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ABSTRACT

This paper describes the activities of installation and commissioning of the magnetic diagnostic enhancement for JET. The new system includes four sub-sets of probes located in the vessel in two opposite octants, for a total of 48 magnetic pick-up coils. The main goal of this enhancement is to improve the accuracy of the reconstruction of the plasma equilibrium and the performance of the real time feedback control of the plasma shape.

After a brief description of the system, the paper focuses on the installation activities, accomplished during the 2007 shutdown using the JET remote handling system. The paper then concentrates on the analysis and interpretation of the data collected during the functional commissioning of the new system, carried out during the restart phase of the machine and the first part of the 2008 experimental campaigns, which proved the accuracy of the new signals and the achievement of the project goals.

1. INTRODUCTION

The enhancement of the Magnetic diagnostic system for JET (EP-MAG) has been developed under the JET-EP programme [1], with the main aim of improving the accuracy of the reconstruction of the plasma equilibrium and the performance of the real time feedback control of the plasma shape [2].

The whole EP-MAG system consists of both in-vessel and ex-vessel sensors, subdivided in several sub-systems. The ex-vessel sensors were successfully manufactured and installed during 2005 shut-down [3], whereas the in-vessel subsystem suffered from some delays during the manufacture phase, which prevented meeting the same target date of installation which was consequently postponed to the following 2007 shut-down.

The design and the procurement of the in-vessel system [4] were carried out in close collaboration between the two Associations involved in the EP-MAG enhancement project in order to meet the following requirements:

- operation and fault condition design criteria for JET in-vessel components [5];
- interface with existing first wall components in a relatively tight geometry;
- installation to be carried out completely by means of Remote Handling.

2. GENERAL LAYOUT OF THE EP-MAG IN-VESSEL SYSTEM

The sensors are grouped in two different sub-systems of two field component (‘tangential’ and ‘normal’) pick-up coils, assembled on rails in order to ease the installation by means of Remote Handling. The two sub-systems, Upper Coils (UC) and Outer Poloidal Limiter Coils (OPLC) indicated in Fig.1, are attached to different structures of the first wall and replicated for redundancy in two Octants, for a total of 48 new pick-up coils. During 2005 two further sets of 7 coil pairs (horizontal and vertical component) were procured and installed in the framework of the “divertor enhancement project”, bringing the number of new in-vessel magnetic sensors to a total of 76.

Most of the new coils are made of a Mineral Insulated Cable (MIC) wound around Inconel formers. This technological choice was justified by the satisfactory reliability given by previous sets of similar coils operated in the past in the JET vessel. The consequent relatively low frequency response (about 50 kHz) is more than adequate for plasma control and equilibrium reconstruction, which require a maximum frequency of 10kHz.

In addition a sub-set of 14 ‘tangential coils’, located on the Outer Poloidal Limiter, is made of titanium bare wire wound onto an alumina ceramic former, so that they can be used for high frequency applications (e.g. MHD studies) up to 1MHz.

3. INSTALLATION ISSUES

3.1 DESIGN

The radiation and contamination issues within the JET vacuum vessel require that wherever possible all installation work is undertaken remotely using manipulators and specialist tools. This avoids unnecessary exposure of personnel and complies with the ALARP principle.

The MAG system was designed with this as a primary requirement and as such had to closely interface with adjacent equipment and also to share its electrical vacuum feed through with the TAE system.

Due to the size and complexity of the outer poloidal limiter array and its associated components it was necessary for each sub-assembly to be designed in a modular form. This design philosophy allowed each sub-assembly to be remotely handled by the JET Mascot manipulator system. Between each of the sub-assemblies there are a number of plug and socket assemblies which electrically connect the sensors to the feedthrough. These were connected remotely.

Close clearances relative to other systems entailed a number of mechanical interface challenges that needed to be solved during the actual installation.

3.2 EX-VESSEL WORK.

In order to install the electrical vacuum feedthroughs at Octants 4 and 8 lower limiter guide tubes, safe access had to be established in very restricted areas adjacent to the machine. Due to the location, rigorous working at height requirements had to be implemented in order to allow safe work. In addition, to maintain the vessel boundary final insertion of the feedthrough, assembly had to be undertaken using flexible plastic isolators.

3.3 IN-VESSEL WORK

Each plug and socket assembly (Fig.2) was remotely connected.

Several stages of in-vessel work were undertaken working from the feedthrough to the final installation of the coils. This included combined in and ex-vessel works as the feedthroughs were installed. In many cases removable remote handling features were added to the assemblies to allow handling by the manipulator.

The various sections included trunking, cabling, socket assemblies, coil arrays and poloidal limiter coil supports and individually removable coils (Fig.2). Installation at Octants 4 and 8 required a total of 220 hours of remote handling time and 2 hours during a manned access phase, for a few operations which were technically not achievable remotely.

