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Design of the New Magnetic Sensors for JET

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ABSTRACT

A new Magnetic Diagnostics system has been designed for the 2005 JET experimental campaigns onward. The new system, which adds to the existing sensors, aims to improve the JET safety,reliability and performance, with respect to: i) equilibrium reconstruction; ii) plasma shape control; iii) coil failures; iv) VDEs; v) iron modelling; vi) MHD poloidal mode analysis.

The system consists of in-vessel and ex-vessel sensors. The former are a set of 38 coil pairs (normal and tangential), located as near as possible to the plasma. Coils are generally grouped in rails, in order to ease Remote Handling invessel installation. The system includes: i) 2 outer poloidal limiter arrays (2 x 7 coil pairs); ii) 2 Divertor region arrays (2 x 7 coil pairs); iii) 2 Top coil arrays (2 x 5 coil pairs).

Ex-vessel sensors, including discrete coils, Hall probes and flux loops (26 in total) will be installed on the iron limbs, in order to provide experimental data for the treatment of iron in equilibrium codes. The design is accompanied by a software analysis, aiming to predict the expected improvement.

I. INTRODUCTION

A new magnetic diagnostics system is being developed for the Joint European Torus (JET) with the purpose of improving the performance of the present system, with respect to the following functions: i) postpulse reconstruction of the equilibrium map; ii) slow real time control of the plasma current and shape (1-5 KHz); iii) detection of MHD modes ($\leq$1 MHz); iv) fast real time control of the vertical position for highly elongated plasmas (10 KHz); v) real time tuning of parameters for equivalent axisymmetric iron modeling.

Two main motivations justify the new installation: i) a number of sensors are faulty with a consequent degradation of functionality; ii) the future JET experimental campaign will include extremely shaped plasmas, which require a better shape reconstruction accuracy, especially in the X-point(s) region.

The new system will be in operation in time for the JET restart in 2005.

II. DESIGN CONCEPT

The new system consists of in-vessel and ex-vessel sensors. In-vessel sensors system are two field component coils, located as near as possible to the plasma and distributed along the poloidal contour. They will therefore operate in an environment of ultra high vacuum and temperatures up to 350 °C. Access for maintenance is restricted and will only be possible during a planned shutdown intervention.

14 coils are fast coils, dedicated to MHD studies, with the rest designed for use at relatively low frequency (up to 50 kHz), allowing more robust mechanical properties. Coils are generally grouped on rails, in order to ease Remote Handling invessel installation. Ex-vessel sensors are mainly dedicated to the detection of iron characteristics and include Hall probes, flux loops and pick-up coils.

The engineering design has been accompanied by the development of Magnetic Analysis software tools aimed at the assessment of the system, the optimisation of the use of sensors in the reconstruction codes and the functional commissioning after installation.

The whole system includes the following subsystems:

- Upper Coils arrays: pickup coils for the detection of the tangential and normal field in the upper invessel region;
- Outer Poloidal Coils arrays: pickup coils for the detection of the tangential and normal field in the outboard in-vessel region;
- Divertor Coils: pickup coils for the detection of the vertical and horizontal field in the lower in vessel region. These coils are embedded in the structure of the new divertor being installed at JET;
- Ex-vessel Probes: Hall probes, pickup coils and flux loops located near the magnetic iron structure of the machine;
- Software tools: a comprehensive set of codes, to be used for functional commissioning, fault analysis, parameter optimisation during operation.

III. PERFORMANCE ANALYSIS

A. MAIN FEATURES OF THE PRESENT SYSTEM

The presently installed magnetic diagnostics in JET have been designed to meet the requirements of the equilibrium reconstruction, MHD mode analysis and diamagnetic measurement [1]. The system includes slow and fast tangential pick-up coils [2], saddle and full flux loops, diamagnetic loops, as shown in Fig. 1. Only a subset of the installed coils is presently used for reconstruction, since some coils are faulty (e.g. some divertor coils and the set of upper coils)

B. PREDICTION OF THE ENHANCEMENT EXPECTED FROM THE NEW SYSTEM

The performance improvement expected from the new system has been assessed by comparing its capability of reconstructing the plasma boundary with the present set of sensors.

The statistical approach adopted [3] considers a large database of equilibria, both experimental and simulated, covering the parameter range of presently achievable plasmas, as well as new JET-EP configurations for 2005 campaign.

