EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(04)06-06

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
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Preprint of Paper to be submitted for publication in Proceedings of the
23rd SOFT Conference,
(Venice, Italy 20-24 September 2004)

ABSTRACT

The assessment of JET magnetics has been carried out using a statistical technique on a large set of sensor data. The results highlight that improved accuracy in the magnetic field reconstruction can be obtained by making an efficient use of the information brought in by the available sensors, in conjunction with the enhanced set of new magnetics. Moreover, the better estimation of the magnetic configuration provides an improved capability to locate the plasma boundary and determine its shape.

INTRODUCTION

During the 2004 shutdown, a new set of magnetic sensors will be installed in JET, designed to upgrade the existing diagnostic system.

As far as the reconstruction capability is involved, it has been fundamental for the sensor definition to understand beforehand how much the magnetic enhancement will -in principle- increase the measurability of the plasma shape, and therefore extend the JET operating space. For this reason, the aim of the magnetic analyses was on the one hand to assess both the present and the newly designed sensors, quantifying noise and systematic errors; on the other, to compare the reconstruction capabilities, using different sets of magnetic sensors.

In the case of JET, this second issue involves the reconstruction of the vacuum field using only magnetic information, mimicking what is done in real time by the XLOC code, and the calculation of the plasma boundary to first-wall distances at the equilibrium.

1. METHODOLOGY

In order to discern between an increased redundancy in the measure and new information brought in by the sensors, a model based statistical analysis was carried out exploiting the correlation function among the magnetic measurements.

In more detail, it was chosen to study the statistical correlation between the set of measurements provided by the real sensors (installed or to be installed in the machine) and a set of measurements from an optimal observer made of densely spaced virtual sensors located as close as possible to the plasma. This is to say that the former stand for the actual measurement capability of the machine, while the latter represent its ideal measurability (see Figure 1).

Two assumptions are made, of considering negligible the both the 3D and the transient effects. Moreover, it is also assumed that for a plasma in equilibrium, the description of the magnetic configuration provided by the observer accounts for the plasma boundary location and shape, and the indistinguishability between two magnetic configurations is reflected in the same boundary location for the corresponding plasmas. As a consequence, the possibility of studying the magnetic vacuum field at the edge of the plasma region to infer the capability of the system to correctly locate the boundary is well posed.

In this framework, two independent analyses were performed, using both experimental and simulated databases spanning the whole variety of already achievable plasmas and the designed new JET-EP configurations for 2005. Thus far, the diversity of the adopted tools and of the databases should corroborate the results of the two studies and provide a crossvalidation between them.

A first study is based on the CREATE-L/I equilibrium codes [1,2] and NAPS magnetostatic code [3], which allowed the creation of an analytical database of around 2000 simulated magnetic configurations. At the same time 38 different plasma shots generated an experimental database of more than 500 magnetic configurations, which were used to assess the current state of the magnetic system. With these data, a statistical analysis was performed, involving the comparison among different sets of old and new magnetic diagnostics. In particular, each real or virtual magnetic measurement x_i is reconstructed from the others (in the real set) according to the following relation:

$$\hat{x}_i = \sum_{\substack{k=1 \\ k \neq i}}^{N_{real}} c_{ik} x_k \text{ , with } \{c_{ik}\} \text{ minimizing } \|\hat{x}_i - x_i\|,$$

where x_i is the reconstructed measurement, be it real or virtual, and the x_k are taken from the set of the real signals. The $\{c_{ik}\}$ matrix is obtained via least square fit, and corresponds to the linear combination of the most significant (retaining 99% information) principal components. A second analysis, similar in principle, but substantially different in both the data and the methodology, was accomplished starting from a wide variety of MAXFEA equilibria [4], created in simulations using a highly refined mesh. The obtained database, comprising around 500 variations of 72 equilibria derived from the list of the approved JET scenarios and from particular shots used to benchmark the reconstruction capabilities of different magnetic or equilibrium codes at JET, has been extended with the configurations, designed for the new divertor structure with the PROTEUS code [5].

Again, also in this second study, the comparison among different sets of sensors is achieved. In this regards, it is assumed that the capability of the real sensors to carry the information on the magnetic configuration in the region of interest is measured by their correlation with the ideal observer.

