# Equilibrium Reconstruction at JET

W Zwingmann, J J Ellis, J Lingertat, D O'Brien.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.

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W. Zwingmann, J.J. Ellis, J. Lingertat, D.O'Brien
JET Joint Undertaking, Abingdon, U.K.

## 1. Introduction

The physical processes at the plasma edge have been recognised to be essential for determining the performance of tokamak fusion devices, especially for the H-mode regime. Since many of the edge diagnostics are sensitive to errors in the location of the plasma boundary, the accurate determination of the magnetic field configuration close to the boundary has become increasingly important. Plasma boundary reconstruction using only external magnetic data is an inherently ill-conditioned problem[1]. In the past, scepticism has been expressed concerning the use of function expansions in the determination of the plasma boundary[2]. We report here on two fast methods that have been developed at JET for boundary reconstruction which make use of novel expansion techniques providing an accurate and stable reconstruction.

## 2. Numerical methods

The local expansion method XLOC was introduced at JET to give a fast and accurate determination of the plasma boundary in the vicinity of an X-point. It has been extended to cover the whole plasma boundary. The vessel is subdivided into 5 sections, the flux function is expressed by

$$\Psi(R,Z) = \sum_{\substack{i=0,j=0 \\ i+j\le 6}}^{6} a_{ij}(R^2 - R_0^2)^i (Z - Z_0)^j \qquad (1)$$

in each section. The coefficients $a_{ij}$ are determined by imposing the vacuum equation for $\Psi$ and fitting to the data by minimising

$$\chi_M = \frac{1}{2}\sum_n (L_n\{\Psi\} - M_n)^2 \qquad (2)$$

where $M_n$ denotes the measured data value, and $L_n\{\Psi\}$ the corresponding computed value. In addition, the five expansions are constrained to match at chosen tie points around the vessel. Thus, the procedure to evaluate $\Psi$ is reduced to a matrix inversion. The plasma boundary is found in the usual way by finding the minimum flux value at the limiter points as well as at any separatrices if they exist inside the vessel. Any X-points of the poloidal field are obtained by a Newton procedure to solve $\nabla\Psi = 0$. Details of the method are found in [3].

FBC(fast boundary code) has been developed to provide accurate smooth boundary values for the finite domain IDENT code. It is based on a global expansion with Legendre and trigonometric functions

The accuracy of the boundary code has given confidence in the execution and interpretation of experiments where the position of the plasma boundary has been a parameter under investigation. The results of XLOC showed that most of the H-mode discharges before 1990 were obtained with the X-point outside the vessel, with the plasma limiting on the protection tiles. Analysis of JET data for 1991/1992 shows that the enhancement of confinement time over the ITER89-P scaling law [5] is not directly dependent on the position of the X-point relative to the vessel wall. This enhancement factor is, however, strongly dependent on the distance at the outer midplane between the separatrix and the innermost flux surface touching the vessel components (the plasma boundary if the X-point is outside the vessel).

## 4. Upgrade for the pumped divertor

During the pumped divertor phase of JET the new divertor coils will be situated close to the plasma boundary. Previous analysis has shown that this may lead to inaccuracies in the reconstruction, so that additional magnetic pick-up coils and flux loops have been installed. The optimal number and location was determined by using the full equilibrium code EFITJ[6], using equilibria generated by PROTEUS as an input. The optimum set is given by figure 4 and is determined by using the distance between the plasma boundary and reconstructed plasma boundary as a figure of merit.

The boundary codes have been adapted for this phase, figure 4 shows a comparison of the EFIT boundary with XLOC and FBC, with a typical deviation of 2 cm.

## 5. Conclusions

Two fast methods for the reconstruction of the plasma boundary have been developed at JET, they use different methods and are therefore complimentary. Both codes are continuously benchmarked against each other, full equilibrium codes and independent diagnostic data. The boundary codes are shown to give an accuracy of the order of 1 cm. A typical reconstruction of XLOC takes place in a millisecond on IBM 3090 or digital signal processors, and will provide accurate real time boundary data for feedback control of the plasma shape.


