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Nonlinear Effects in New Magnetic Pick-up Coils for JET

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ABSTRACT

In the framework of the JET Magnetic Diagnostic Enhancement, a set of pick-up coils (UC subsystem) wound on metallic Inconel® 600 former was manufactured. For cross-validation purposes, two different calibration methods were used. A discrepancy in the range of 3% was observed, which can be explained when considering the dependence of the calibration coefficients on the field strength, which in turn is mostly due to the nonlinear behaviour of the Inconel former.

For this reason a specimen of Inconel was analysed by means of a magnetometer, which showed a nonlinear and hysteretic behaviour occurring at low field level (below 5mT). The calibration coefficients are also measured at low field (0.1-2mT) and so are affected by such peculiar ferromagnetic behaviour. Moreover, the ferromagnetic behaviour might be sensitive to mechanical and thermal treatment performed during probes manufacturing and testing.

Therefore the achievable accuracy for the calibration of coils wound on Inconel formers is limited by the following effects:

i) the field level in operation can be completely different from the field used in the calibration procedure
ii) measurements of the magnetic properties on Inconel specimens can not be extrapolated to the former, because of unpredictable effects of mechanical and thermal treatments made on the coil
iii) residual magnetization;
iv) temperature variations during operation.

1. INTRODUCTION

A new magnetic diagnostics system has been developed for the Joint European Torus (JET) with the purpose of improving the performance of the present system [1].

Sensors are two field component coils, located as near as possible to the plasma and distributed along the poloidal contour. They will operate in an environment of ultra high vacuum and temperatures up to 350°C.

Coils (Fig.1) are made of a Mineral Insulated Cable (MIC) with 1mm of outer diameter, wound around Inconel formers. The MIC are terminated in the proximity of the coils to allow a transition to more robust braided cables which are inserted during installation into a suitable system of in-vessel conduits [2].

The comparison and validation of different magnetic probe calibration procedures is of particular importance, because sensors made by different manufacturers and calibrated with different procedures are installed close together and used as an integrated diagnostic system.

During such a cross-calibration activity, a subtle nonlinear effect was discovered which led to unconsistencies between calibration results of different procedures. An investigation activity was undertaken to explain this effect.

2. CALIBRATION PROCEDURES COMPARISON

A calibration procedure is necessary to identify the magnetic section *NA* of an inductive sensor, where *N* is the total number of the coil turns and *A* is the average area of the single turn.

This parameter can be calculated only in particular cases, when the geometry of the coil is very simple and accurate dimensional measurements can be performed.

In all the other cases it is necessary to stimulate the coil with a varying magnetic field and measure the induced voltage.

In RFX calibration procedure [3], a solenoid with very well-known geometrical and electrical characteristics is used, so that magnetic field intensity and direction in each point inside the solenoid can be calculated from the solenoid winding current measurement. The knowledge of the mean field inside the coil and the induced voltage allows calculating the magnetic section. This procedure requires high accuracy in the measurement of both solenoid current and coil voltage. The region of field uniformity inside the solenoid is not very large, so a precise positioning of the coil is also needed, but the coil shape does not affect calibration accuracy, provided that the coil is relatively small compared with the solenoid.

In JET calibration procedure [4], large Helmoltz coils are used to obtain a very uniform magnetic field. Two reference probes, whose magnetic section is calculated from dimensional measurements, are placed inside the field high uniformity region at a fixed distance and with parallel axes. The induced voltages in the two probes are measured and their ratio recorded. Then, one of the two probes is substituted with the coil under test, and the induced voltage compared with the untouched reference probe voltage. Comparing the results, the coil magnetic section can be derived from the knowledge of the reference probes magnetic sections. This method does not require the precise knowledge of the magnetic field, and is also insensitive to small systematic errors in the voltage measurements. However, its accuracy is limited by the uncertainty in reference probes magnetic section determination. If the coil to be calibrated has a shape different from reference coil, or is not placed in the same position, field non-uniformity can affect accuracy.

With proper choice of instrumentation, and taking all the precautions in order to minimize errors, both the methods can reach a satisfactory high level of accuracy, close to 0.1%.