The correlation between the two sets of measurements is obtained by modelling a linear relation between the magnetic field on the virtual sensors and the information brought by the real measurements, being they both the magnetic signals and some shaping coil currents. In this sense, the magnetic information around the boundary can be directly related to the currents of the poloidal circuits, and to the already available or the designed sensors. In the attempt to capture an overall view over the reconstruction capability, being **R** the matrix of real measurements and **V** the set of the virtual ones, listing the various equilibria as columns, it follows:

$$\mathbf{V} = \mathbf{K} \cdot \mathbf{R} \text{ ,}$$

which simply is a matrix form of (1) and **K** is given the name of correlation matrix. Besides, the study of the **K** matrix appears from these relations equivalent to the analysis of a transformation matrix between the space of the real measurements and that of the virtual ones. In all cases, opportune normalisations are necessary to equalise the data range and to introduce a numerical regularisation over the datasets.

2. RESULTS AND DISCUSSION

Starting from the assumption that each sensor carries a certain level of redundancy, it follows that its measurements can be reconstructed from the remaining signals with a good accuracy. If this is not the case, either the sensor is malfunctioning or its measurement is misinterpreted. Following this approach, the assessment of present sensors is possible and the results of the analysis are exemplified in Figure 2: when the predicted measurement and the actual sensor signal do not match, the sensor is flagged as not reliable and is not used in the magnetic reconstruction algorithms.

Furthermore,the reconstruction in real time of the first three current moments provides fundamental information on the plasma current, and the current centroid displacement [6]. Therefore, to quantify the increase in the plasma measurability introduced by the Magnetics Enhancement, the identification of these quantities starting from the XLOC set of sensors and an extended version derived from it using also new measurements were performed and cross checked among different databases. The results show that the already good accuracy characterising the present XLOC configuration can be further improved by the insertion of the new coils, in particular those in the divertor area and the outer poloidal limiter.

Moving on to the analysis of the correlation matrix **K**, the element $k_{i,j}$ of **K** gives the indication of how much the j^{th} real signal contributes to the reconstruction of the field in the ith virtual location, and by analysing **K** either by columns or by lines, the sensitivity of respectively virtual or real measurements is determined. For example, it can be appreciated from Figure 3 how the contributions of the real signals is reduced by sharing the reconstruction task among a larger amount of coils (as expected), but it is also noteworthy how the new sensors present a more uniform pattern. Broadly speaking,this results in an improved robustness and noise rejection as the whole system is less dependent on single measurements. The comparison among the sensors used by the different sets shows that the insertion of the new coils effectively support the existing pickups and saddle loops all around the vessel but in the inner board, where their influence for the reconstruction is likely to be limited.

A further step has been taken in addressing the noise propagation issue by introducing a model of the noise on the magnetic sensors.

The error is estimated with a standard deviation of about 1.5% but not less than a predetermined threshold value, the latter condition standing only for the already existing sensors. The previous considerations are still valid, obtaining a large reduction of the reconstruction noise everywhere around the plasma, with the exception of the inner part of the machine. At the same time, the use of all the available magnetics can, on the theoretical ground, improve the reconstruction capability. This last remark is due to the fact that, this analysis was carried out studying the statistical correlation between sets of measurements, considering the total amount of available information and with no concern about the efficiency of its use.

For this reason, the analysis of the boundary shape modification was approached also using the code used for the real time reconstruction. One plasma configuration (JET Pulse No 49935, at t=24 – Standard Fat Configuration) was chosen as a test-bed to investigate how the reconstruction is affected when changing the sensor set and validate the possibility of using the new magnetics to improve the accuracy with a certain level of confidence. Firstly, the new sensors were reconstructed from the JET pulse file and added to the sensor original magnetic telegram packet to simulate as much as possible the operation conditions. Then, the magnetic signals have been corrupted with the noise and fed back to XLOC for the boundary reconstruction and sensitivity analysis. The adaptation of the code to accommodate the new sensor input proceeded by weighting the signals from the poloidal array and the divertor coils at 50%, while the top coils are considered in full. This action must be undertaken in order to keep the balance among the five regions where XLOC operates the best fit, and may represent a major source of difficulty when modifying the code configuration, thus preventing a more exhaustive study on several plasma configurations.

The results (Figure 5), show an enhanced noise rejection for all the shape parameters in the divertor region, both as regards the X-point location (RXPT, ZXPT) and the strike values (RRSO, RZSO, RRSI, RZSI). Similar conclusions can be drawn even for the radial gap ROG and for the top part of the machine (TOG4, TOG5 in particular). When plotting the gap error results together with the correlation errors derived reported in Figure 4, these results agree and prove the consistency of the used methods (Figure 6).