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$$\Psi = \frac{\mathrm{sh}\,\xi}{\sqrt{\mathrm{ch}\,\xi - \cos\eta}} \sum_{m=0}^{M} (P^1_{m-1/2}(\mathrm{ch}\,\xi)(A_m \cos\eta + B_m \sin\eta) + Q^1_{m-1/2}(\mathrm{ch}\,\xi)(C_m \cos\eta + D_m \sin\eta))$$

$$\text{with } R = R_0\,\mathrm{sh}\,\xi / \sqrt{\mathrm{ch}\,\xi - \cos\eta}, \quad Z = R_0 \sin\eta / \sqrt{\mathrm{ch}\,\xi - \cos\eta} + Z_0. \tag{3}$$

The coefficients are fitted to measurements via a cost function, with a least squares term given by (2) plus a smoothing term with weights $w_b$ and $w_i$

$$\chi = \chi_M + w_b \int_{\Gamma_b} \left(\frac{\partial^2 \Psi}{\partial s^2}\right)^2 ds + w_i \int_{\Gamma_i} \left(\frac{\partial^2 \Psi}{\partial s^2}\right)^2 ds, \tag{4}$$

where $\Gamma_b$ is the vessel boundary, $\Gamma_i$ an appropriately chosen inner surface. The ill-posedness of the problem is therefore removed by the smoothing term.

Figure 1 presents a comparison between the numerically generated boundaries of the full equilibrium code IDENTC and the boundary codes XLOC and FBC. There is good agreement, with an error being typically less than 2 cm for the whole boundary except in the vicinity of the X-points, where the boundary codes are more precise. This result is typical and was obtained for a range of shots. XLOC is in routine use at JET since 1990 and works well for arbitrary plasma configuration. Figure 2 shows a comparison between XLOC and IDENTC, using data for the 1990-1992 JET experimental campaign.

### 3. Experimental results

The standard interpretation of the divertor diagnostics uses the magnetic configuration found by XLOC. Some discharges allow for comparison with raw data from independent diagnostics, such as the Langmuir probes, CCD camera and Hα signal.

If the X-point of a discharge is swept across the target tiles so that the strike points of the separatrix cross a Langmuir probe, changes in the probe characteristics will result. Although the physics of the transition region between scrape-off layer and private flux region is not yet fully understood, it is reasonable to assume that the transition takes place where rapid changes in the Langmuir characteristics occur. Figure 3 shows the floating potential of the probe. There is a clear and distinct change of the floating potential within a narrow region, when the strike point crosses the probe.

For divertor discharges, the CCD camera recording of the light emitted from the target plates shows well localised hot spots. They should coincide with the maximum of the parallel heat flux. Recent analytical work on the magnetic flux geometry allows for determining the hot spot position as a function of the X-point position[4]. They are not necessarily the strike points of the separatrix. The position of the hot spots agrees with the position derived from XLOC data within 1 cm.

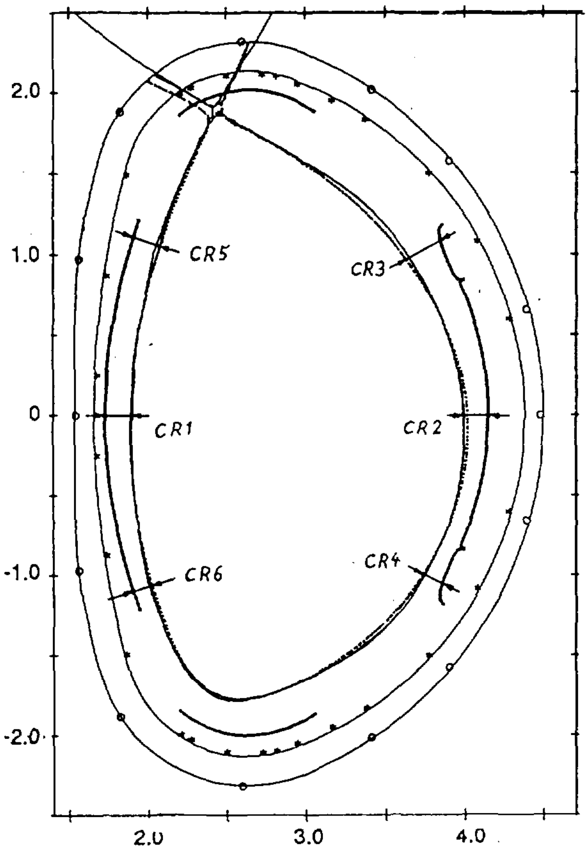


*Fig. 1. Plasma boundary, determined by XLOC and FBC, compared with IDENTC (dashed curve). Circles give the location of flux probes, asterisks of magnetic field probes. CR1-CR6 are distances to vessel components.*

