EFDA–JET–CP(06)04–07

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** See annex of J. Pamela et al, "Overview of JET Results",*
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
SOFT Conference,
(Warsaw, Poland 11th – 15th September 2006)

ABSTRACT
A new system of magnetic probes was installed during the 2005 shutdown and was commissioned during the 2005/06 restart phase of JET. The system is made of traditional pickup coils and Hall sensors, all located outside the vessel.

Direct field measurements from Hall sensors are used to correct the drift of the integrators of the pickup coils signals. This feature will be crucial for future ITER-like devices, where long lasting flat top phases are expected, in a high neutron yield and a high temperature environment.

After a general overview of the system, the paper describes the major manufacturing and installation issues, including the construction of the supports and probes as well as the acceptance tests before and after installation.

The functional commissioning of the system includes the integration of the new signals in the JET Data Acquisition System and the analysis of several discharges with and without plasma. The critical aspects of the assessment of the reliability of the signals are shown and commented on.

1. INTRODUCTION
A new system of magnetic probes was installed during the 2005 shutdown and was commissioned during the 2005/06 restart phase of JET. The system has been developed in the framework of the JET enhancement project on magnetic diagnostics, which aims to improve the equilibrium reconstruction and the real time control in JET, by means of 98 new field measurements as well as of new software tools.

The subsystem presented in the paper includes only probes located outside the vessel and it is made of 8 pickup coils, 8 Hall sensors and 6 flux loops. The objective of this subsystem is twofold: i) provide experimental data for a better modelling of the iron in the axisymmetric codes for plasma equilibrium reconstruction; ii) test the reliability of direct field measurements. The new sensors are located very near to the iron structure, so to provide useful information for the online tuning of the code parameters representing the iron characteristics.

Direct field measurements from Hall sensors are used to correct the drift of the integrators of the pickup coils signals. This feature will be crucial for future ITER-like devices, where long lasting flat top phases are expected, in a high neutron yield and a high temperature environment.

The Ex-Vessel Probes (EVP) system consists of two different subsystems, Limb probes and Collar probe, both manufactured in accordance to a detailed engineering design [1].

The Limb probes are intended to provide the measurement of the vertical component of the magnetic field in the proximity of the lower surface of the upper horizontal Limb at 3 different radial positions in two toroidal locations. The system is constituted by six supporting structures, each equipped with three different magnetic sensors: a flux loops, a pick-up coil and a Hall sensor.

The Collar subsystem consists of two pick-up coils and two Hall sensors, supported by a beam to be inserted in the inner region of the iron structure, aimed at measuring the radial and vertical components of the magnetic field leaking out of the *iron shoe*.

In the remaining of the paper, manufacturing, installation and commissioning issues are illustrated and commented.

2. MANUFACTURING ISSUES

The procurement of the main components of the EVP system was finalized through a supply contract, for the manufacture of the support structures, whereas the manufacture of the coils, the assembly and bench tests before installation were carried out directly at Consorzio RFX. The system was completed by the procurement of transmission cables and a new cubicle with data acquisition system, which were managed by the JET Operator in support of the diagnostic enhancements.

The support structures of the Limb probes consist of 6 subsets of fibreglass plates to be bolted to the iron Limbs by means of suitable brackets made of steel (fig. 1a). During the design phase [1], three flux loops were designed to measure the average vertical field spanning over 1/8 of the machine in the toroidal direction and 40 mm in the radial direction. To make the installation easier, each of the three flux loops was divided in three windings, adjacent along the toroidal direction, which are connected in series by standard LEMO connectors. At a second stage a further set of 3 Limb probes were added, but with extension along the toroidal direction limited under the shadow of the Limb (fig.2), to avoid interference with other components of the machine.

The winding of the flux loops is made of enamelled copper wire sealed in grooves carved out of the fibreglass plates.

The pick-up coils are made of the same copper conductor, wound on a former made of Peek, which houses also the Hall sensors in suitable grooves. In the Collar system the radial and the vertical coils are wound onto a single former, forming a 2 magnetic field components sensor (fig.1b).

