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** See annex of J. Pamela et al, "Overview of JET Results ",*
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ABSTRACT.

A new ex vessel magnetic diagnostics was installed in JET during 2005 shut down, with the objective of: 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 from Hall probes. The latter are of great interest for future ITER-like devices, where long lasting flat top phases are expected, in a high neutron yield and a high temperature environment.

The experimental data achieved during the restart phase were analysed with the aid of simulation codes. Each individual signal was assessed for inclusion in the general JET Diagnostics system. The system is ready for use in the 2006 experimental campaigns.

1. INTRODUCTION

Accurate measurement of the field is an essential aspect of any magnetically confined fusion experiment. The position of the magnetic boundary must be carefully determined and controlled in real time, given the implications of the magnetic topology not only on the plasma performances but also on the safety of the machine. More generally the plasma equilibrium must be known with adequate accuracy for the interpretation of the vast majority of physical phenomena happening inside the plasma. This has become even more crucial in the last years with the development of the so-called advanced scenarios, which rely on the details of the current profile to trigger and control Internal Transport Barriers. From the diagnostic point of view, the magnetic equilibrium is essential for the interpretation of many measurements, in particular the line integrated ones, which require an accurate magnetic topology to be inverted and provide local information.

In JET, even if the magnetic boundary has always been determined and controlled satisfactorily, some reservations about some details of the equilibrium reconstructions are in place due to the effects of the iron core. Therefore, in order to benchmark the iron code models and provide better equilibrium reconstructions, a new set of ex vessel magnetic sensors was installed during the last shutdown. The new system can play an important role for the determination of the potential impact of the iron on the vertical displacement events and therefore the disruptions, an issue of particular relevance in the perspective of ITER. The new set of sensors are also expected to provide useful information about the ripple of the toroidal field, another subject of intense research at the moment to determine the appropriate value for ITER. Moreover, since for the first time pick-up coils and Hall probes were located in the same position, direct comparison between the measurements of these two different measuring techniques will be possible, in an environment very close to the next step. The scope of the project therefore encompasses theoretical, physical, modelling and technological issues.

The new system has been implemented in the framework of an enhancement of the JET Magnetic Diagnostics [1]. According to the engineering design [2], it includes 22 sensors, divided into six *limb* probes and one *collar* probe (*fig*.1).

Each *limb* probe measures the z-component of the field, by means of three different sensors: i) a pickup coil; ii) a Hall sensor; iii) a narrow flux loop.The *collar* probe measures the r- and z-component of the field by means of 2 pickup coils and 2 Hall sensors.

2. ACQUISITION AND HANDLING OF THE SIGNALS

The magnetic signals are generated by pick-up coils, saddle loops and Hall probes. The signals are passed down to the Data Acquisition System (DAS) through about 100m of twisted pairs contained in multi-core cables. The pick-up coil (or saddle loop) signal is proportional to the time derivative of the magnetic field (or the magnetic flux). The DAS performs an analogue integration and 16 bit digitisation. The Hall probe signals do not require integration, but the Hall probe does require a current supply, which is received from the DAS. The DAS channels have 1.5kV isolation after the ADC, to avoid accidental high voltage versus earth.

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. 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 probes for one second, and measures and stores any offset present. It then reapplies the current to the Hall probes. At the end of the pulse, the integrated signals are drift compensated. Between pulses, the DAS samples the Hall probes every 30 seconds, taking an average over one second of data at 5kHz.

3. ELECTROMAGNETIC INTERPRETATION OF THEMEASUREMENTS

The functional commissioning of the new system aims at including the signals from the probes in the general JET diagnostics system. To this purpose, the signals from each individual sensor were cross-checked, also with the aid of simulation codes. This activity was done analysing several test runs during the restart phase of the 2006 experimental campaigns. In particular the following issues were investigated and assessed: i) residual magnetization of the iron core; ii) drift of the measured signals; iii) lack of uniformity of vertical magnetic field.

For the functional commissioning of the Limb probes, a comparison between the three different kinds of sensors was performed using a number of typical pulses. As pick-up coils and Hall sensors are located in the same position, they give the same measurement, apart from initial magnetization and drift/offsets (*fig* 4).

