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Refurbishment of JET magnetic diagnostics

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In a tokamak device magnetic diagnostics play a key role in the understanding of plasma physics, for control and safe operation. JET plasmas have magnetic fluctuations from a large variety of MHD instabilities and is equipped for spectral and mode number analysis with fast magnetic Mirnov coils. By the end of 2016 experimental campaign C36B, JET lost several pick-up coils used both for equilibrium reconstruction (slow coils) and MHD analysis (fast Mirnov coils). In order to restore the JET MHD modes analysis capability for the coming DT campaign, 27 faulty in-vessel coils were refurbished. A new design was proposed to try to diminish the failure rate, mitigating the possible cause that led to those coil failures. New sensors will use Glidcop® wire and will be remotely-handleable (RH) compatible. Prior installation, a calibration procedure and electrical tests were carried out in the laboratory. The calibration was performed using a Helmholtz coil together with a known reference coil to determine the effective coil area (NA) at constant magnetic field (0 Hz) and the transfer function amplitude, with respect to the reference coil, up to 200KHz. Two out of the 27 newly manufactured coils could not be installed due to the impossibility of re-terminating the existing in-vessel cabling during the in-vessel manned intervention.

Keywords: MHD coils, Mirnov coils, Calibration, Remote handling.

1. Introduction

JET tokamak is equipped with hundreds of magnetic sensors distributed over the torus, designed to withstand neutron fluence. JET plasmas have magnetic fluctuations from a large variety of MHD instabilities. Data from fast magnetic Mirnov coils is mainly used for spectral analysis and mode number identification[1]. By the end of 2016 experimental campaign C36B, JET lost several pick-up coils used both for equilibrium reconstruction (slow coils) and MHD analysis (fast Mirnov coils). Slow coils are based on a MIC (Mineral Insulated Cable) wound around a stainless-steel former, while the Mirnov coils are based on non-insulated cable wound around a ceramic alumina former. In order to restore the JET MHD mode analysis capability for the coming DT campaign, 27 faulty in-vessel coils were refurbished.

A new revised design was proposed to try to diminish the failure rate, mitigating the possible cause that led to those coil failures. New fast sensors will use Glidcop® wire (instead of previous Titanium wire, **Ti**) wound around a ceramic former and they will be equipped along with remote-handleable capabilities.

Prior to installation a calibration procedure and electrical tests were carried out in the laboratory. The calibration was performed using a Helmholtz coil together with a known reference coil to determine NA at DC (0 Hz) and the transfer function amplitude, with respect to the reference coil, up to 200kHz. Two of the newly manufactured coils weren't installed due to the impossibility of re-terminating the existing in-vessel cabling during the in-vessel manned intervention.

2. Overview

Magnetic fluctuations coming from MHD instabilities can be analysed using the data from a set of fast magnetic pick-up coils designed for high frequency MHD activity study (up to 500 kHz). They were designed with **Ti** wire wound in a single layer onto a ceramic former (see Fig.5) with a return wire through the centre of the coil. A typical coil diameter of 35 mm was used with about 70 turns of 0.5 mm diameter wire with 1.5 mm pitch. The coil length is about 100 mm. The coils are in the torus vacuum, shielded by individual stainless-steel cases with a longitudinal slot, tangentially oriented to respect the poloidal magnetic field lines. The plasma facing surface of the stainless-steel case is protected by a carbon tile case.

The JET MHD coil set (see Figs. 2-5) consist of:

- 7 *High Resolution Array Coils* (*HRCA*), named H3xx, outboard of the plasma distributed toroidally and poloidally at Octant 3, which are basically used for high toroidal(n) and poloidal(m) mode analysis.
- 6 *Toroidal Array Coils* (*TCA*), named T0xx.
- 2 *Outer Poloidal Limiter Tangential Coils* (*OPLTC*) (at octants 4 & 8), P402 and P802, are distributed toroidally around the torus outboard of the plasma, which are used for low MHD toroidal mode analysis.
- 3 *Inner Coils*, named I80x, are inboard in the high field side region of the plasma and 2x7 slow *Outer Poloidal Limiter Tangential Coils* (at octants 4 & 8), named PP80x and PP40x, outboard of the plasma.