During manufacturing and assembly of the coils the actual magnetic section of each probe was calibrated with an accuracy of 0.5% in the range 0.1÷10 kHz, using a precise and stable AC magnetic field source (average value = 0.2 m^2); moreover the magnetic sensitivity of the Hall probes (certified by the manufacturer) was verified (average value = 0.1mV/T)

Dimensional tests were performed after the final assembly of the 7 subsets of the EVP system to assess the maximum deformation of the fibreglass plates. The tests were performed fixing the steel supports to a reference plane and measuring the deformations by means of a comparator with sensitivity of ±0.01mm (fig.3). The results showed that in the worst case the Left Plate of the Outer Limb Probes (1670mm long) can have a maximum bending at the cantilever end of 4.52mm (that corresponds to 0.27% or 0.16°), which is definitely acceptable for the probe measurement point of view.

The manufacture of the EVP system took three months and it was delivered to JET in April 2005, meeting the revised 2004/05 shutdown plan.

3. INSTALLATION ISSUES

The installation of the limb probes took place on two opposite limbs (limbs 3-4 and 8-1), after accurate marking of the bracket position, removing minor interferences (figs. 4 to 7). The attachment of the 6 assemblies to the JET structures was realized by bolting the brackets to the limbs. After having placed the assemblies in the position as from drawings, the actual position with respect to the centre of the machine was determined by means of photogrammetry and other high precision tools [2].

The installation of the collar probe took place in Octant 4, after accurate marking for reaching the required depth (figs. 8,9). The brackets were loosely fixed to Octant 4.

The collar assembly was craned into position, and lowered up to the reaching of the mark and finally bolted to the retaining bracket. The final probe position was adjusted to reach the vertical alignment using an inclinometer.

All the sensors were then electrically tested to ensure that no damage had occurred during the installation process and finally to the data acquisition system.

4. COMMISSIONING OF THE EVP SYSTEM

4.1 DATA ACQUISITION SYSTEM

The magnetic signals are generated by pick-up coils, flux loops and Hall sensors. The signals are passed down to the Data Acquisition System (DAS, Fig. 10) by means of about 100m of twisted pairs contained in multi-core cables. The pick-up coil signals are proportional to the time derivative of the magnetic field, whereas the flux loop signals are proportional to the time derivative of spatial averages of the magnetic field. The DAS performs an analogue integration (for the pick-up coils and flux loops only) and a 16 bit digitisation. The Hall sensor signals do not require integration, but the Hall sensors do require a current supplies, which are provided by DAS. High voltage could accidentally occur between the earth and the sensor. Because of this, the DAS channels have 1.5kV isolation after the ADC.

A number of parameters are required for DAS operation. Calibration coefficients and toroidal field compensation coefficients for the signals are loaded from Central Parameter Database *(level-1)* before the start of each pulse. These values are stored in the JET Pulse Files (JPF).

At the start of each pulse, the DAS measures the drift of each integrated channel. It then turns off the current supply to the Hall sensors for one second, and measures and stores the offset values provided by the Hall sensors. It then reapplies the current to the Hall sensors.

During the pulse, the signals are sampled at 5kHz between SJP (Start JET Pulse, the central timing signal at 25.0 seconds) and EJP (End of JET Pulse) and stored in memory.

At the end of the pulse, the integrated signals are drift compensated. Data collection then proceeds in two phases. First, the drift coefficients and two subsampled sets of the compensated signals are stored in the JPF. The signal names for the subsets use prefixes CQE (100Hz subset) and C2E (500Hz subset). The subsampling allows the data to be collected quickly to avoid any delay in the start of the *chain1* process. Finally, the 5kHz derived signals are collected and stored in the DPF (Delayed Pulse File). The signal names use the prefix CDE for the 5kHz data.

Between pulses, the DAS samples the Hall sensor signals every 30 seconds, taking an average over one second of data at 5kHz. These values are stored in the CODAS (Control & Data Acquisition Systems) continuous recording (cgrt) system.

