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F.Sartori, A.Cenedese, F.Milani and JET EFDA Contributors

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F.Sartori<sup>2</sup>, A.Cenedese<sup>1</sup>, F.Milani<sup>2</sup> and JET EFDA Contributors\*

<sup>1</sup>*Consorzio RFX, Ass. Euratom-ENEA sulla Fusione, Cso Stati Uniti 4, I-35127 Padova, Italy*

<sup>2</sup>*Euratom/UKAEA Fusion Association., Culham Science Centre, Abingdon, Oxon OX14 3DB, UK*

\**See annex of J. Pamela et al, 'Overview of Recent JET Results and Future Perspectives',  
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## ABSTRACT.

XLOC, a magnetic flux reconstruction code, with more than 8 years of successful application in the JET plasma control feedback, has been rewritten as an object oriented modular code. This paper will describe the state of this code and show how it has been applied to real-time control and measurement applications.

## 1. INTRODUCTION

The plasma boundary reconstruction code XLOC (Milani [1], O'Brien [2]) has been used routinely in JET since 1994 (Puppini [3], Sartori [4]) as a component of the Plasma Position and Current Controller. During this period the code has been evolving and maturing as a very flexible software component and its real time applications have multiplied, especially because of the needs of the real time project, implemented via the Real-Time Data Network (RTDN, Felton [5]). In a tokamak the measurement of the plasma boundary gives very important information both because of the need to control the plasma-wall interactions and because of the relation between shape and fusion performance. Since the plasma boundary is determined by the magnetic field distribution, the JET device was instrumented with many pickup coils, saddle loops and full flux loops. These probes measure the field produced by the combination of the plasma current, the poloidal shaping currents, the induced currents in the passive structures and the magnetisation of the iron transformer core. While equilibrium codes fit the plasma equilibrium equation to this data and the known shaping currents, XLOC simply extrapolates the flux in the vacuum by fitting the magnetic measurements to a much simpler model derived from the Grad-Shafranov equation (Freidberg [6]):

$$\Delta^* \psi = \begin{cases} -2\pi\mu_0 Rj & \text{inside the plasma} \\ 0 & \text{inside the vacuum (XLOC)} \end{cases}$$

XLOC then uses the extrapolated magnetic field to reconstruct the plasma shape. (Fig.1)

## 2. XLOC FLUX EXTRAPOLATION

### 2.1 FLUX MAP

In the toroidal geometry  $(R, Z, \phi)$  of a tokamak, given the assumption of axisymmetry, it is very convenient to express the magnetic field in terms of the function  $\psi$ , defined such as  $B_z = \frac{1}{R} \frac{\partial \psi}{\partial R}$ ,  $B_R = -\frac{1}{R} \frac{\partial \psi}{\partial Z}$ ,  $B_\phi = \frac{\partial \psi}{\partial \phi}$ . This function has the obvious advantage of being a scalar function of  $R$  and  $Z$  only, and in addition of corresponding to the flux of the field through a disk of radius  $R$  centred on the torus major axis at a height of  $Z$ .

XLOC describes the magnetic flux using a very simple polynomial model: where  $(i+j) < 7$  and  $r = R^2 - R_0^2$ ,  $z = Z - Z_0$ .  $(R_0, Z_0)$  is an arbitrary point in the poloidal plane used as a centre of the expansion. If a base of functions  $\mathbf{F}_{28}$  is defined as  $\mathbf{F}_{28}(r, z) = \{1, r, r^2, \dots, r^7, z, rz, r^2z, \dots, r^6z, \dots, z^7\}$ , then the flux calculation can be expressed as  $\psi(r, z) = \mathbf{F}_{28}(r, z) \cdot \bar{\mathbf{a}}$ . The 28  $\bar{\mathbf{a}}$  coefficients are

constrained using the  $\Delta^* \psi = 0$  (which is expressible as a linear isomorphism within the space of functions  $\{\mathbf{F}\}$ ) thus reducing the overall degrees of freedom to 13  $\bar{\mathbf{c}}$  coefficients. The flux can now be written as  $\psi(r, z) = \mathbf{G}_{13}(r, z) \cdot \bar{\mathbf{c}}$ , where  $\mathbf{G}_{13}$  is a new base of functions composed of linear combination of the members of the  $\mathbf{F}_{28}$  base, each satisfying the vacuum G-S equation.