2.1 CROSS CALIBRATION OF A TEST PROBE

To evaluate the actual accuracy of the two calibration procedures [5], it was decided to build a cylindrical single layer test coil, very similar to the reference probes used in JET procedure. The test coil magnetic section was calculated from dimensional measurements. The most critical measurement, the coil diameter, was performed in different positions. The maximum and minimum measured diameters are used to estimate the magnetic section accuracy, which results better than 0.1%.

In optimal conditions, with field below 1mT and frequency of 300 and 1000Hz, the magnetic section measured with RFX procedure differs from calculated one of no more than 0.1%, which can be considered a very satisfactory result. A slight dependence is observed in function of frequency and calibration fields, but it remains within ±0.3%, and can be considered an effect of noise for low frequency and low intensity field and power amplifier distortion at higher intensity fields, as discussed in [3].

In JET calibration procedure a systematic difference of about 0.3% is observed, not influenced by frequency or field intensity in the ranges considered.

When comparing RFX and JET results for test probe, the discrepancies in the magnetic field range 0.5-1mT, where both the methods should attain the best accuracy, are of about 0.2%, and both the procedures indicate a magnetic section slightly inferior to the calculated one. It is possible that the calculated section is slightly overestimated, possibly because the wire dimensions are less than the nominal ones used in the calculation.

The 0.2% uncertainty is comparable with instrumentation accuracy, and should not be critical for data analysis.

2.2 CROSS CALIBRATION OF A NORMAL PROBE WITH COPPER WINDING

The same procedure described in previous paragraph was applied to an Normal Upper Coil (Fig.2), where the Mineral Insulated Cable multi-layer winding was substituted with a single layer copper enamelled wire winding. In this way it a precise calculation of the probe magnetic section was possible. In this case the former shape and manufacturing precision causes an uncertainty on magnetic section of about 0.12%, larger than for the test probe.

In Fig.3 the JET results are reported compared with corresponding RFX values. Not only the measured section is larger than the calculated one, but also it results strongly field dependent, exhibiting a maximum near 1mT. Neither RFX nor JET calibration equipments allow to explore a wider range of magnetic fields. Small frequency dependence is also observed, but this is in agreement with the expected filtering effect of the conductive probe former.

The good agreement between RFX and JET results remains and the same small difference of about 0.2% is observed.

This complex behaviour is certainly due to the presence of the metallic former, which seems to have some ferromagnetic-like effect. The change of magnetic section due to this effect is more than 4% in the field range 0.1-2mT.

This phenomenon has several negative consequences:

As probes operate in fields very higher than the ones used for calibration, measured magnetic sections are not representative of probes behaviour in JET operation. In addition, in calibration procedures only fields parallel with probe axis are used. On the contrary, in JET probes operate in presence of strong transverse fields.

JET and RFX use different magnetic field intensity for calibration: about 0.4mT for JET and 0.7mT for RFX. This field difference can account for about 3% difference in magnetic section measured with RFX procedure and JET procedure.

As Inconel is considered a non-magnetic material, its spurious magnetic properties are not specified nor measured, so no data are available on magnetic characteristics of the inconel used for probe manufacturing. As a consequence, the observed behaviour could be not the same in other normal probes, and could also be different for different types of probes.

3. MEASUREMENTS ON COILS FORMER MATERIAL

A Magnetometer Lakeshore Model 7407 in use at Universit del Sannio has been used to measure the magnetic characteristic of a spare specimen of Inconel 600.

The specimen has square section and dimensions 5mm × 5mm × 1mm. It is put in the magnetometer with its longer dimensions parallel to the magnetic field. In this case the demagnetizing field is low, and the magnetic field *H* is approximately the same inside and outside of the specimen.

The plot in Fig.4a) shows that the magnetization *M* is quite low, but also that the ferromagnetic-like behaviour is confined in the field level range used to calibrate the magnetic probes.

Outside of this low level field range ([-5mT, 5mT] for this sample) the behaviour is paramagnetic.