A dedicated data collection system provides fast magnetic signals to be recorded at 2 MHz for up to 32s in each JET pulse.

3. Refurbishment

The main aim in refurbishment of the lost magnetic sensors is restoring capabilities for MHD analysis, which

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is relevant for many programmatic objectives, including analysis of toroidal mode number of fast particle modes

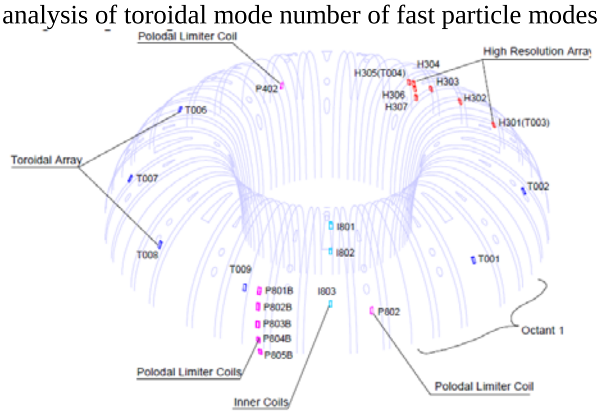

Fig. 1 JET MHD fast coils overview.

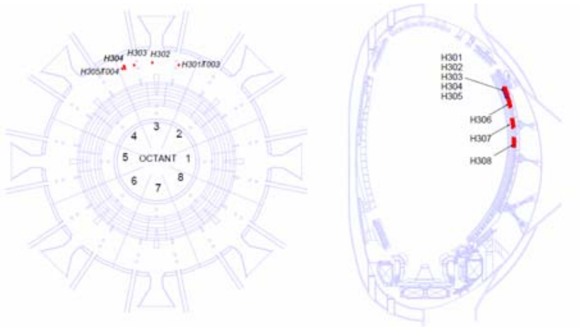

Fig. 2 HRCA toroidal view(left), poloidal cross-section view(right).

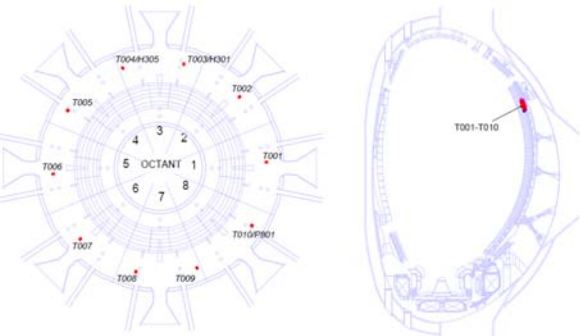

Fig. 3 TCA toroidal view(left), poloidal cross-section view(right).

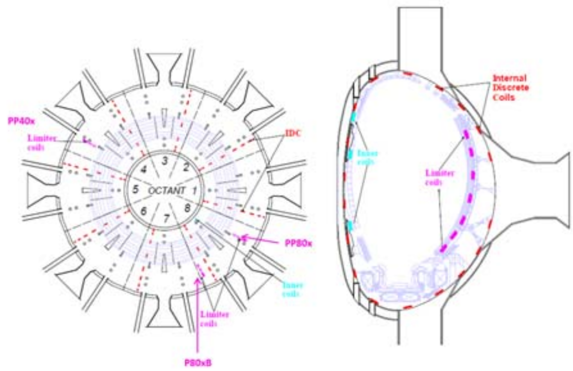

Fig. 4 IC and OPLTC toroidal view(left), poloidal cross-section view(right).

for the DT campaign, characterization of core and pedestal modes, disruption and ELM studies. In the final conceptual design recommendations that comes from the post mortem analysis [2] of removed faulty coils, played an important role. A potential cause of the coil failures was identified as the formation (due to deposition) of chemical layers, which affected the mechanical properties of the **Ti** wires due to hardening. Moreover, in some of the faulty coils (TA, HRCA) the MICA plates (meant to close the coil case electric gap) were observed to have disintegrated. This is compatible with the formation of the **Ti** chemical compound, which develops at high temperature. To deal with issues found was improved electrical insulation (inserting ceramic insulators and coating inside the coil casing), to reduce thermal loads, electrical forces, risk of electric arcs and movement of wire. The scope of the project was to procure a set of in-vessel coils, to replace failed ones, with sufficient sensitivity and bandwidth to allow accurate measurements and analysis of MHD activity within the JET tokamak plasmas.