3.4 TESTING

All subassemblies were bench tested before installation. This included fitting to precise mechanical jigs to ensure the accurate dimensions required to facilitate remote installation. Electrical tests were also completed and repeated at each installation stage by the remote fitting of test plugs when possible to validate the performance of the wiring before the final installation of the individual coils and the upper coil arrays.

4. COMMISSIONING OF THE MAG SYSTEM

4.1 SIGNALS VALIDATION

The assessment of the performance of the new coils has been carried out verifying the consistency of the signals, also by using equilibrium codes, with the aim to include the new signals in JET magnetic diagnostic set, once positively validated.

The CREATE MSWTools [6] is a 2D equilibrium code that includes in its formulation a complete linearised iron model, an eddy current model and a plasma model as a set of fixed filaments carrying currents obtained as a linear combination of the plasma current moments, coming from a linear combination of the magnetic measurements.

The entire set of new measurements has been reconstructed using the MSWTools for a number of pulses without including them in the magnetic input. A list of standard and specific dry-runs, designed to observe strong radial and vertical fields with phases of fast transitions and steady state, has been run with the aim of verifying the toroidal field and drift compensation, the polarity and gain corrections, and the geometrical position and orientation.

To compare the experimental and reconstructed signals, the following formula has been evaluated:

$$\%\text{Difference} = 100^* \frac{\|\text{Mag\_exp-Mag\_rec}\|_2}{\max(\|\text{Mag\_exp}\|_2, \|\text{Mag\_rec}\|_2}$$

A satisfactory agreement has been verified with discrepancies for the new UC and OPLC sets of 4% on average. Figure 3 shows an example of comparison between an experimental signal and the correspondent reconstructed one for a dry run.

During the commissioning, 1 out of the 48 probes failed, presenting an open circuit at the ex-vessel terminals, probably due to a failure of an in-vessel connector. A few other coils showed sporadic unreliable behaviours during some plasma runs, with signals coherent among different octants and with the reconstructions only for a limited interval of time (fig.4). The reasons of this behaviour are still under investigation.

4.2 FUNCTIONAL COMMISSIONING

The following step of the commissioning was the reconstruction of the new signals, validated on dry-runs, in experiments with plasma, again not introducing the new signals in the confidence set. In this condition the field structures are more complex due to the presence of the plasma itself; this caused an increase of the discrepancies between experimental measurements and reconstructions. A fair agreement has been obtained for the tangential set of coils, while a less satisfactory result has been obtained for the normal sets, respectively 3% and 15% on average, with the higher discrepancies obtained for the new coils placed in positions not covered by other measurements. This is an implicit proof of the lack of information carried by the previous set of coils that can be instead provided by the new coils.

A significant improvement in the reconstructions of the new signals in plasma-runs is obtained introducing the new coils in the MSWTools confidence set, with discrepancies for the all new sets reduced from 9% to 5% on average. The MSWTools is searching for a best fit with the coils and this is one reason of the improved agreement. Nevertheless the agreement of the standard and new confidence set, extended to the new coils, has been verified with relative difference for both the sets equal to 4% on average. This leads to the not trivial result to obtain a better prediction of the new coils using them in the reconstructions, verifying the coherence within the new set and towards the other coils.

A particular indication of the enhanced performance in the reconstruction of JET upper region is achieved including the UC set in specific plasma pulses, designed to make the upper null field point to enter and exit from the vacuum chamber with a rate of 10cm/sec. This movement is detected by the change of sign of the experimental measurements of the new upper tangential coils when they are crossed by the X-Point (fig.5). Comparing the reconstructions obtained using MSWTools standard set versus the new set, the latter shows a better global reconstruction of the coils and better time reconstruction of the time instant where the experimental tangential coils change sign. The additional information coming from the upper set can therefore be very important for plasma configurations at high triangularity and elongation (quasi double null).

The extension of the confidence set to the OPL normal coils brings new information on the radial field in the outer region close to the plasma, previously provided by the saddle flux loops positioned on the vessel. The advantage of the new set, compared with the saddle coils, is an expected reduced effect on the coils of eddy currents circulating in the vessel during fast transients. This could bring useful information for the vertical stabilisation system (VS) for fast vertical plasma movements (fig.6). The implementation of this aspect is currently in progress.

CONCLUSIONS

The enhancement of the magnetic diagnostic system was successfully installed in the JET machine during the 2007 shutdown and started the acquisition of signals during the restart phase of the machine in spring 2008.

Despite the unreliability of some signals, the overall satisfactory conclusion of the functional commissioning of the system has demonstrated the positive contribution of the new signals to a more accurate plasma equilibrium reconstruction and feedback control of the plasma position and shape.