Moreover, since the JET machine has a 1/8 symmetry, also the signals from local sensors located in corresponding positions on the limbs 3−4 and 8−1 are expected to give measurements in good agreement (*fig* 4−5). On the other hand, the flux loops signals are expected to be slightly different, because they measure the field averaged in toroidal direction. This is confirmed by the sensors located on Limb 3−4 (*fig* 4), where the difference between local field (pick-up and Hall) and average field (flux) measurements increases with the radius. This is consistent with the fact that near the centre of the machine the air gaps between the horizontal iron limbs are small, and therefore the field configuration is almost axisymmetric. In the case of Limb 8−1 (where the flux loops span over the iron limb only, see *fig*.1) the average field is larger than the local field value at the centre of the limb. This indicates that a flux concentration takes place on the edge of the iron limbs, as qualitatively shown in *fig*.6.

Regarding the Hall sensors (see *fig* 4–5) the noise is generally larger than for the other sensors and is even larger in the outer part of the Limb, especially during the plasma phase. The noise level for Hall sensors is approximately 50μV (mainly due to the cabling) and might be reduced using a low-pass filter. The initial and final "flat" parts of the Hall signal are the pre-pulse and post-pulse iron residual magnetic field; the difference is the variation of the iron residual magnetic field due to the pulse, which appears to be ~3mT.

This is confirmed by the comparison with the pick-up coil signals on the same location, which also follow the same waveform with a constant offset. The fact that the offset between the two measurements is constant proves that the drift of the pick-up coil integrators is negligible and that the difference between the initial and final values of the magnetic field is real and not negligible.

However, at the beginning of the following pulse the initial value measured by the Hall probe appears to be close to the initial value of the previous pulse, and not close to the final value as expected. This means that some other variation of the magnetization takes place outside the data acquisition window. The difference between the flux loop and the pick-up is variable due to the fact that the flux loop is little affected by the iron core and therefore the final residual magnetic field measured by this sensor is negligible.

For the Collar probe, the signals produced by the pick-up coils and by the Hall sensors are well reproducible but not consistent to each other. It has been noticed that, in the zero-TF-current dry runs, the signal difference ($Bz_{\text{pick up}} - Bz_{\text{Hall}}$) is consistently equal and opposite to the difference ($Br_{\text{pick up}} - Br_{\text{Hall}}$). This might indicate the existence of a ground loop on the Hall probes, which might produce a reduction of the Bz_{Hall} signal and an identical increment of the Br_{Hall} signal. An empirical software correction scheme, based on this evidence, seemed to improve the situation in pulses with non-zero TF current as well. This gives further strength the hint regarding the ground loop. A complete review of the cabling and ground connections is suggested, in order to find out any anomaly that might be the reason for this behaviour, such as ground loops and undesired connections between cables, particularly for the Hall probe cables. A verification that the A/D converters are operating in differential mode is also advisable.

CONCLUSIONS

The analysis carried out during the JET restart runs has shown that the new ex-vessel probes in JET can effectively be used for the measurement of the residual magnetic field and of non-axisymmetric effects due to the iron core.

A good agreement has been observed when comparing Hall signals and pickup signals from the six limb probes.

The same comparison made for the collar probe is not satisfactory. Work is in progress to explain the discrepancy. Possible reasons being investigated, are swapping of cables, misalignment of sensors and erroneous calibration constants. All working hypotheses will be used to address detailed checks on the machine, which will be carried out during the next shut down, planned for autumn 2006. Hall sensors are proven to provide signals which can be satisfactorily used in addition or in alternative to the traditional pickup coils.

Therefore probes based on Hall effect appear to be functionally well suited for extensive use in tokamak magnetic diagnostics. This is indeed a necessary condition for use in ITER-like devices where, in addition, the capability to withstand high neutron fluxes has to be proven.