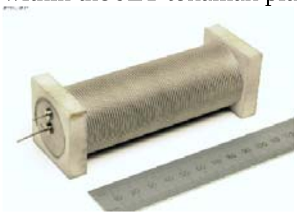

Fig. 5 Ti Mirnov Coil

Fig.6 New fast coil parts

Fig.7 Coils assembled along with base plate

Fig. 8 Coil fully assembled.

Two main changes were adopted in the new design:

- to reduce cost of future intervention all new coils are remotely-handleable (RH) and no in-vessel manned intervention is required.
- all new fast coils will have GLIDCOP® AL-15 instead of **Ti** wire, wound around a grooved ceramic former. Such material will basically be tested for the first time in a nuclear fusion environment and it was chosen due to its improved properties. It consists of a pure copper matrix containing finely dispersed sub-microscopic particles of Al_2O_3 which act as a barrier to dislocation movement. The dispersed Al_2O_3 is thermally stable so that it acts to retard recrystallization of the copper. Consequently, significant softening does not occur as the result of high temperature exposure. Along with superior strength retention, thermal and electrical conductivities are higher than conventional copper alloys.

Moreover, the coils shall fulfil also the following operational criteria:

- Sensitivity $NA \sim 0.06 – 0.09\ m^2$
- Bandwidth up to 1 MHz
- All new coils must have identical design providing the same sensitivity (*NA*) and frequency response.
- Coil locations and orientation must be the same of the replaced ones (see Figs 1-4), with the exception for H304 which position was corrected to the same poloidal angle as the remaining one in the HRCA.
- Comply with the criteria to be used in the design and assessment of components installed inside the JET torus,

(including vacuum compatibility, temperature range and power loadings).
- Have a minimum lifetime of 10 years in the JET in-vessel environment.
- Be re-woundable if the coil wire fails.

The list of new design changes is shown in Fig. 9, such as:
- remove all corners in ceramic parts by introducing chamfers or larger corner radii
- ceramabond (high temperature ceramic paste) all ceramic mating parts to limit movement.
- replace Ti wire with GLIDCOP® AL-15
- reduce diameter of dowels to ease remote installation
- replace MICA with plasma sprayed coating
- fit ceramic end plate covers.

The main phases of coil assembly process are resumed in the Fig. 10. Once the coil former with wound wire is enclosed in the coil case and back plate along with the protective shield case, it will be RH secured to the base plate, which was manually welded to the JET vacuum vessel.

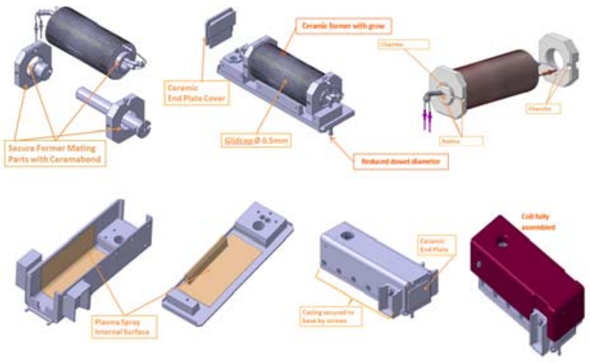

Fig. 9. Overview of main design changes in order to prevent operational issues on the magnetic sensors.

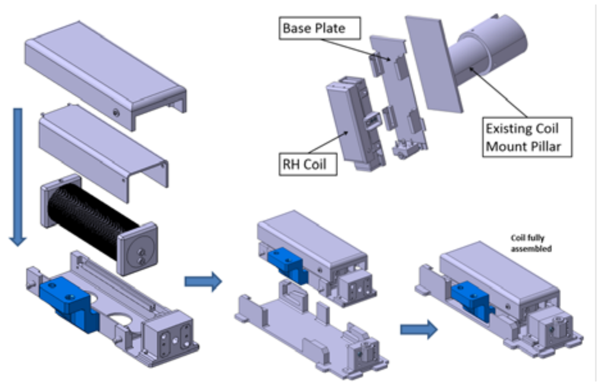

Fig. 10. From left to right assembling process of one of the IC.