CONCLUSION

First of all, these analyses show that the assessment of JET magnetics is possible.

Secondly, and more importantly, their results are substantially in agreement and seem to prove that an enhanced reconstruction can be obtained, with a noise amplitude reduction in localised parts of the boundary (up to 50% on the outboard).

Finally, the methodology sets also the guidelines for the development of software tools useful for the experimental commissioning and measurement validation of the sensors. In this respect, a new set of codes are currently being developed.

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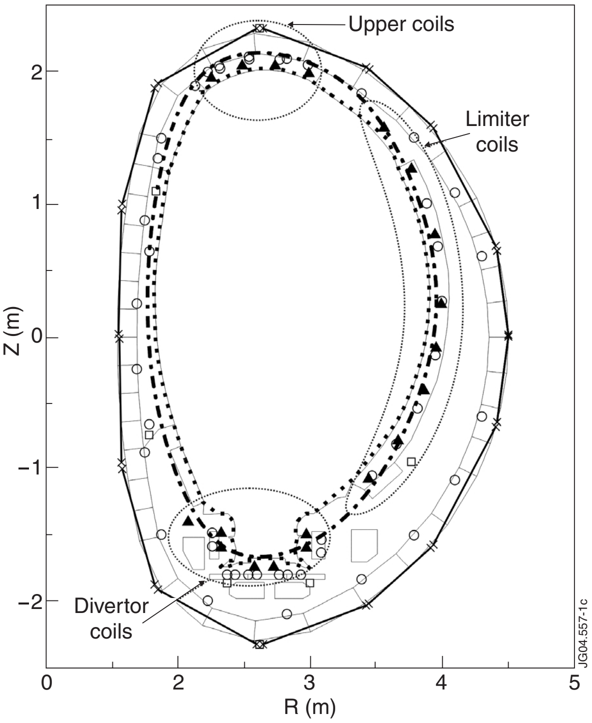

Figure 1: Location of the real and virtual sensors in the magnetic analyses. Existing (open symbols) and designed (solid symbols) sensors. The virtual sensors are in one case placed on the first wall, in the other located on the elliptic dash-dotted curve.

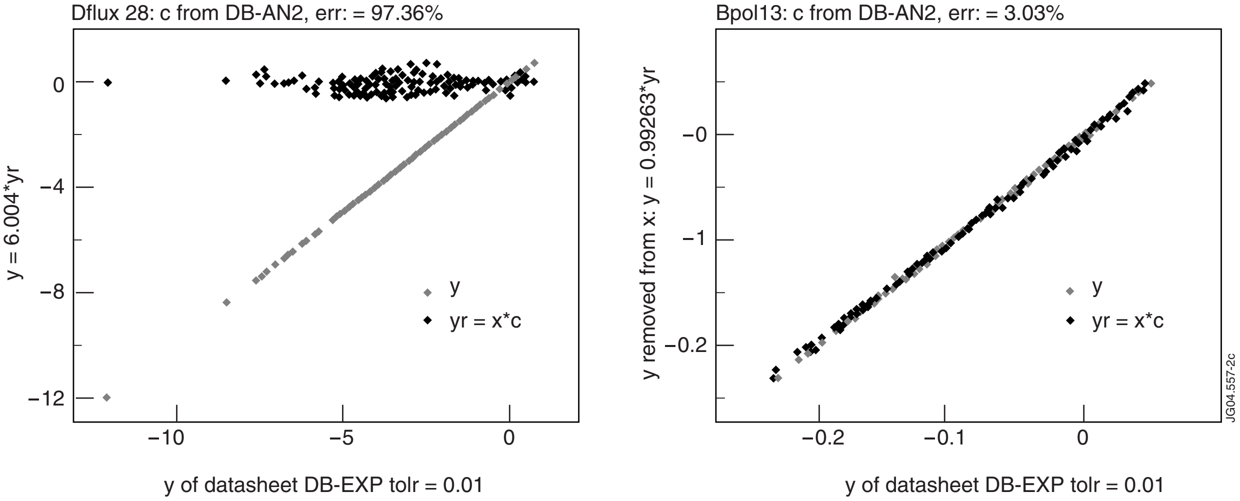

Figure 2: Example of broken/misinterpreted (left) and working (right) sensor.