4.2 SIGNAL ANALYSIS

The consistency and reliability of the whole measurement chain for the new probes (sensors, cabling, integrators and data acquisition equipment) has been assessed during several (standard and customized) dry runs and regular plasma pulses [3]. Two independent approaches were used:

a) using an axisymmetric equilibrium reconstruction code [4], the time history of the expected magnetic field components at the location of the new probes have been calculated. The signals produced by the new measurement probes have been compared with the calculated time histories and a matrix of correlation factors has been determined, which somehow expresses the quality of the agreement of the new signals with the expected values.
b) the signals produced by an homogeneous subset of the new sensors have been directly compared with those produced by another subset homogeneous of sensors located in a corresponding position

   The first method is a general-purpose approach, which has already been used in other cases [4] and is efficient for the automatic identification of any inconsistency such as polarity changes, calibration constant errors, short- or open- circuits due to cabling etc in a large array of magnetic probes.

In the case of the EVP system, the value of each correlation factor obtained has been widely used as an indicator of the existence of major problems, since the method was effective only in pointing out polarity errors, and other major problems, but was not considered sufficient for assessing the consistency of the new measurements.

In fact, due to the various spatial resolutions and different working principles of the sensors, the EVP system is intrinsically sensitive to the toroidal asymmetries and magnetization phenomena, which arise because of the 8 Limbs of the JET Iron Core.

For this reason, a second method based on the specific properties of the EVP system was developed, exploiting the physical symmetries and redundancies in order to debug and validate the measurement signals produced by the EVP system.

As shown in table 1, the results obtained prove that, after the necessary initial debugging of cabling and data acquisition system [2], all the Limb probes measurements are very well-consistent and reliable. The only problem seems to be a HF noise which is apparent on some Hall sensor channels during the plasma phase only. As expected, for the Limb probes, no TF-compensation is necessary.

For the Collar probes, on the other hand, the signals produced by the pick-up coils (referred as ECC4R and ECC4V) and by the Hall sensors (EHC4R and EHC4V) are well reproducible, but not consistent to each other by up to 30%.

Several working hypotheses have been put forward to explain this behaviour, such as swapping of cables, misalignment of sensors and erroneous calibration constants.

Even though some software corrections appear to work in particular conditions, a consistent interpretation of the signals has not been found so far and none of the correction schemes tested has proven to be effective in all the cases considered.

The existence of a ground loop on the Hall sensors, which might produce a reduction of the EHCV signal and an identical increment of the EHCR signal has also been considered without success.

A complete review of the hardware is suggested, in order to find out any anomaly that might be the reason for this behaviour.

CONCLUSIONS

The new set of Ex-Vessel Probes was successfully manufactured and installed in JET. The system was also successfully commissioned up to the production of digitalized signals, included in the experimental data made available to all JET users.

The analysis of the signals both in plasmaless and in plasma discharges has shown that all signals from Limb probes are physically correct and can then be used for JET studies.

On the contrary the signals form the collar probe present some discrepancies with respect to a comparison among Hall sensors and pickup coils as well as to the comparison with model predictions. Work is in progress to understand the reasons for the discrepancies in two different directions. From one side possible cabling mismatch or other hardware inconveniences will be investigated. From the other side a 3D magnetic analysis will be performed for an accurate prediction of the measurements.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the contract of Association between EURATOM/ENEA, was carried out within the framework the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The authors would like to acknowledge A. Barzon, F. Basso, L. Lotto and D. Fasolo for their invaluable commitment in the manufacture, assembly and bench test of the probes performed at Consorzio RFX.

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Comparison #	Subset #1	Subset #2	Probes	Purpose of the comparison:	Result of comparison (difference and comments)
1	Bz Pick-up coils on Limb 3-4	Bz Pick-up coils on Limb 8-1	3-3	local measurements of Bz with 1/8 periodicity (no residual magnetization)	OK (< 2% ± 2mT typical)
2	Bz Hall sensors on Limb 3-4	Bz Hall sensors on Limb 8-1	3-3	local measurements of Bz with 1/8 periodicity (including residual magnetization)	OK (< 2% ± 2mT , but with HF noise on some Hall channels)
3	Bz Flux Loops on Limb 3-4	Bz Flux Loops on Limb 8-1	3-3	integral measurement of Bz with different toroidal spans	OK (the different toroidal span combined with the effect of the stray field from the Limb produces differences of ~ 40%)
4	Bz Pick-up coils on Limb 3-4	Bz Flux Loops on Limb 3-4	3-3	local measurements of Bz vs. integral measurements on 1/8 of the machine	OK: (the local field value is ~20% larger than the (averaged) field value on one Octant)
5	Bz Pick-up coils on Limb 8-1	Bz Flux Loops on Limb 8-1	3-3	local measurements of Bz vs. integral measurements on the thickness of the Limb	OK: (the local field value is ~20% smaller than the (averaged) field value on the Limb)
6	Bz Pick-up coils on Limb 3-4, Bz Pick-up coils on Limb 8-1	Bz Hall sensors on Limb 3-4, Bz Hall sensors on Limb 8-1	6-6	local measurements of Bz with and without residual magnetization	OK: up to 3-4 mT offset due to residual magnetization (HF noise on some Hall channels)
7	Bz Pick-up coil on Collar 4	Bz Hall sensor on Collar 4	1-1	local measurements of Bz with and without residual magnetization	NO (difference ~ 20mT, >20%)
8	Br Pick-up coil on Collar 4	Br Hall sensor on Collar 4	1-1	local measurements of Br with and without residual magnetization	NO (difference ~ 50mT, >30%)

