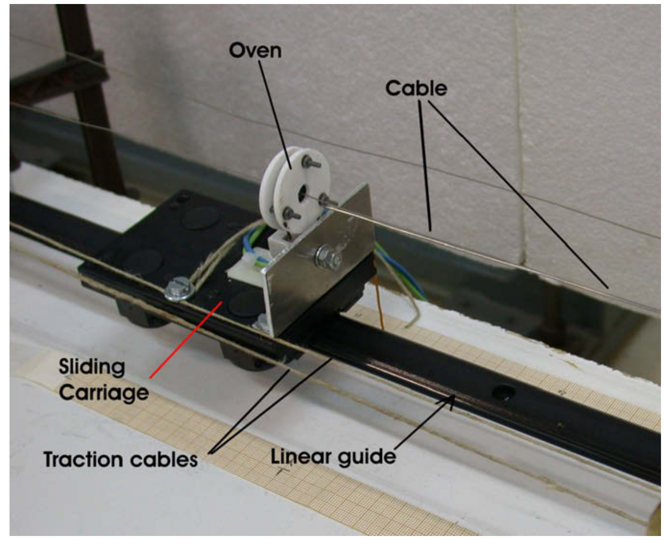

Fig. 1. Detail showing the circular oven mounted on the sliding carriage with the cables that moves it and the cable under test.

– As in MI cables, when thermal scans are realized, positive and negative peaks are obtained and randomly distributed, but this EMF curve has a repetitive behaviour.
– When the heat is maintained at a certain point, the EMF increases up to a value and remains almost constant.

- *System #1*: (CuNi conductor).

TIEMF peak structures are quite similar in shape to those observed in Cu MI cables but with lower values. Scanning at about 74 °C produced several peaks from 50 to 110 nV with a maximum of 300 nV, compared with peaks of around 3 μV and maxima around 5 μV obtained in the previously studied Cu MI cable. The suggested model of TIEMF being produced by the high damage observed in MI cables agrees with this decrease. The possible problem with the coated cable is the existence of Ni–Cu alloy and therefore possible variation of composition with position. It is well known that in Ni–Cu this variation produce strong thermoelectric effects.

- *System #2*: (SS conductor).

As previously observed in SS MI cables, the SS coated cable presents a higher noise level (from ±25 nV to ±50 nV) than for NiCu, although 2–4 times less than for the mineral insulated type SS cable, due to the much lower resistance per metre in the present case. The noise reduces the accuracy of thermoelectric measurements for this cable type. With these errors, TIEMF was not clearly observed with this set-up, although some structure seems to appear at certain points of the order of 50 nV for 50 °C temperature increase, and would be comparable to that obtained in the SS MI cable. Hence the system was improved to decreases this noise. More detailed results are presented below.

3.3. Type 2 test results (oven scan)

The analysis with the very small oven gives us very useful information about the 'fine structure' of the Seebeck coefficient along the cables. By decreasing noise, increasing the spatial resolution and varying the temperature and scan speed we can study TIEMF variations with finer detail.

- *System #1*: (NiCu conductor).

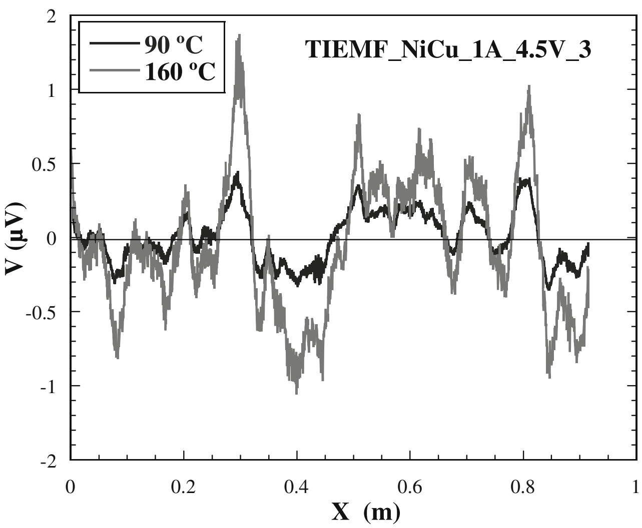

Fig. 2. Comparison between TIEMF values scanning at a temperature of 90 °C (black curve) and 160 °C (grey curve) recorded as a function of distance along the NiCu cable.