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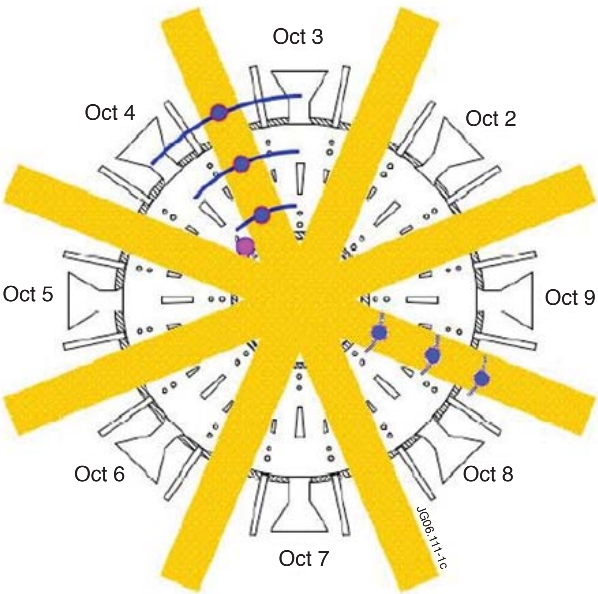

Figure 1: Toroidal view of the JET machine, showing the Ex-Vessel magnetic diagnostic system. The location of the 6 limb probes and the collar probe.

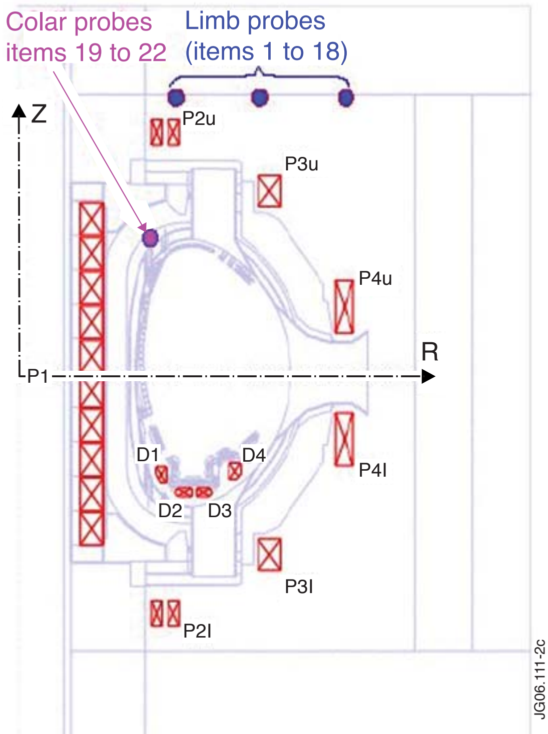

Figure 2: Simplified cross-section of the JET machine, the location of the Collar probe and the three Limb probes is indicated.