Table. 1: Consistency check of the EVP system, subsets of probes used for comparison and purpose of each comparison.

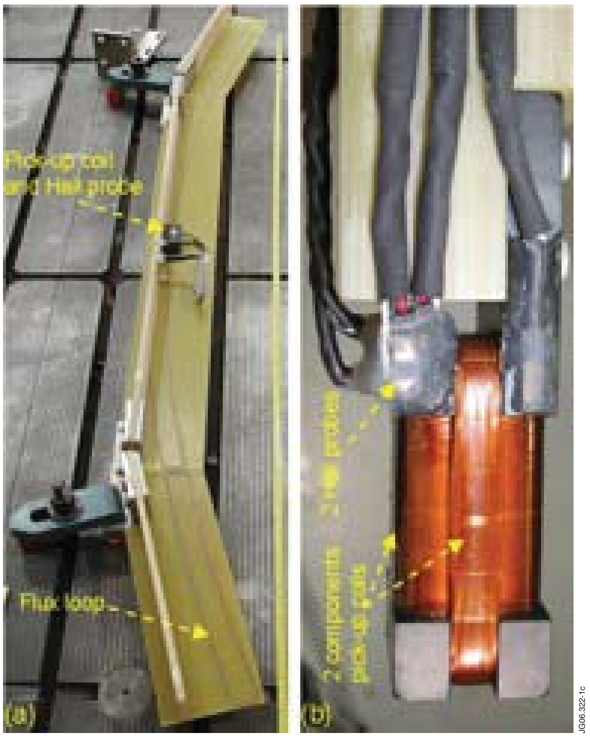

Figure 1: Limb probe subset for limb 3-4 (a); Collar probes (b)