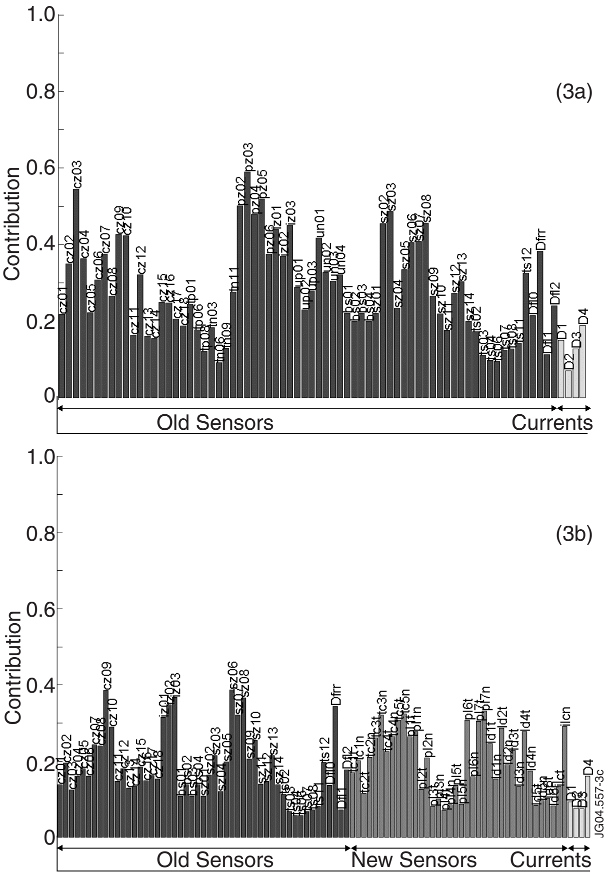

Figure 3: Contribution of the real sensors to the reconstruction of the virtual measurements (normalised with respect to the number of employed sensors).

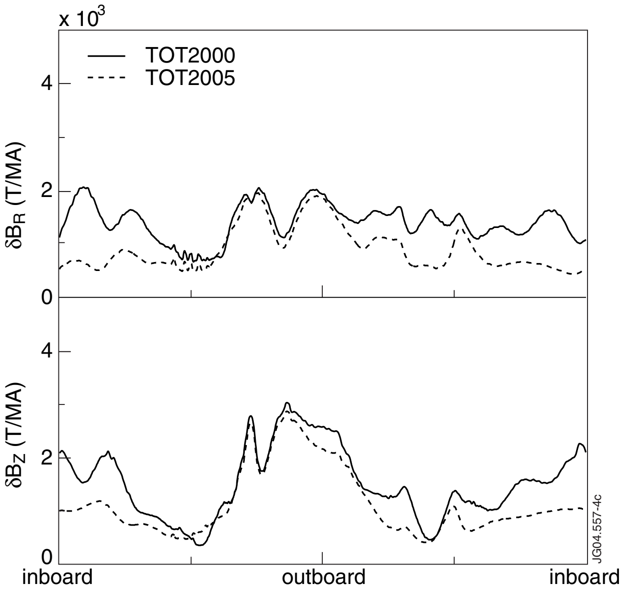

Figure 4: Error propagation on the virtual measurements. The maximum error on the ideal observer has been computed together with its relative error bar, in proportion to the plasma current. TOT2000 and TOT2005 indicate the existing and the augmented sets of sensors.