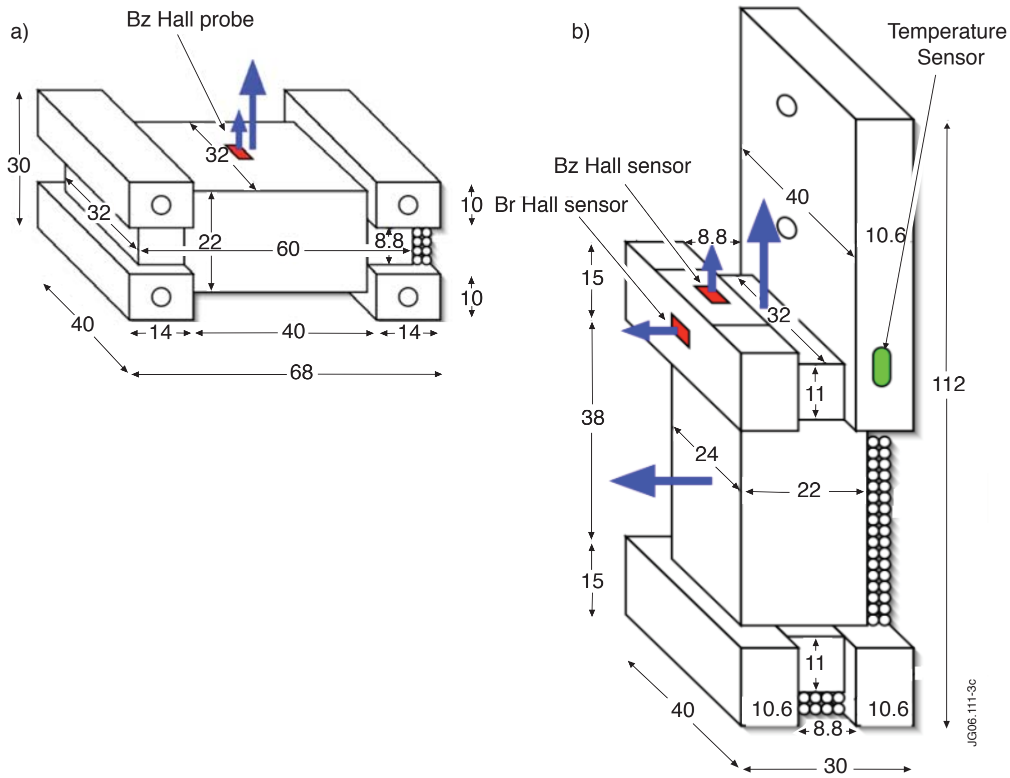

Figure 3(a): Insulating former for the B_z pick-up coil and Hall sensor for the Limb probes. b) Collar probe: insulating former for the B_r and B_z pick-up coils and Hall sensors, as well as the temperature sensor.

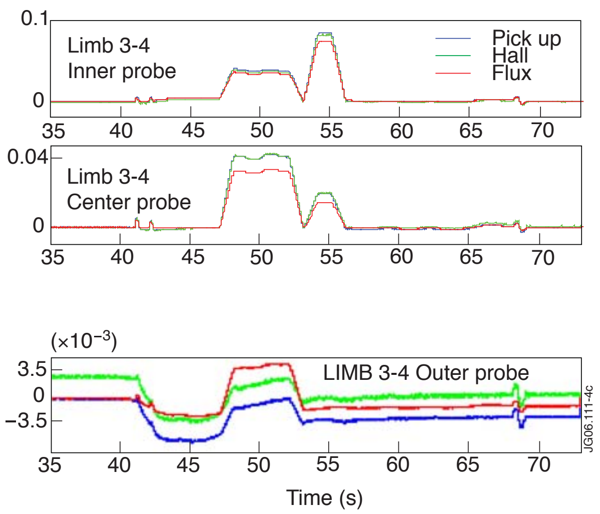

Figure 4: Comparison between experimental signals produced by Limb 3-4 in the same poloidal position for inner, center and outer probe. Standard dry run Pulse No: 65737 considered. The Hall probe signals are filtered.

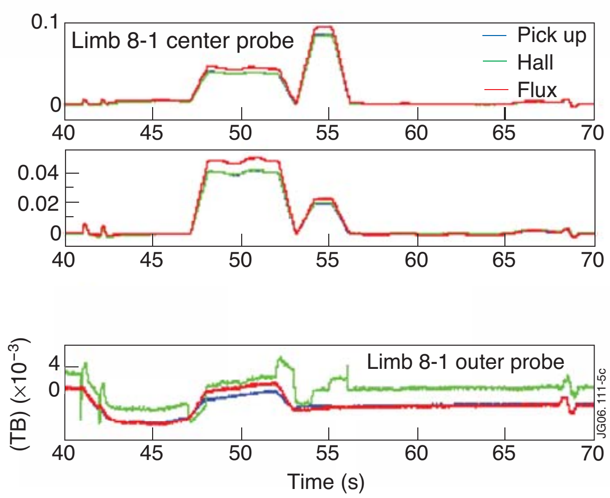

Figure 5: Comparison between experimental signals produced by Limb 8-1 in the same poloidal position for inner, center and outer probe. Standard dry run Pulse No: 65737 considered. The Hall probe signals are filtered.

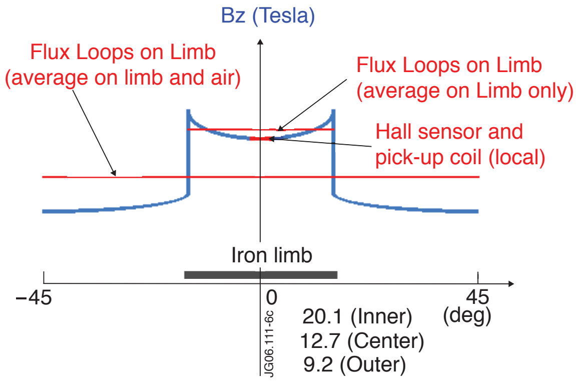

Figure 6: Qualitative distribution of the vertical component of the magnetic field B_z as a function of the toroidal coordinate and corresponding measurements of the pick-up coils and flux loops.