ACKNOWLEDGMENTS

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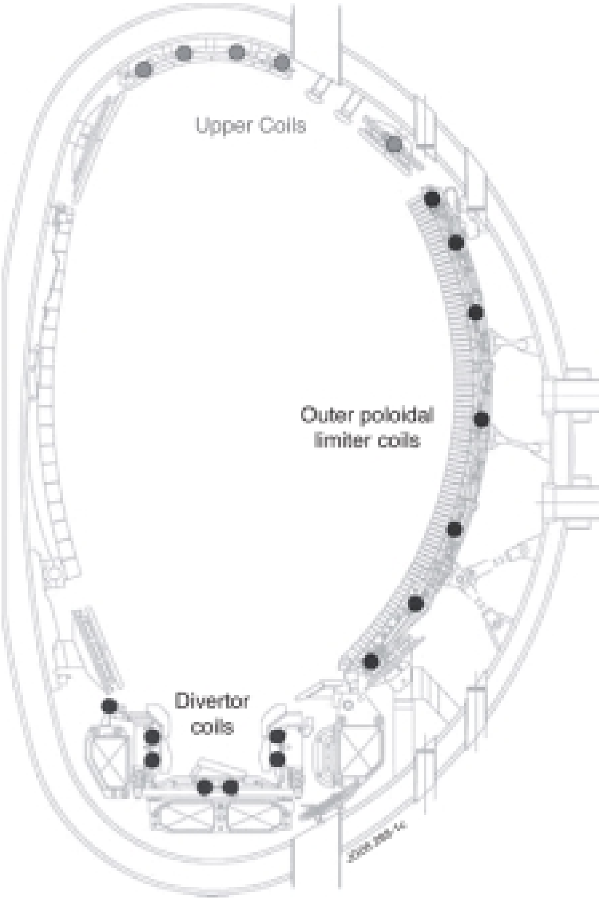


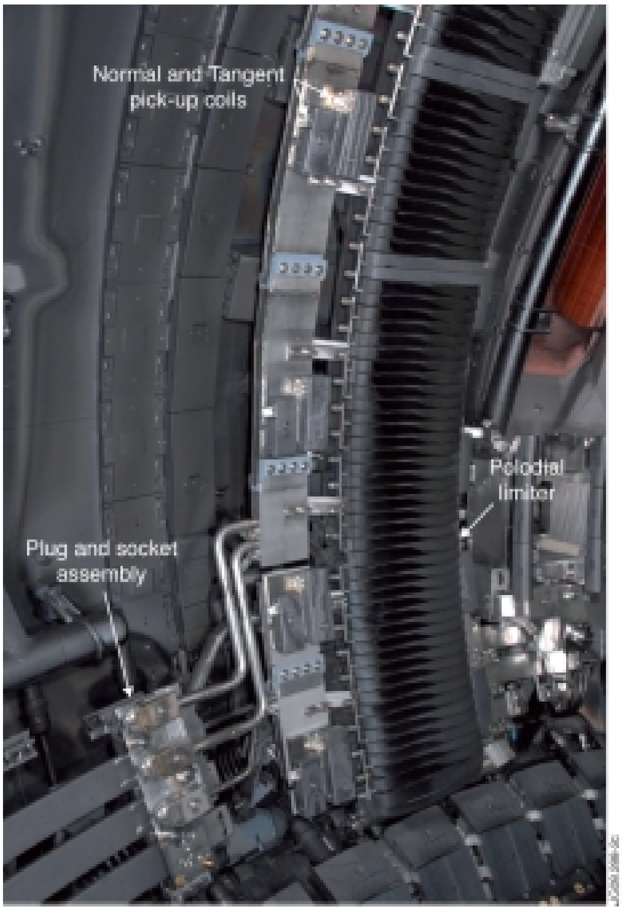
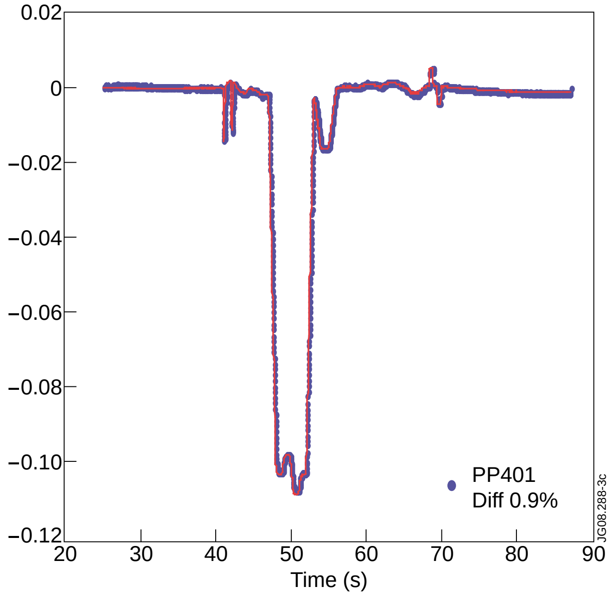


Figure 1: Poloidal distribution of the JET-EP in-vessel magnetic coils (replicated in 2 toroidal locations).