Figure 4b) shows the experimental relative differential permeability:

$$\mu_{r,\,diff}(H) = \frac{1}{\mu_0}\,\frac{\delta B}{\delta H} \tag{1}$$

along with an analytic non-hysteretic approximation, given by:

$$\mu_{r,\,diff}(H) = \mu_{r,\,\infty} + \frac{\mu_{r,\,diff,\,max} - \mu_{r,\,\infty}}{1 + (H/H_0)^2} \tag{2}$$

The maximum value, for the sample tested, is $\mu_{\mathrm{r,diff,max}}$=1.05.

4. NUMERICAL SIMULATIONS

4.1. MONODIMENSIONAL ANALYTICAL MODEL

A monodimensional model was developed to estimate the induced voltage on the probe of Fig.2. This model is approximate, since it assumes that the probe has infinite length. Let *N* the number of turns, *a* the internal radius of the Inconel former and δ its thickness. We have:

$$v(t) = N\pi a^2\,\mu_0\left[1 + \alpha\mu_{r,\,diff}(H(t))\right]\frac{\delta H}{\delta t}, \quad \alpha = 2\,\frac{\delta}{a} + \frac{\delta^2}{a^2} \tag{3}$$

If the former were non-magnetic we would have:

$$v(t) = N\pi a^2\,\mu_0\left[1 + \alpha\right]\frac{\delta H}{\delta t} \tag{4}$$

The variation of the induced voltage due to the Inconel magnetism is then:

$$\Delta\nu_{\%}(t) = 100\,\frac{\alpha}{1+\alpha}\,\mu_{r,\,diff}\,(H(t)) - 1) \tag{5}$$

Eq. (5) still holds for a linear former substituting $\mu_{\mathrm{r,diff}}(H)$ with a constant μ_{r}. In this case we have:

m_{r}	1.1	1.2	1.3	1.4	1.5	1.6
$\Delta v_{\%}$	1.1	2.2	3.2	4.3	5.4	6.5

To justify a difference of 5% in the measured magnetic section with respect to the calculated one, the former relative permeability should be about 1.5. This value represents a lower limit, as the finite length of the actual probe is not considered.

4.2. SIMULATIONS WITH A FINITE ELEMENT METHOD SOLVER

To confirm and improve the results obtained with the 1D model, the calibration operations were simulated with a Finite Element Model code.

The poloidal flux per radian ψ and the poloidal flux density $\boldsymbol{B}_{\mathrm{pol}}$ are

$$\psi\,(r,\,z,\,t) = \frac{1}{2\pi}\iint \mu_{S\,(r,\,z)}\,\boldsymbol{B}{¥}d\boldsymbol{S}, \qquad \boldsymbol{B}_{pol} = B_r\,\hat{\boldsymbol{r}} + B_z\,\hat{\boldsymbol{z}} = \frac{1}{r}\,\nabla\psi \times \hat{\varphi} \tag{6}$$

where $S(r,z)$ is the circular surface having radius r and distance z from to the plane $z = 0$. The field lines of the poloidal flux density coincide with the curves $\psi = \mathrm{const}$. In the magnetoquasistatic case and in axysimmetric cylindrical geometry, the Ampere law projection along the toroidal direction can be expressed in terms of ψ [6]:

$$L\psi + \frac{\sigma}{r}\,\frac{\delta\psi}{\delta t} = J_{\varphi,\,ext}, \qquad\qquad L = -\,\frac{\delta}{\delta t}\left(\frac{1}{\mu r}\,\frac{\delta}{\delta r}\right) - \frac{1}{r}\,\frac{\delta}{\delta z}\left(\frac{1}{\mu}\,\frac{\delta}{\delta z}\right) \tag{7}$$

As of the nonlinear and hysteretic behaviour of the Inconel, in the former μ is a complicated function of the magnetic field. A simple way to solve this equation is to assume μ = const. Then in the frequency domain we have:

$$L\tilde{\psi} + \frac{i\omega\sigma}{r}\,\tilde{\psi} = \tilde{J}_{\varphi,\,ext} \tag{8}$$

Eq. (8) was solved for σ_{former} = 0 S/m (no former shielding effect) and σ_{former} = 1e6S/m (Inconel conductivity), and for various frequencies and former relative permeabilities, using a mesh made of 39808 triangles. The experiment simulated is the calibration of the coil in Fig.2 with the Helmholtz Coils facility available at JET. Results are summarised in Fig.5: a relative permeability of 1.7 would be needed to explain the 5% difference in measured magnetic section, so the simple monodimensional model led to an underestimation, as expected.

