Design and experimental validation of an eddy currents probe

F. Villone[1], P. Testoni[2], R. Albanese[3], G. Betta[1], P. Calderoni[2], D. Capriglione[1], L. Ferrigno[1], M. Laracca[1], R. Palmaccio[1], A. Rasile[1], G. Rubinacci[3], S. Ventre[1]

[1] *CREATE, DIEI, Università degli Studi di Cassino e del Lazio Meridionale, Italy*

[2] *Fusion For Energy, Barcelona, Spain*

[3] *CREATE, DIETI, Università degli Studi di Napoli Federico II, Italy*

1. Introduction

Eddy currents induced in passive structures are of paramount importance for the functioning of a tokamak. First of all, they are the key ingredient in slowing down plasma instabilities from Alfvén to electromagnetic time scales [1], allowing active magnetic control and hence the actual possibility of having a long-lasting discharge. Moreover, during a disruption, large eddy currents are induced in the vessel and other conducting structures, giving rise to significant electromagnetic forces that may be even challenging for the integrity of the device [2]. It is hence very important to have a reliable indication of such eddy currents; this is usually done in an indirect way, by measuring the magnetic field in proximity of the vessel and using suitable modelling assumptions to retrieve the value of current density [3]. In this paper we present the design and experimental validation of a probe directly measuring eddy currents flowing in a conductor. The proposed probe is a dipole-like sensor, in contact with the conductor under analysis. In the past, dipole-like sensors have been already proposed for current measurement, especially in MRI applications [4], but also in fusion devices [5-6]. An experimental campaign has been carried out on a dedicated test facility, designed and built at the LAMI Lab, Univ. of Cassino. Magnetic field time derivatives of the order of 100 T/s and induced current densities of the order of several MA/m^2 on EUROFER sheets have been achieved, thus demonstrating experimentally that the proposed probe is a viable solution for the measurement of eddy currents in ITER.

2. Working principle

We refer to the layout of the probe sketched in Fig. 1. In a massive conductor (gray in Fig. 1), characterized by its electric resistivity η, a current density **J** is flowing. We want to measure **J** with a probe made by two conducting terminals, γ_{CA} and γ_{BD}, electrically connected (e.g. welded) to two points A and B of the conductor. A voltmeter is inserted between the points C and D.

Consider now a line γ_{AB} inside the conductor in the immediate proximity of its boundary surface. According to the Faraday-Neumann-Lenz law, the line integral of the electric field **E** along the closed curve $\gamma=\gamma_{AB} \cup \gamma_{BD} \cup \gamma_{DC} \cup \gamma_{CA}$ is equal to the opposite of the time derivative of the magnetic flux ϕ_γ linked with γ:

$$\oint_\gamma \mathbf{E}\cdot\hat{\mathbf{t}}\,dl = -\frac{d}{dt}\iint_{S_\gamma} \mathbf{B}\cdot\hat{\mathbf{n}}\,dl = -\frac{d\Phi_\gamma}{dt} \quad (1)$$

With this careful choice of γ, we can assume that $\Phi_\gamma \approx 0$. Therefore, we have:

$$\oint_\gamma \mathbf{E}\cdot\hat{\mathbf{t}}\,dl \approx 0 \quad (2)$$

If we assume that the terminals γ_{BD} and γ_{CA} are made by perfect conductors, we have:

$$\int_{\gamma_{AB}} \mathbf{E}\cdot\hat{\mathbf{t}}\,dl + \int_{\gamma_{DC}} \mathbf{E}\cdot\hat{\mathbf{t}}\,dl = 0 \quad (3)$$

If we suppose that terminals C-D are in a region where the electric field is conservative, the voltage measured by the voltmeter does not depend on the line γ_{DC} used to connect points C and D and is equal to:

$$v_{CD} = -\int_{\gamma_{DC}} \mathbf{E}\cdot\hat{\mathbf{t}}\,dl = +\int_{\gamma_{AB}} \mathbf{E}\cdot\hat{\mathbf{t}}\,dl = \int_{\gamma_{AB}} \eta\mathbf{J}\cdot\hat{\mathbf{t}}\,dl \quad (4)$$

Hence, measuring the voltage v_{DC} and knowing the resistivity η of the conductor, we can measure the line integral of the current density **J** along γ_{AB}.