The database has been analyzed by means of the boundary reconstruction code used at JET, (XLOC [4]), which is consistent with the statistical approach.

The present set of working sensors was then compared to the enhanced one in terms of reconstruction error in presence of noise. The results (fig. 2) show that the installation of the new sensors reduces significantly the reconstruction error with the exception of the inboard region of the boundary. Indeed new sensors on the inboard first wall would be beneficial, but severe engineering constraints prevented in practice the installation of sensors in that region.

During the JET restart in early 2005 the analysis will be repeated with real signals coming from old and new sensors, in order to provide a functional commissioning of the new system.

IV. ENGINEERING DESIGN

A. UPPER COILS SUBSYSTEM

The Upper Coils (UC) subsystem is made of two identical assemblies to be installed, using only Remote Handling techniques, in two opposite toroidal positions of the JET vacuum vessel. Each assembly includes a mechanical structure supporting 4 pairs of coils (Top Coil Array), attached to the Dump Plate, and a smaller structure supporting 1 pair of coils (Upper Outer Coil Pair) attached to the disused Upper Saddle Coils (Fig. 3).

The final design of the UC subsystem has been carried out fulfilling all of the operational and fault condition design criteria for JET in-vessel components [5]. Proper electrical ground connections have been chosen to minimize the circulation of eddy and halo currents through the structures. 3D electro-mechanical analyses have been carried out with the worst disruption scenarios in order to guarantee a sufficient safety factor.

The Upper Coils are made of a Mineral Insulated Cable (MIC) with 1mm of outer diameter, wound around Inconel formers. An extensive set of tests has been performed on cables and vacuum tight terminations to guarantee their reliability and compliance with JET environment. The coils in the Top Coil Array are protected from the direct exposure to plasma by the Dump Plate CFC Tiles, whereas the Upper Outer Coil pair is enclosed in the mechanical structure made of Inconel. The relatively low frequency response (about 50 kHz) is more than adequate for plasma control and equilibrium reconstruction, which require a maximum frequency of 10 kHz.

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, partially shared with the OPL Coils. The Top Coil Array and Upper Outer Coil pair, though mechanically detached, have been conceived to share a single Remote Handleable Plug and therefore they are joined by signal cables. Preliminary tests on mock-ups have been performed in order to guarantee the compatibility with the features of the Remote Handling system.

B. Outer Poloidal limiter arrays

The outer poloidal limiter arrays will be located in octants 4 and 8 inside the vessel. Each array will include 7 fast tangential sensors and 7 slow normal sensors. The primarily construction of the fast tangential sensors consist of bare titanium wire wound around a ceramic former. The slow normal sensors are primarily constructed from mineral insulated cable wound around a metallic former. Both sensor types will be protected from the plasma by its own carbon fibre composite tile.

Due to the size of the array and the compatibility with the Remote Handling installation procedure, it is necessary for each sub-assembly to be designed in a modular form at the outset (fig. 3). Between each of the sub-assemblies there will be a number of plug and socket assemblies. Each plug and socket assembly will be remotely connected and disconnected.

The mechanical support for the sensors consist of a curved and straight mounting beam manufactured from Inconel.

Electrical breaks have been introduced in to the mounting beams between each of the supports to prevent halo currents passing through the beams.

The sensors are electrically connected to a new feedthrough, to be shared with the supply leads of the Toroidal Alfven Eigenmodes [TAE] antenna. Each TAE antenna will operate at 10-500 kHz, 600V and 10A (30A max), which overlaps at the lower end with the frequency range of interest to the magnetics sensors. For this reason the design of the feedthrough includes provisions to limit the RF noise induced on the magnetics wiring.

C. Ex vessel sensors

The numerical codes used for equilibrium reconstruction need an equivalent axisymmetric iron model, whose accuracy directly affects the accuracy of the reconstruction, especially during some critical phases of the discharge.

In this respect, the ex-vessel probes are mainly intended to provide useful experimental data, since: i) the new probes will be located near to the iron structure; ii) Hall probes produce absolute fieldmeasurements, so that the errors due to the time integration of the coil signals can be corrected; iii) Hall probes also provide data for the computation of the effect of the residual magnetization at the beginning of the pulse.

The preliminary tests which have recently been performed with the proposed Hall probes prove their suitability for the aims of the new system. The combination of Hall sensors and inductive probes will allow a complementary effect, thanks to their different properties.