## 2.2 REGIONS

A simple polynomial cannot fit well the whole flux distribution outside the plasma. For this reason, the flux is modelled using 5 polynomials, each valid in a different region, a section of space surrounding the plasma. (See figure 2). Doing this also allows using a smaller order polynomial while at the same time better fitting the measurements.

Since the  $\mathbf{G}_{13}(r, z)$  vectors are just a transformation of the space, they can be calculated off-line on a set of co-ordinates: the result is called  $\bar{\mathbf{g}}$  coefficients. The  $\bar{\mathbf{c}}$  coefficients are instead a transformation of the magnetic measurements and have therefore to be calculated in real-time.

## 2.3 FIELD

XLOC calculates the flux in real-time by multiplying the  $\bar{\mathbf{c}}$  vector with the  $\bar{\mathbf{g}}$  vector. The poloidal field can instead be obtained by using the  $\bar{\mathbf{c}}$  vectors with two new polynomial bases whose members are obtained with the following equations:

$$B_z = \frac{1}{R} \frac{\partial \mathbf{G}_{13}(R, Z)}{\partial R} \cdot \bar{\mathbf{c}}, \quad B_r = -\frac{1}{R} \frac{\partial \mathbf{G}_{13}(R, Z)}{\partial Z} \cdot \bar{\mathbf{c}}$$

## 2.4 $\bar{\mathbf{c}}$ COEFFICIENTS CALCULATION

The polynomial coefficients  $\bar{\mathbf{c}}$  are calculated by fitting the polynomial model to a user-defined set of measurements, the selection of which is based on the vicinity to the region of interest. The minimisation of the error  $e = \sum w_j \cdot (\text{meas}_j - \mathbf{G}_{13}(r_j, z_j) \cdot \bar{\mathbf{c}})$  (where meas is the measured flux, and r, z its position) leads to a linear relation between the measurements and the  $\bar{\mathbf{c}}$  coefficients:  $\bar{\mathbf{c}} = \mathbf{T}_{13 \times N} \cdot \{\mathbf{meas}\}_N$ , where the  $\mathbf{T}$  matrix is a constant depending only on the choice of measurements.

## 2.5 TIE POINTS

In order to minimise the difference between polynomials on the boundary of the regions, the soft tie points are introduced: the difference between two adjacent expansions is added to the minimisation process  $e = \dots + \sum_{i \in \text{regions}} \sum_j (\mathbf{G}_{13,i}(r_j, z_j) \cdot \bar{\mathbf{c}} - \mathbf{G}_{13,i+1}(r_j, z_j) \cdot \bar{\mathbf{c}})$ . In addition hard tie points are defined as points where the polynomials are forced to coincide:  $\mathbf{G}_{13,i}(r, z) \cdot \bar{\mathbf{c}} = \mathbf{G}_{13,i+1}(r, z) \cdot \bar{\mathbf{c}}$ . In order to minimise the discontinuities in the boundaries the tie points are concentrated in the areas where the last flux surface crosses the border of regions (see fig 2)