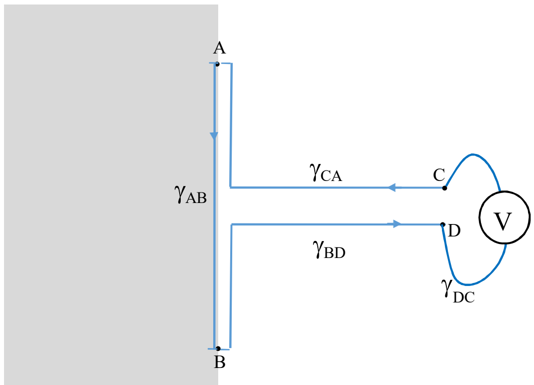

Fig. 1. Layout of the proposed probe

From this derivation, we can also identify the following main sources of errors:

- The magnetic flux $\Phi_\gamma \neq 0$. This critically depends on how close can be the terminals and on construction details (e.g. twisting of wires, etc).
- The wires are not perfect conductors or the electrical contact (welding) between the terminals and the massive conductor may introduce a resistive term. In this case, a resistive term as $(R_w+R_c)\ i_{wire}$ should be added. Assuming C-D as open circuit (ideal voltmeter) this should be negligible.
- The different electronegativity of the materials may introduce contact electromotive voltages) whose values depend on materials and the temperature of the joints.

2. Test facility

The experimental test facility is made of the following parts:

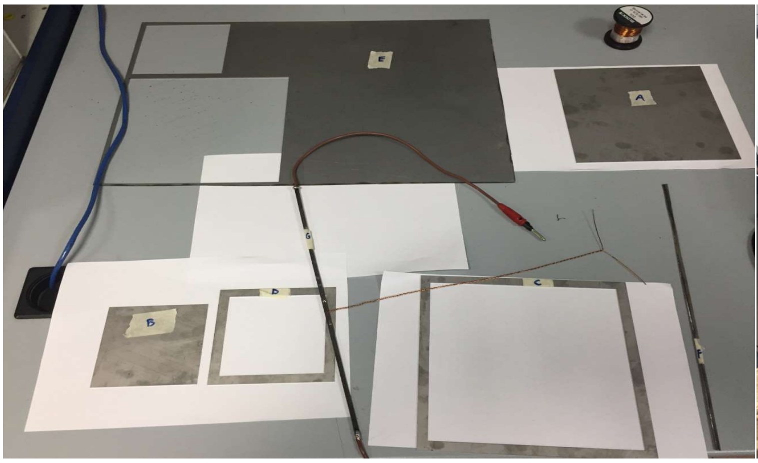
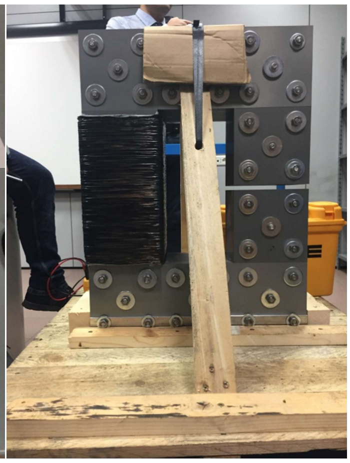

Fig. 2. EUROFer specimens and transformer

- Specimens of EUROFER in which eddy currents are induced
- Probes to measure induced current density
- Transformer to induce currents in specimens and to provide magnetic field variations
- Driving circuit to feed the transformer

Several specimens (Fig. 2) have been produced (sheets, rings, strips), through laser cut. The probes have general applicability to tokamaks and specifically to many ITER components; we use EUROFER 97-3 (thickness 1.2 mm) as material because one possible application is in Test Blanket Modules (TBM) box. The probes have been built using an enameled copper (diameter 0.75 mm). The enamel material is Polyurethane, used as electric insulator in windings for transformers and other electric machines. Temperature above 100° can be tolerated, which is suitable for present application but not for ITER. A dozen of probes have been produced and brazed on specimens. A C-shaped transformer has been designed and built (Fig. 2), with a 1 cm air gap in which the specimens are inserted. The driving circuit provides a DC charge of the transformer, followed by a fast discharge on a damp resistor to get the desired time variation. This way, only a small voltage is required in the charging phase (only DC resistance of solenoid must be compensated), and the discharge time is controllable through the value of the damp resistance. The switch is made by a power IGBT.