The ex-vessel sensor system (Fig. 5) consists of 13 sensors grouped in 2 subsystems, named Collar probes and Limb probes respectively. The system is duplicated for redundancy and comparison on another Octant.

The Collar Probes will be attached to the bottom end of a 2 m long support rail, which will be inserted in a vertical hole already existing in the iron structure of the machine.

The Limb Probes measure the vertical field under an upper horizontal iron limb. The probes are located on three support rails aligned along the toroidal direction at different radial positions, so that the radial distribution of the stray vertical field can be measured.

The pick-up coils and the Hall probe contained in each rail measure the vertical field at the centre of the limb, whereas the narrow flux loop measures the vertical field averaged over 1/8 of the machine.

V. CONCLUSIONS

The new system of magnetic sensors adds to the present set and should provide a significant improvement of the traditional functions of the magnetic diagnostics, especially for the experimental campaigns characterized by extremely shaped plasmas. Hall probes are expected to improve the iron modeling.

In addition the system should contribute to a better integration of various diagnostics for real time profile control, and could also provide experimental input for ITER relevant studies in the field of plasma control.

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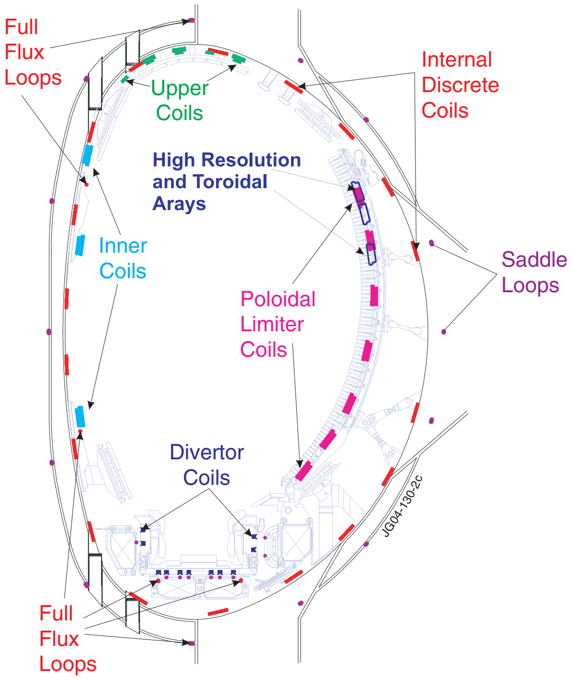

Fig.1: Present JET magnetic sensors: upper coils and some divertor coils are not in use.

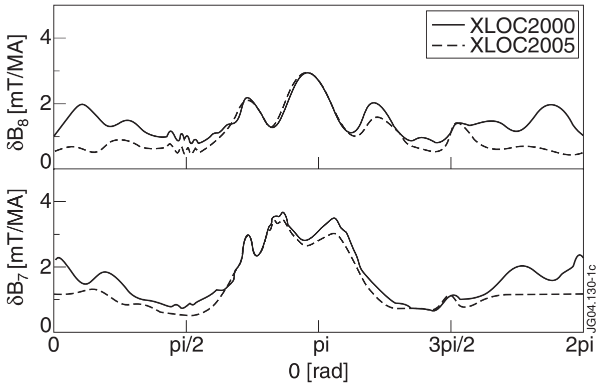

Fig.2: Error in the magnetic field reconstruction with the present system (XLOC2000) and the new system (XLOC2005): radial and tangential field components. The error is plotted versus the machine section poloidal co-ordinate (θ=0 corresponds to the outboard).