## 2.6 THE DIVERTOR CURRENTS.

In the JET divertor area, the plasma shape is strongly determined by the current flowing in 4 poloidal circuits (divertor coils). In order to use this information XLOC fits the field measurement after having removed the contribution from these coils:  $\text{meas}'_j = \text{meas}_j - \mathbf{G}_{4,D}(r_j, z_j) \cdot \bar{\mathbf{I}}_D$  (where  $\bar{\mathbf{I}}_D$  is

the vector of divertor currents and  $\mathbf{G}_{4,D}(r_j, z_j)$  a function describing the flux produced by the coils). Finally the analytic expression of the field produced by the coils is added back to the flux reconstruction:  $\psi(r, z) = \mathbf{G}_{13}(r, z) \cdot \bar{\mathbf{c}} + \mathbf{G}_{4,D}(r, z) \cdot \bar{\mathbf{I}}_D$ . In practice the  $\bar{\mathbf{c}}$  vector is expanded to 17 elements by adding the four divertor currents while the Green function of the four conductors, obtained by modeling each turn as a filamentary current, are added to the  $\bar{\mathbf{g}}$  vector.

## **2.7 THE PLASMA TYPE**

The plasma boundary corresponds to the last closed flux surface inside the vessel. This surface is either the most external one not crossing any solid object or is a separatrix. Since the flux absolute value decreases monotonically from the centre of the plasma moving toward the walls, the point in the first wall where the flux is maximum is where the plasma touches. If the plasma most external surface is the separatrix, this can be detected by the fact that the flux at the X-point is bigger than anywhere else on the walls.

## **2.8 THE X POINT**

The calculation of the X-point involves a 4 cycles Newton Raphson iteration, searching for the zero of Br and Bz. The search starts from a point where the X-point normally resides, and is barred from finding a point too far away by limiting the number of iterations and checking the convergence error.

# **3. XLOC UTILITY ALGORITHMS**

## **3.1 THE GAPS.**

In XLOC a gap is defined as the distance between a point and the plasma boundary (see figures 1 and 2), measured along a predefined segment. To calculate this, the segment is reduced to a set of points in which the  $\bar{\mathbf{g}}$  coefficients are pre-calculated. Since the flux function is monotonically growing towards the plasma centre, the search of the boundary can be performed using bisection: starting from the segment centre, by comparing the flux to the flux on boundary the algorithm can decide on which part of the segment to keep on searching. As a result the number of iterations is always the base 2 logarithm of the number of points.

## **3.2 THE STRIKE POINTS.**

The strike point is the location where the plasma deposits some of its energy when in X-point configuration. It can be found following the boundary surface beyond the X-point until it touches the divertor. For this reason it can be calculated with a similar technique to that of the gaps: the intersection is searched on a set of four almost straight curves together outlining the divertor shape. The actual produced measurement is in fact the distance from the divertor centre either projected on the R axis or on the Z axis (Fig.1).

## **3.3 THE BOUNDARY.**

XLOC constructs the boundary as a list of points of the curve. Each point is obtained using a gap with the exception of those in the area near the X-point where the flux distribution is not monotonic.

In that area, the danger of having two points of the segments with the same flux is avoided by searching only the segment portion that is above the projection of the X point (Fig.2).

#### **4.4 THE SENSOR SIMULATION.**

XLOC being able to reconstruct a flux map is able to predict, with some precision, the measurement that a given magnetic sensor would produce. This feature had been successfully used in creating a magnetic validation code.

#### **4.5 THE ANGLE CALCULATION.**

The trajectory followed by the particles when hitting a surface depends primarily on the magnetic field direction in that point. A very important piece of information is the toroidal angle of this trajectory, because of the interaction between the particles and the protection tiles. This angle can be easily calculated by XLOC by computing the ratio between B poloidal and B toroidal.

### **5. XLOC CODE ARCHITECTURE.**

XLOC is a highly efficient code optimised for real-time: instead of being designed for a maximum average speed, the algorithms were engineered to always complete in the same time. Without this constraint, it would be very difficult to guarantee that a real-time application based on XLOC always meets its timing requirements. The resulting implementation is a very fast code that, if executed on a modern processor (1GHz), can produce plasma shape geometrical information in few hundred microseconds.