4. Calibration

The new fully assembled coils (but without the base plate) were calibrated in the lab prior the installation. The assembled coils were placed into a sinusoidal varying uniform magnetic field generated from a Helmholtz coil. The calibration process was required to estimate:
- coil sensitivity **NA** at low frequency (0Hz), where **N** is number of turn and **A** the average area of single turn. For slow coils, the NA cannot be computed using the technical drawing charts of MIC cable (due to the poor accuracy in order of few percent).
- transfer function (TF) amplitude (against a reference known coil) up to 200 kHz.

The lab calibration setup consists of (see Fig.11):
- 1 Helmholtz coil, which gives uniform magnetic field at his axis center, proportional to N (number of turn) and IA current applied to them, AWG-10 (2.59 mm diameter) copper wire so that they may be driven with 20 amperes continuously. The Model 6402 is about 0.65 m diameter and weight about 30 kg. Was assumed that manufacture precision is very high in other words the two parts of Helmholtz coil are perfect co-axis and well within a design tolerance of ±2 mm in both radius and axial separation. The two coils plane are parallel with the accuracy ±0.2 °.
- 1 Reference coil, known N=50, Ø=26mm, L=6mm, NA=0.0265m^2;
- 1 Audio amplifier (provides the current to feed the Helmholtz coil) Yamaha P7000S amplifier;
- 1 Signal generator (input sinusoidal wave to the audio amplifier);
- 2 high precision and low noise RMS voltmeters;
- 1 computer for calibration automation.

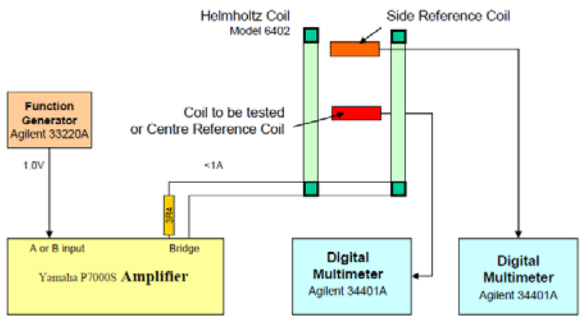

Fig. 11 Set up of equipment calibration in the lab.

During the calibration process in the lab, the contribution of transmission cable (with for JET consist of a couple of hundred meters) was neglected. To ensure minimum of distortion and the best possible homogeneity of magnetic fields within the test volume, ferromagnetic objects (which tend to distort the magnetic fields in areas near the object) were kept away from calibration instruments and it was also essential to use fully wooden desks. All units (Functional Generator, Amplifier, Helmholtz Coil and Digital Voltmeter) were placed reasonably far away from each other. Particular location of the Yamaha P7000S amplifier must be chosen very carefully, because it has ferromagnetic casing. Except for the wire, the entire Helmholtz coil structure is made of non-conductive, non-magnetic materials including linen phenolic, nylon and Formica. Handling the Helmholtz Coil is critical, so it must be carefully moved at all times, taking precautions to avoid subjecting it to thermal or mechanical shock.

Main disadvantages of the calibration equipment adopted are: not suitable to calibrate large bore coils and the coil alignment inside the Helmholtz is a complicated task. The coil sensitivity **NA** together with the UXT1 (isolated integrator with ADC) parameters, is used to calculate as ADC bits to magnetic field conversion factor (or calibration factor ***CF***) known. The ADC receives an integrated analogue input ***V***:

$$\boldsymbol{V} = \frac{\boldsymbol{NA}}{\boldsymbol{\tau}}\boldsymbol{B} \qquad (1)$$

where τ is the integration time, than the calibration factor, is given by:

$$\boldsymbol{CF} = \frac{\boldsymbol{U}}{\boldsymbol{b}}\frac{\boldsymbol{\tau}}{\boldsymbol{NA}} \qquad (2)$$

where ***U*** is the ADC's input double full scale deflection (U = 5.0 V for UXT1) and ***b*** is ADC accuracy ($b = 2^{16}$ for UXT1).