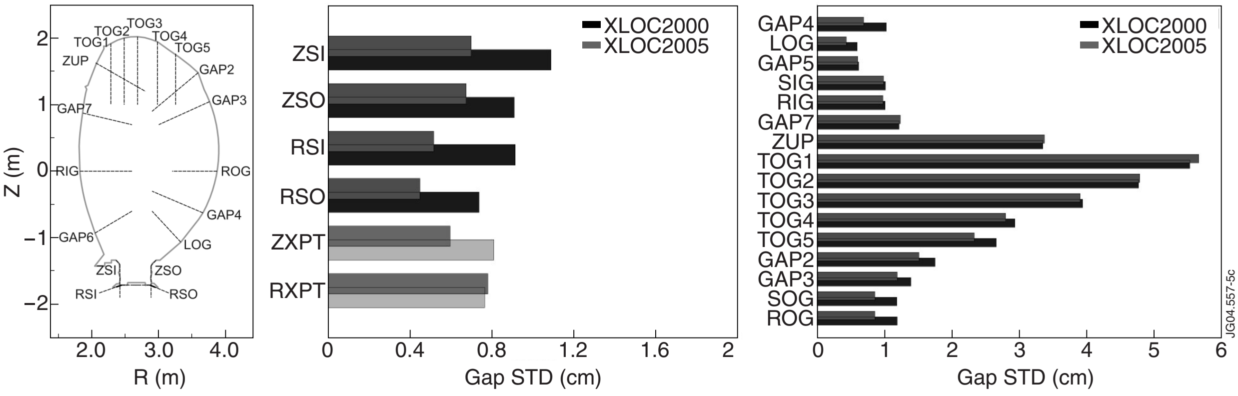

Figure 5: Gap location map (left) and reconstruction error on shape: divertor region (centre) and first wall (right). The position of the X-point is also indicated (RXPT,ZXPT).

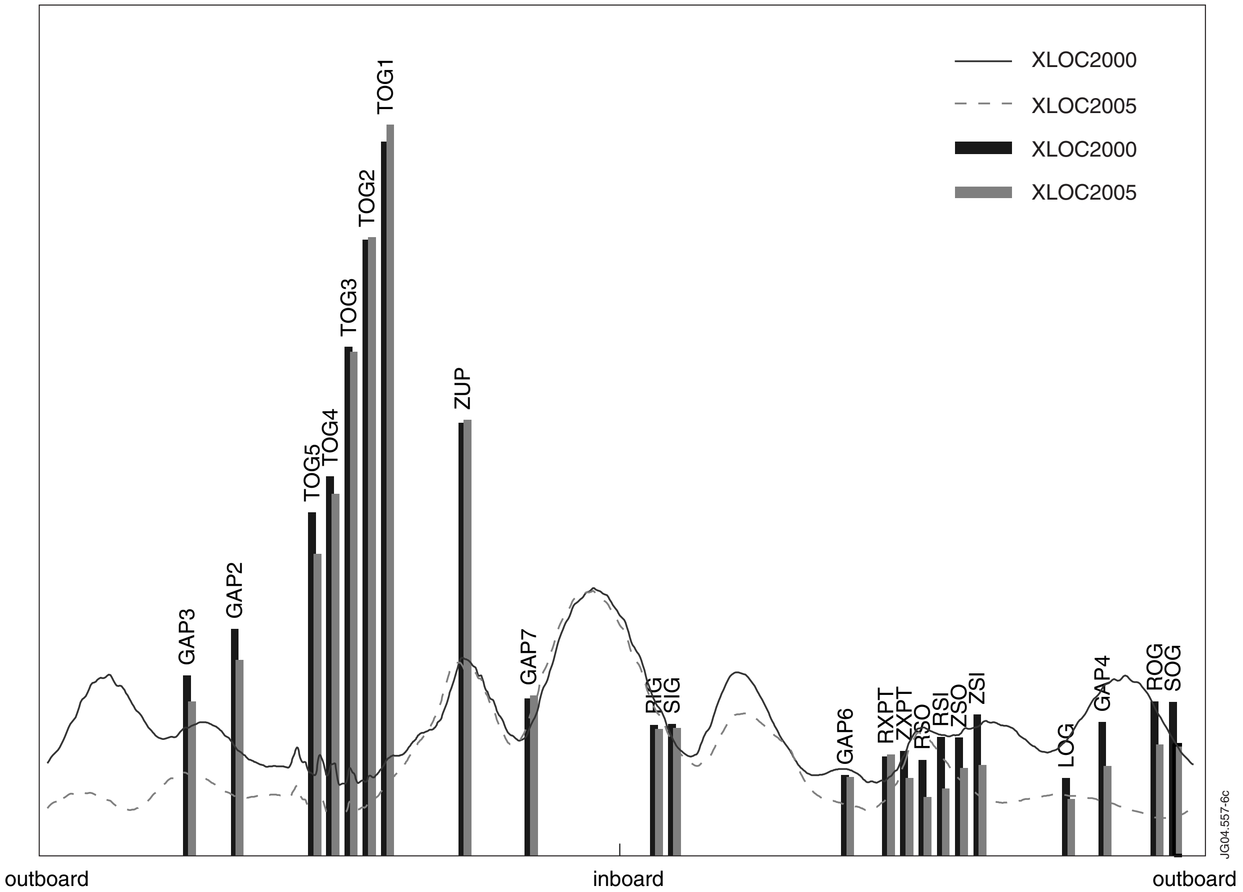

Figure 6: Statistical correlation error (only the radial component is shown) and error on gaps.