XLOC is logically divided in three parts: offline calculations, real-time flux reconstruction and a geometric measurement library. The choice of magnetic sensors, the division of the space into regions, and the description of the first wall, are all user selectable parameters located in the XLOC configuration file. XLOC offline reads this file before every pulse and creates all the matrices and tables needed by the real-time parts. The flux reconstruction code transforms the real-time data from the JET magnetic measurements into a two-dimensional magnetic flux map, the X-point position and the point of contact of the plasma with the first wall. The last part of XLOC is a set of software tools that, by using the flux map as input, allow the measurement of any desired geometric property of the vacuum field.

From the old “C” version used on the DSP (Digital Signal Processor) control systems (Shape Control, first wall protection code, WALLS) a more recent object oriented “C++” version, XLOC++, has been developed for the PC RTDN applications (Beta-Li, EQUINOX, q-Profile) and has been planned for use on the new PowerPC VxWorks applications (Extreme Shape Controller, WALLS update). In this version XLOC has been subdivided in several interconnecting software components: an object for the flux reconstruction, and one for each different magnetic and geometric measurement. The object constructor and initialisation methods, which are executed offline, implement the XLOC++ offline calculations. The real-time methods only perform the minimum number of operations necessary to achieve the result, having delegated as much as possible to the offline code, as in the original XLOC.



## **6. XLOC APPLICATIONS**

### ***6.1 SHAPE CONTROLLER.***

SC, JET real-time plasma shape control system, is the original application where real-time XLOC was developed. Being directly connected with the real-time magnetic measurement system, it can reconstruct the flux map every 2ms with a delay of just above 1.ms which is partially due to delays in the acquisition. After having calculated four strike points, 12 gaps and the X-point for its own use, it then broadcast the flux map information to all the applications using RTDN. These applications do not need anymore to compute the flux map and can proceed directly to calculate the desired geometrical or magnetic measurements.

### ***6.2 WALLS.***

This system is designed to protect both some first wall areas and a divertor tile from an excess deposition of plasma power, and to prevent the strike points from reaching some unprotected areas above the divertor. To do that, in addition to calculating 20 gaps and 4 strike points, it computes the toroidal angles of the particle trajectories and the size of the areas exposed to the plasma power in the divertor. It is the second application implementing real-time XLOC, and it has been built with the same software and hardware architecture of SC. Being a protection system, it could not depend on SC's flux map availability and is therefore independently connected to the real-time magnetic data feed (Cenedese [7]).

### ***6.3 BETALI.***

This is the first application making use of the object oriented XLOC++. It uses the flux map produced by XLOC in SC to calculate over hundred gaps and thus describe the complete plasma boundary. On the resulting closed curve it then calculates the S1 S2 S3 Shafranov integrals of the magnetic field and the second order moment of the plasma current column. With this information it then derives the poloidal b and the internal inductance "li", together with other confinement parameters (Barana [8]).

### ***6.4 EQUINOX.***

This is a very fast plasma equilibrium code (~2ms on a 1.5Ghz machine) that solves the Shafranov equation using as boundary conditions only the magnetic measurement on a closed curve surrounding the plasma. Since the magnetic measurements are scattered in the poloidal plane in such a way that it is impossible to draw a closed curve through all of them, it was decided to use the flux map produced by XLOC++ as the input. XLOC++ is used to extrapolate the flux and the field on a curve coinciding with the first wall, on the top part of the machine, and with the divertor tiles, on the bottom (Bosak [9]).

### ***6.5 Q-PROFILE:***

This code uses the line averaged density from the 8 interferometer channels combined with the data from the polarimeters to calculate a good approximation of the q profile. Specially tailored gaps,

provided by XLOC++, are used to calculate a real-time approximation of the plasma shape and to measure the length of the intersection between the interferometer lines of sight and the plasma. In addition, the information of the field and flux on the outboard and inboard mid-plane has instead been used to estimate the magnetic axis. (Riva [10])

## **DISCUSSION**

Eight years of operation as part of the Shape Controller have proven that XLOC is a very reliable code, in all circumstances producing reasonably accurate results. While this code precision varies from the 1-2 cm in the midplane to 4-8cm in the machine top, its repeatability is very good. Because of its speed and inherent robustness XLOC has recently become design choice for RTDN applications where there is need for a real time plasma boundary measurement or flux reconstruction. The recent object oriented design has moreover simplified the implementation work by providing a fully reusable and modular code.