The results obtained heating at 90 °C are shown in Fig. 2. Noise has been greatly reduced and in this case peaks from 200 to 400 nV are clearly observed.

The scanning velocity was chosen so that reducing it more did not change the curve (although more details are revealed). Increasing the scanning speed too much reduces the peak heights as the cable has no time to reach the oven temperature.

As expected, increasing the temperature of the oven increases the peak heights and more details are observed. A comparison of the curve at 90 °C with a heating at around 160 °C, also shown in Fig. 2, demonstrates the intrinsic nature of the peaks.

- *System #2*: (SS conductor).

With the new configuration we were able to reliably measure TIEMF in this cable. In Fig. 3 we present the results obtained in the same conditions as Fig. 2 (for NiCu).

One observes an important difference, although the SS peak values are comparable with NiCu, the peaks in the SS cable are much narrower, presenting a quite different fine structure, oscillating rapidly from positive to negative values along the cable. This explains why with temperature gradients normally applied, wider than here, these peaks tend to cancel each other, and are not clearly observed. Only very precise measurements reveal them.

3.4. Simplified TIEMF model

A simple model has been developed to try to understand the TIEMF results. As local impurities or physical changes in the conductor material are the most probable causes, a simple model can be established. The observed TIEMF will occur when a thermal scan is made on a cable with a Seebeck coefficient S_A through a small region (B) with a different Seebeck coefficient S_B. One must study the evolution with time of the hot spot along this cable section when doing a small oven scan test. Temperatures of the cable ends (very far away) are always constant and taken as T_A. When the hot spot is arriving near the S_B region, cable temperatures on the left and right side of B region (T_1 and T_2, respectively) are now different. Writing the basic equations of EMF caused by the several temperatures gradients we obtain:

$$V = (T_1 - T_A) * S_A + (T_2 - T_1) * S_B + (T_A - T_1) * S_A \quad (1)$$

And reordering:

$$V = (T_2 - T_1) * (S_A - S_B) = \Delta T * \Delta S. \quad (2)$$

We obtain that the TIEMF voltage is given by the T gradient along the B region and the dependence on Seebeck coefficients.

For the time evolution of this voltage, during the thermal scan there is a small voltage for positive ΔS that increases rapidly when the hot spot approaches the B region but when we are heating near the centre of this B region, the thermal gradient is almost zero. Following the left to right movement of this spot the TIEMF voltage changes sign and goes to high negative values rapidly and decline to zero as the hot spot finally moves away. Details of this model are beyond the scope of this paper and will be published elsewhere, but the width of the TIEMF curve is given by approximately the width of the temperature curve created by the oven if the region B size is much smaller than the oven size.

When B region size is much greater than the width of temperature gradient the picture changes, and it is easy to see that in this case the TIEMF is a double reproduction of the temperature curve.

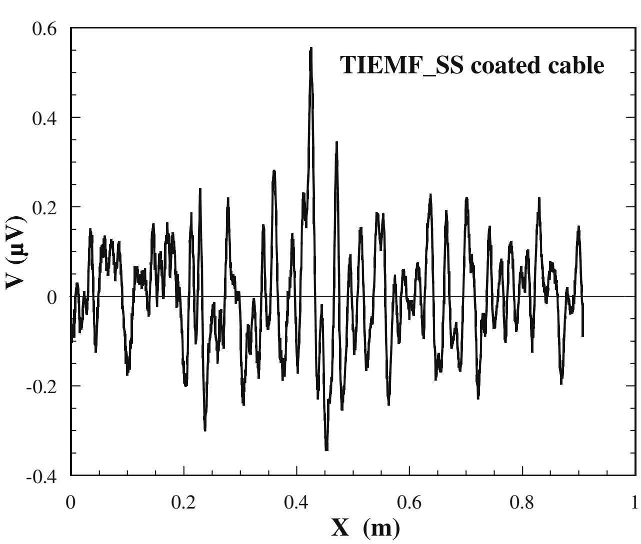

Fig. 3. TIEMF values recorded as a function of distance along the SS cable scanning at a temperature of around 90 °C.