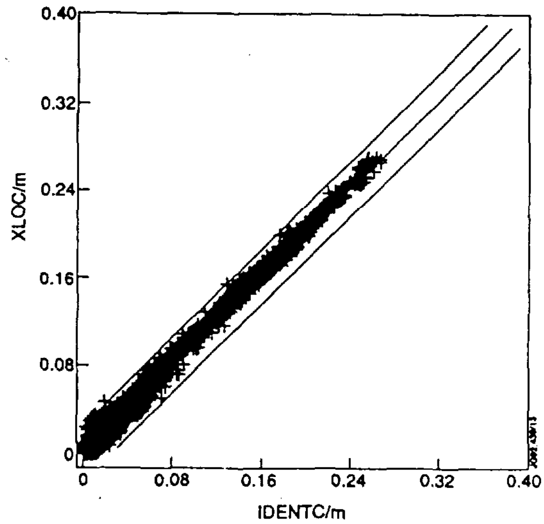


*Fig. 2. Distance plasma - RF antenna, comparison of XLOC with IDENTC for 1990-1992 discharges.*

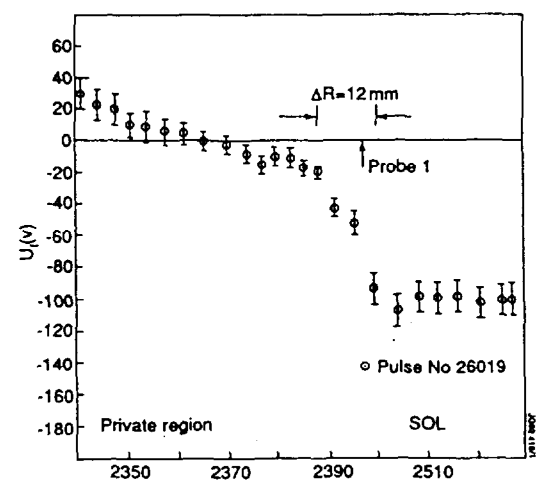


*Fig. 3. Floating potential of Langmuir probe, plotted as a function of the inner strike point calculated by XLOC for shot 26019.*

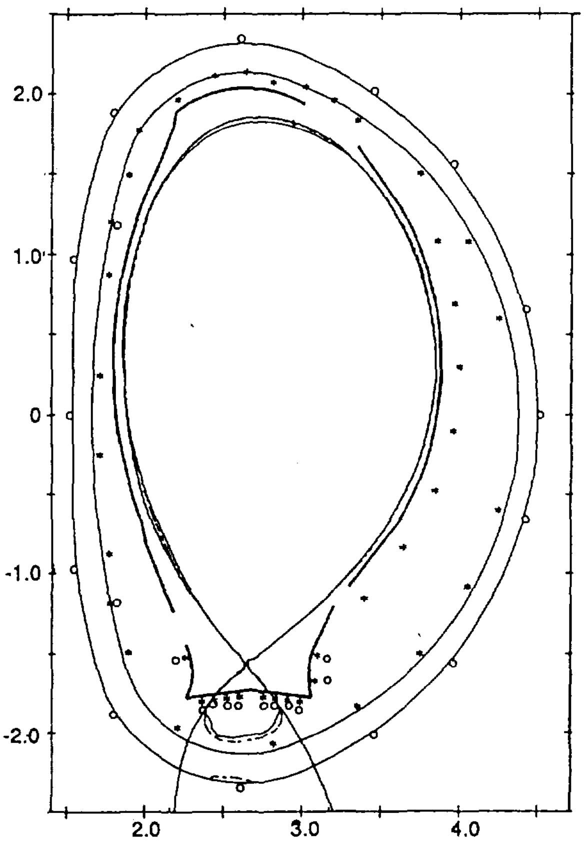


*Fig. 4. Upgraded magnetic diagnostics for the pumped divertor. XLOC and FBC boundary compared with PROTEUS (dashed curve) for a 5 MA plasma.*