DISCUSSION AND FUTURE ACTIVITIES

From a qualitative point of view, the peculiar ferromagnetic behaviour observed on the analysed sample allows to justify the dependence of the effective magnetic section from the amplitude of the magnetic field used to calibrate the coils, and the fact that the measured section is higher than the one calculated on the basis of coil geometrical characteristics.

From a quantitative point of view, however, the observed value of the relative permeability are too little to justify the experimental *NA* values: 1.05 maximum permeability was measured when 1.7 would be required.

However, the mechanical and thermal treatments performed during probes manufacturing and testing, can enhance the ferromagnetism of the Inconel formers. Such behaviour is known and described in literature [7].

So, it is possible that the inconel material used for the magnetometer measurements is magnetically different from the actual former material.

On the other hand, extracting a material sample from the tested coil would require mechanical working that could furter modify its magnetic properties.

An alternative approach, which will be followed in the next future, is to carry out a series of measurements on a set of material samples, subjected to different machanical and thermal treatments similar to the one experienced by the coils, in order to evaluate the effects on their magnetic properties.

CONCLUSIONS

Magnetic section of magnetic probes made from Inconel could result a non linear, time dependent function of field and temperature, severely limiting the attainable accuracy. For this reason, the use of such material or other alloys with spurious magnetic properties is not recommended for new designs.

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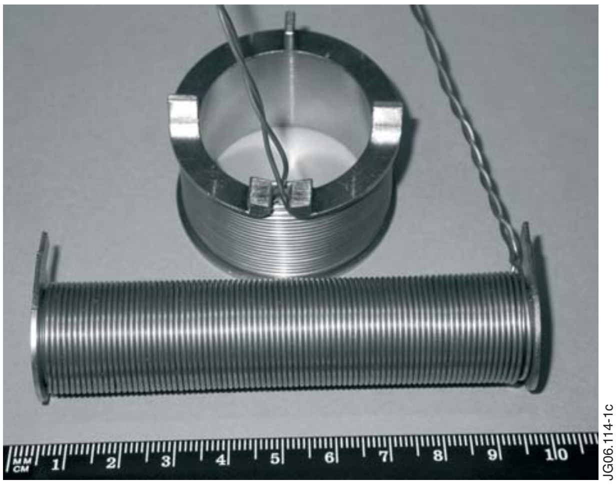

Figure 1: New JET EP Upper Normal (top) and Tangetial (bottom) Coils.

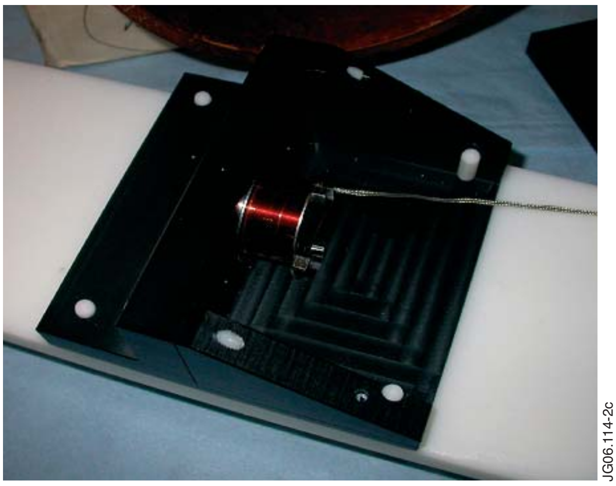

Figure 2: Inconel Former Normal Coil with Single Layer Copper Winding.