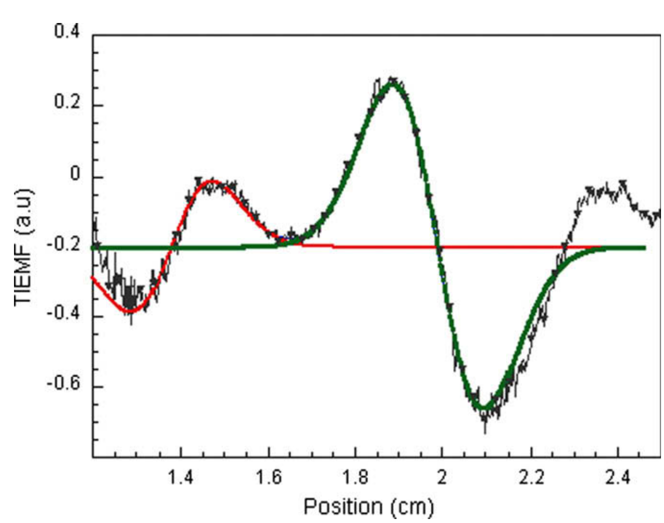

Fig. 4. Fit of experimental TIEMF by two processes (1st negative to positive, 2nd positive to negative) due to inhomogeneities in the wire, following the TIEMF model.

Therefore the two maximum (positive and negative) are well separated. The scanning method is an important tool to estimate the size of the inhomogeneities, and the reason why we decreased the furnace dimensions. When observing in detail the curves obtained there is a trend to observe high positive/negative values packed together therefore supporting the idea that the size of these regions is quite small.

A simplification has been made supposing that the temperature profile is Gaussian (although it is asymmetric) just to calculate and roughly fit the experimentally observed TIEMF curves to the Eq. (2) dynamically. Even with this simplification we can fit quite well some of the observed peaks as shown in Fig. 4, where two consecutive processes have been fitted.

The problem with the real TIEMF curves is that there are many regions with quite different Seebeck coefficients and spatial size and in general each curve overlap with the next, making the analysis more difficult. However this type of analysis indicates that more work can be done in the future to extract valuable information about the defects and their influence on TIEMF in cables.

4. Conclusions

- Using the air flow method, the results for coated Ni Cu wire give lower TIEMF than Cu MI cables, but clear TIEMF peaks are still observed. In addition problems have been reported for the insulation coating, the resistance decreasing rapidly even at moderate temperatures and voltages, as well as breaking off easily when coiling the wire [13].
- Results for coated SS wire indicate low TIEMF, but again the coating resistance decreased rapidly with temperature and voltage [14].
- The use of the new small oven reveals very clearly the TIEMF peaks and their spatial structure, especially in steel, demonstrating clearly their fine spatial structure, much narrower than in CuNi.
- Despite the differences in manufacture and origin, the contrasts between the two ceramic coated cables are in general agreement with those observed between Cu and SS MI cables.
- The use of a small scanning oven together with equations from a simple model allows one to describe and for the first time fit the TIEMF.
- As expected, coated cables show lower TIEMF than MI cables, but the present insulating coating is too fragile to withstand ITER operation. Additional insulation would be needed, increasing the final design complexity of magnetic coils and cabling. These two coated cables are therefore unsuitable for magnetic diagnostics, with no great advantage over standard MI cables. Cables with better coating quality must be examined in the near future.

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