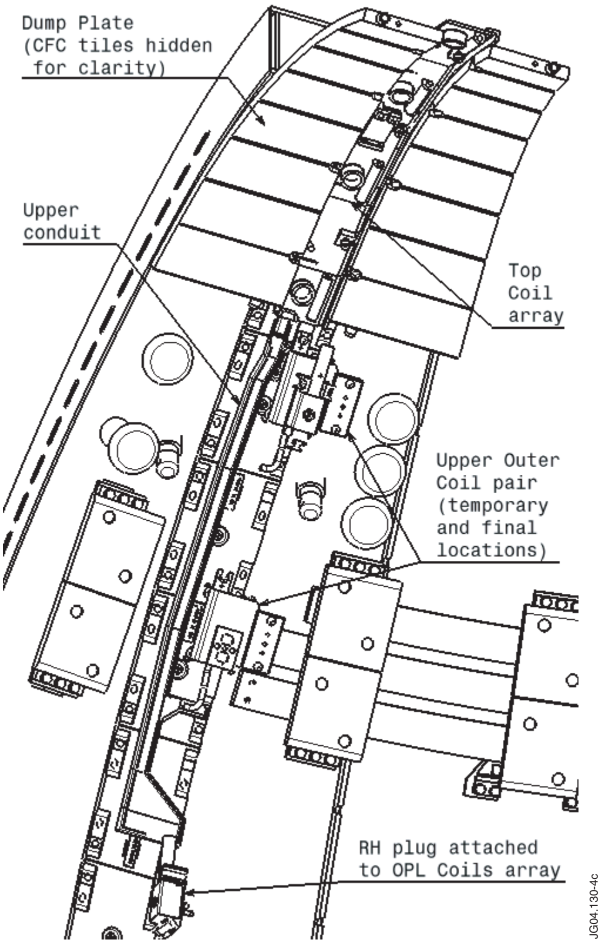

Fig.3: Upper Coils subsystem

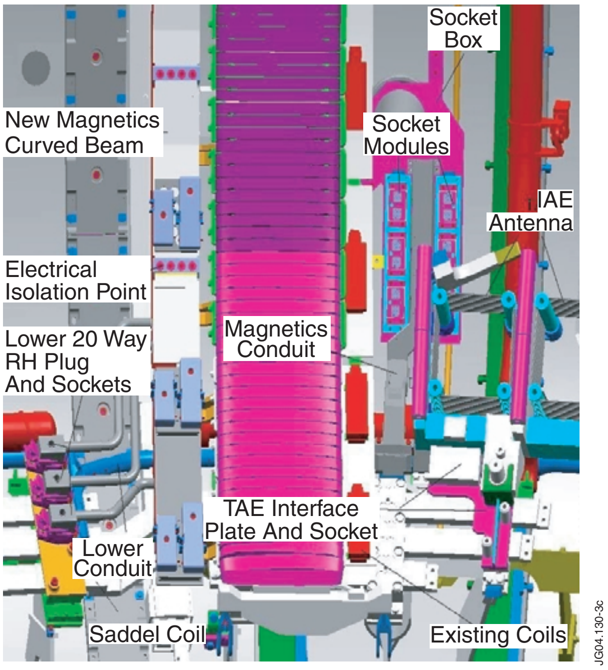

Fig.4: Outer Poloidal Coils subsystem

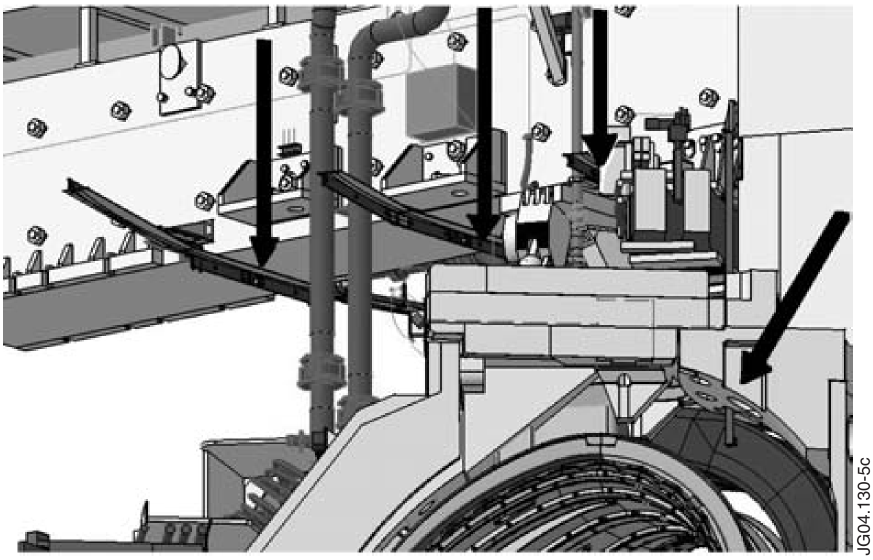

Fig.5: Ex-vessel probes. Limb probes are indicated by the 3 vertical arrows. Collar Probes is indicated by the single oblique arrow.