The coil sensitivity **NA** is a function of frequency **f** of the applied magnetic field **B(f) = B sin (ωt)**, to be identified for each coil, we used the lab setup described in Fig. 12, doing:

- a sweep frequency between 100 Hz to 600 Hz, with step of 20 Hz;
- $\boldsymbol{NA(f)} = \boldsymbol{V^{RMS}_{MHD}(f)/V^{RMS}_{Ref.Coil}(f)}$
- linear extrapolation to the 0 Hz by a linear fit on *NA(f)* to obtain *NA(0 Hz).*

The result found is NA ~ 0.083m^2 for Hs, Is and Ts fast coil , while for the coil PP403,PP407 and PP80x family NA ~ 0.065m^2.

To build the transfer function amplitude (see Fig. 12) up to 200 kHz, a frequency sweep between 150 Hz and 200 kHz with frequency step of 15 kHz was done;

- Absolute amplitude is obtained under the assumption that the reference coils frequency response is mostly constant (no significant attenuation) up to 200 kHz.

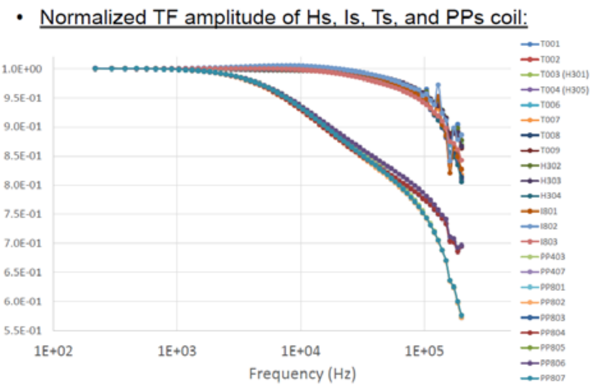

Fig. 12 Normalized TF amplitude of new coils

5. Installation

JET structures are slightly radioactive and exposure to radiation has to be kept to a minimum, whenever is possible, the modifications to the machine are done using Remote Handling (RH) techniques. The original MHD sensors were manually installed in 1993, when remote removal was not a requirement and never anticipated.

An in-vessel manual intervention was required to remove the existing faulty coils. To be successful and to expose at low maximum dose rate the personnel involved, every detail had to be meticulously planned and practiced and many factors and risks needed to be considered. Every step of the planned activity was mocked up and practiced in the In-Vessel Training Facility (IVTF), which mimics the internal features and surface of the JET Machine. Such training gave a high level of confidence that each activity can be achieved safely and within the allotted time frame.

The main point of this manual phase was to remove and replace these sensors with new remotely handleable ones in preparation for the next JET DT (Deuterium-Tritium) campaign. Manning intervention is a short but highly intensive set of activities. For the intervention to be successful, every detail must be meticulously planned and practised, and many factors and risks need to be considered (e.g. the time for each activity or the dose rate calculated for each person involved). Faulty magnetic sensors during removal process were enveloped with a custom-made isolator. The isolator will contain all the debris throughout the removal process thus keeping the vacuum clean and free from contamination.

Electrical tests were performed from J1T (JET Torus Hall) at the plugging socket (socket to in-vessel coil location), w/o new coil. Moreover, TDR (Time-Domain Reflectometry) measurements were performed jointly with electrical continuity check, to detect any cabling fault or anomaly, such as electrical interruption. Then the new coils were placed and well secured with RH.

25 broken MHD coils were remote-handling replaced with new ones, but 2 coils of the TA set(P401 and P801) were not installed due to the lack of accessible space to re-terminate the in-vessel cable located in a partially closed cable conduit.

Conclusions

To re-establish JET MHD capabilities 27 new fast coils were procured with a new design and remote handleable capabilities. A manned intervention was required to remove old coils and to place the coil base plate to accommodate the new coil.

25 broken MHD coils were remote-handling replaced with new ones, but for 2 coils of the TA set could not installed.

The MHD coils were calibrated in the lab in terms of coil sensitivity at DC (0Hz) and computation of transfer function amplitude up to 200 kHz MHD JET capability can be handover to MHD analyst.

Acknowledgments

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References

[1] E. Giovannozzi, Proceedings of EPS 2014

[2] M. Baruzzo, Proceedings of SOFT 2018