3. Experimental results

The first results refer to a probe brazed on a ring placed in the air gap of the transformer. Different exponential discharges have been attempted (time constant τ), corresponding to increasing induced current densities. Fig. 3 shows the experimental arrangement and the actual measurements, which are in very good agreement with a simple analytical estimate.

Figure 4 shows four probes brazed on the EUROFER sheet at increasing distances from the centre: 2cm, 4cm, 6cm, 8cm, and the corresponding measurements delivered by the probes, confirming the theoretical expectation that the current density is increasing linearly from the centre to the periphery of the specimen. In Fig. 4 also a X-like probe is reported, made of two orthogonal sensors, able to discriminate the actual direction of the current density.

The results reported in this paper demonstrate the effectiveness of the proposed probe for the measurement of eddy currents induced in EUROFER specimens in ITER-relevant range of parameters. The same probe can be used also to measure currents injected (not induced) in conductors, like for instance halo currents during disruptions, and can be in principle easily upgraded to a Lorentz force density sensor, by adding a magnetic field sensor and suitably combining magnetic field and current density measurements.

The work leading to this publication has been partially funded by Fusion for Energy under Grant F4E-GRT-0640. This publication reflects the views only of the author, and F4E cannot be held responsible for any use which may be made of the information contained therein.

[1] Lazarus E A, Lister J B and Neilson G H, *Nucl. Fusion* **30** (1990) 111

[2] Hender T et al, *Nucl. Fusion* **47** (2007) S128

[3] J.M. Hanson et al, *Nucl. Fusion* **56** (2016) 106022

[4] P M Glover and R Bowtell, Phys. Med. Biol. 52 (2007) 5119–5130

[5] S. Peruzzo, "Correnti elettriche tra il plasma e la camera di contenimento dell'esperimento RFX: rilevazione ed analisi", PhD Thesis (in Italian), 1998

[6] S. Gerasimov, CCFE, private communication

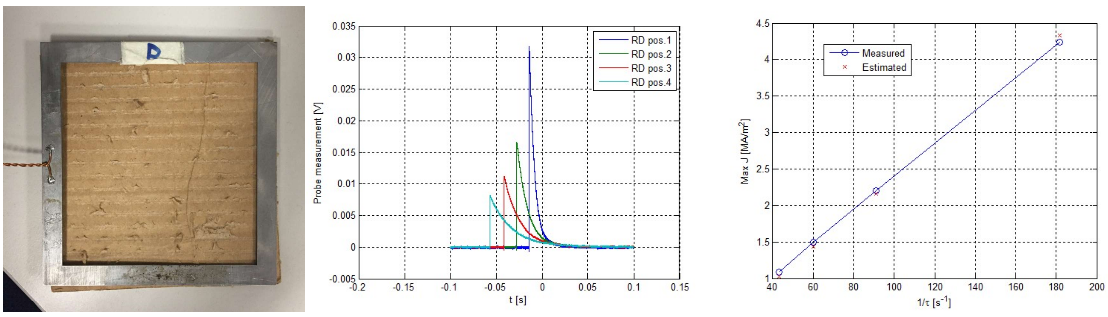

Fig. 3. Probe brazed on a ring: arrangement and experimental results

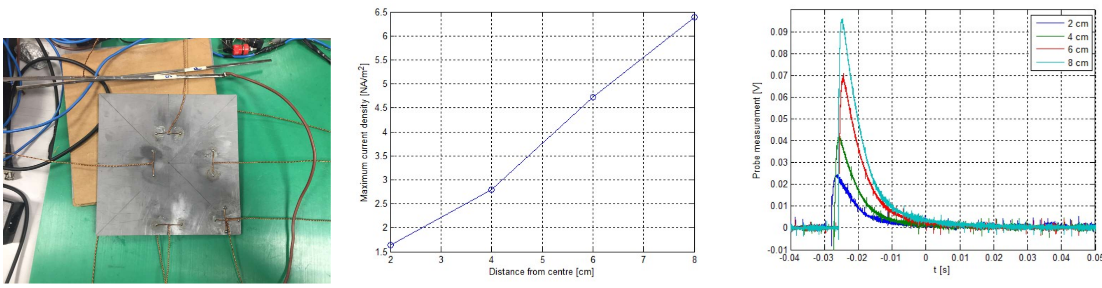

Fig. 4. Probes brazed at different distances from the centre of the specimen