Figure 2: "Reduced" Limb probes for limb 8-1

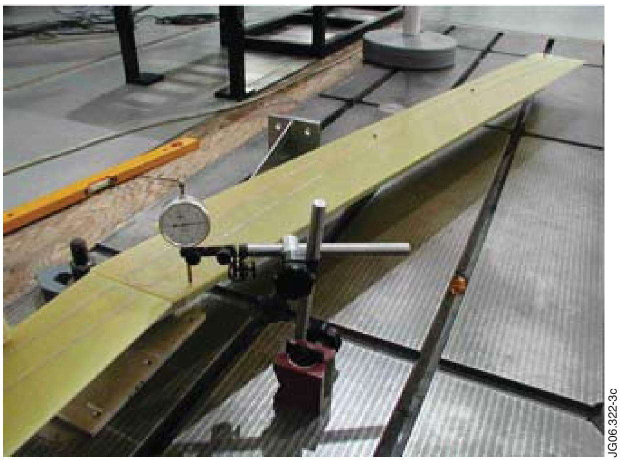

Figure 3: Dimensional tests of the EVP final assembly

Figure 4: Centre probe as installed on limb 3-4

Figure 5: Outer probe being installed on limb 3-4

Figure 6: Centre probe as installed on limb 8-1

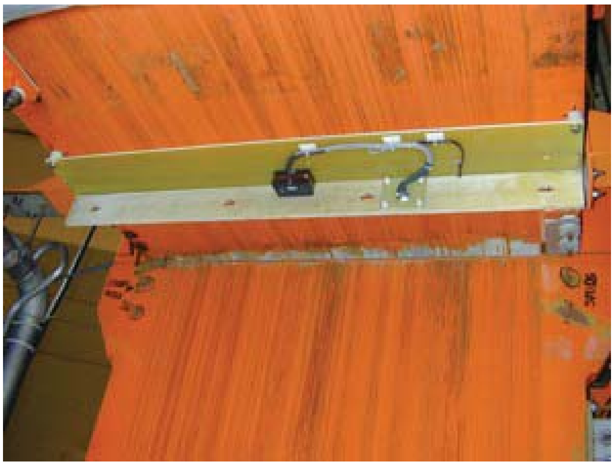

Figure 7: Outer probe as installed on limb 8-1, close to the outer vertical limb

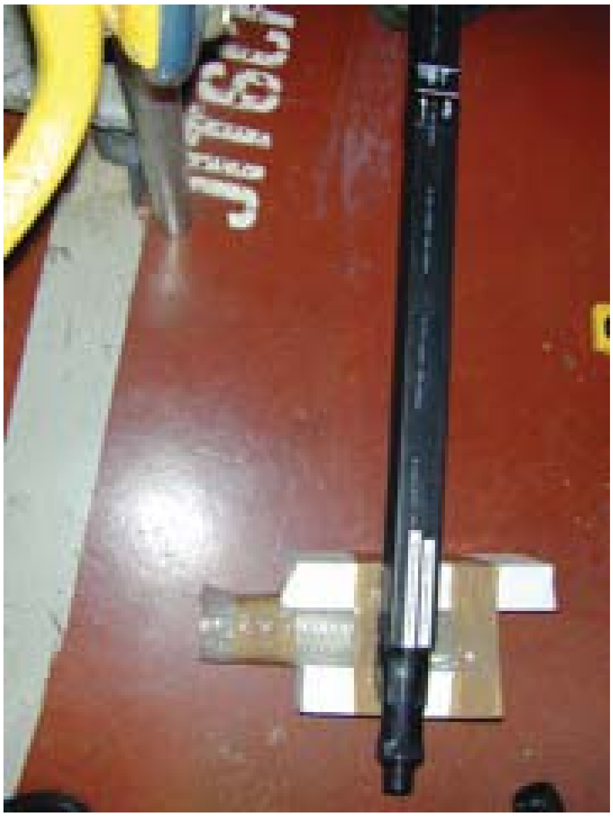

Figure 8: Collar probe as marked before installation

Figure 9: Collar probe as installed in octant 4

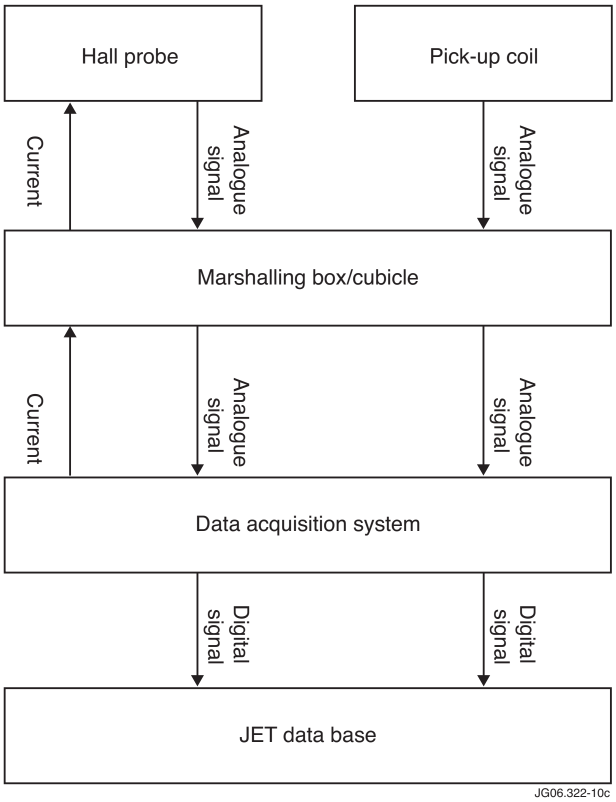

Figure 10: JET KC1E Data Acquisition System