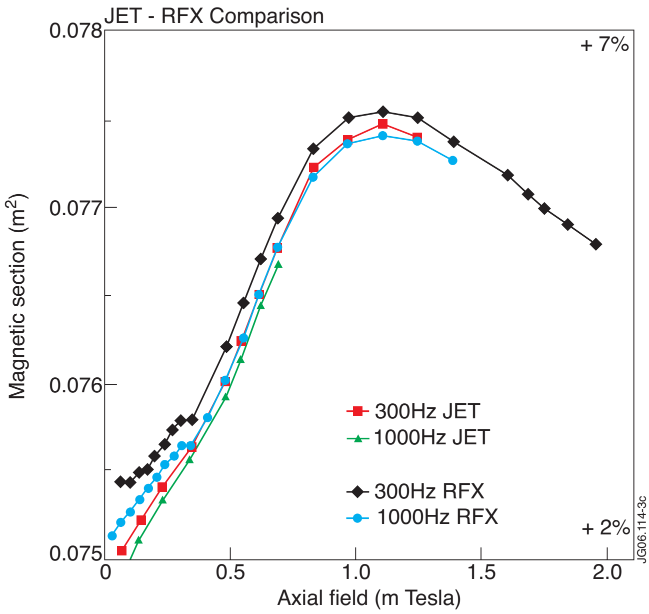

Figure 3: Comparison of measured magnetic sections of Inconel former normal coil with copper winding with RFX and JET procedures.

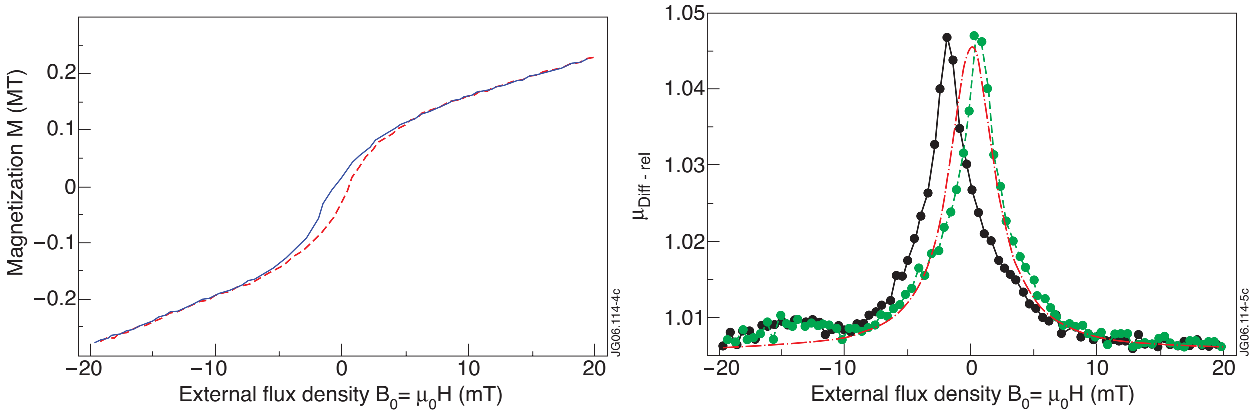

Figure 4: Mesurements on Inconel sample:
(a) Magnetization versus external field, (b) relative differential permeability versus external field.

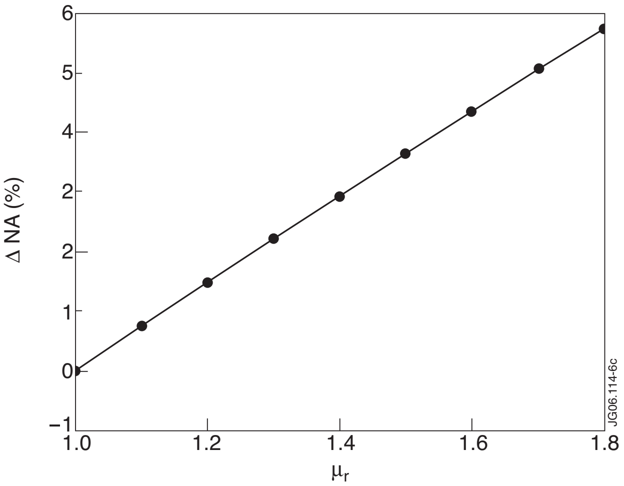

Figure 5: Effect on coil effective magnetic section of different relative permeabilities of the former.