XLOC is still being actively developed: a new improved version will try both to introduce a single expansion for the flux and to use the information about the passive structures, the current on the active coils and the principal plasma moments. This enhancement should remove the problem of regional flux maps, which are not well joined at their boundaries, and should provide a better flux map extrapolation toward the plasma centre and the outside.

## **ACKNOWLEDGEMENTS**

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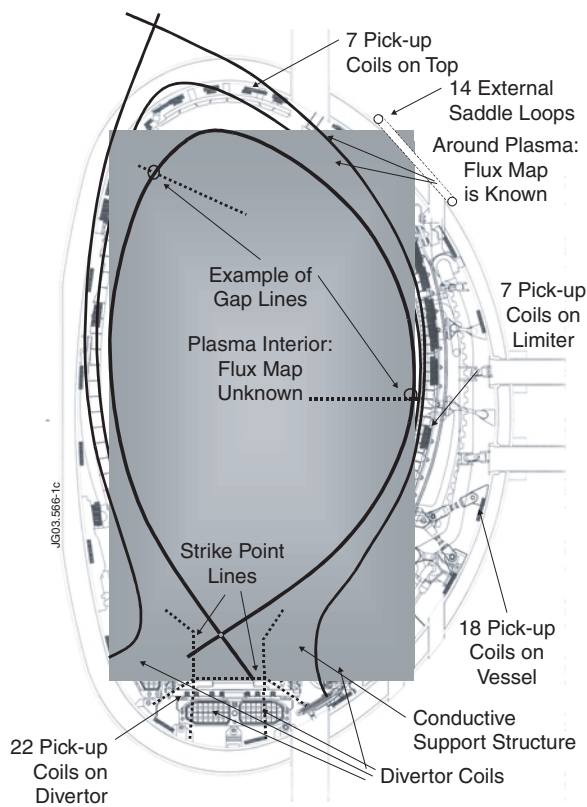


Figure 1: The vessel and the plasma. Two flux surfaces are plotted as well. An example of gaps and the strike points together with the location of the acquisition coils.

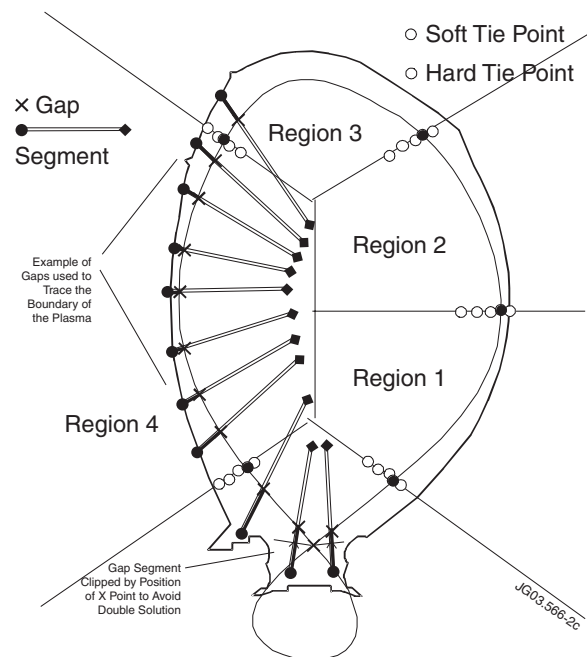


Figure 2: The division of the space in regions the placement of soft and hard tie points, and the boundary made with gaps.