Figure 2: In-vessel view of the Outer Poloidal Limiter Coils.



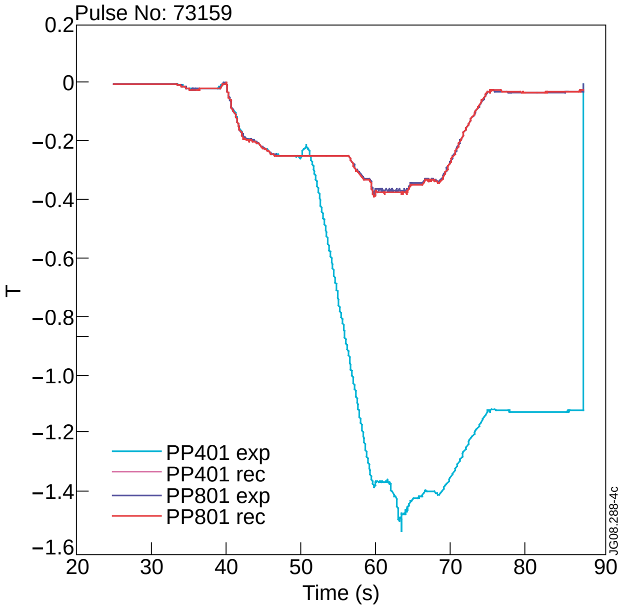


Figure 3: Comparison between experimental (blue) and reconstructed (red) signal for a dry run.

Figure 4: Evidence of failure of a signal during a plasma run.

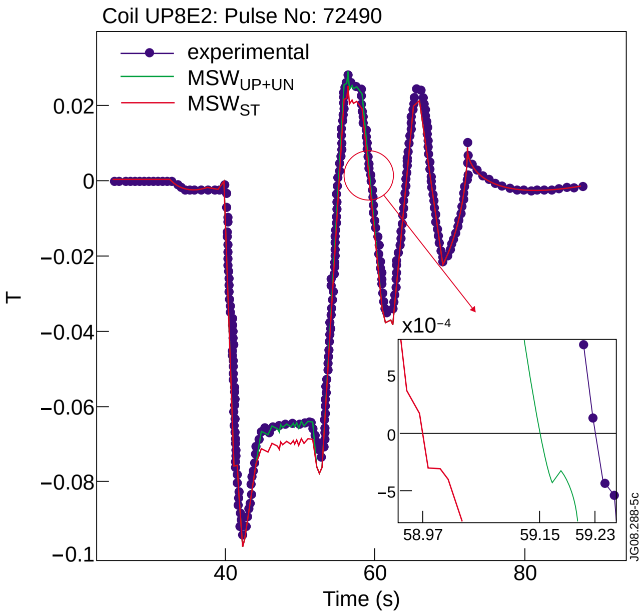


Figure 5: Coil UP8E2 experimental signal versus MSW with trusted set of coils that include the new upper tangential and normal (UP+UN) and MSW standard set (ST) for the Pulse No: 72490. The new information included with the new UC helps the precision in a region important for plasma configuration at high triangularity and elongation (quasi double null).

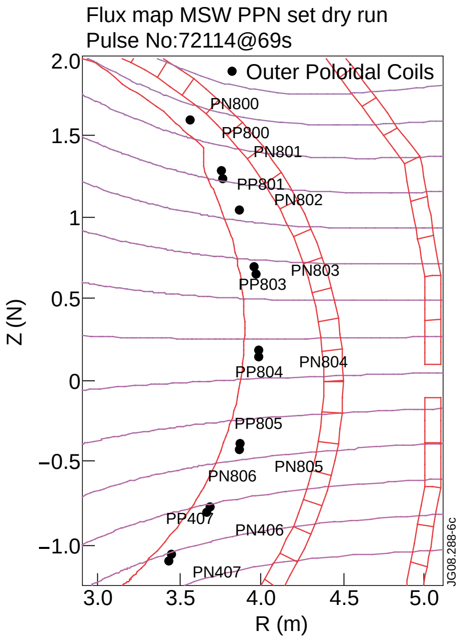


Figure 6: Dry-Run flux Map from MSWTools with new set of confidence extended to the OPLC, during the dry-run 72114. Highlight on the new information of the normal coils (not present in the old set) PNX0Y, with the length of the arrows proportional to the reconstructed field, in correspondence of a Fast Radial Field Amplifier (FRFA) step, useful for VS system, far enough from the vessel and its parasitic currents during fast transients. parasitic currents during fast transients.