EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

EFDA–JET–CP(02)05/09

A. Cenedese, F. Sartori, V. Riccardo, P.J. Lomas

JET First Wall and Divertor Protection System

JET First Wall and Divertor Protection System

A. Cenedese[1], F. Sartori[2], V. Riccardo[2], P.J. Lomas[2]

[1] *Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Corso Stati Uniti, 4, I-35127 Padova, Italy*
[2] *Euratom/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, Oxon OX14 3DB, UK*
Corresponding author: A. Cenedese - JET K1-06 Culham Science Centre, Abingdon, Oxon OX14 3DB, UK
e-mail: Angelo.Cenedese@jet.uk; tel.: 0044.(0)1235.465036; fax: 0044.(0)1235.464554

Preprint of Paper to be submitted for publication in
Proceedings of SOFT 2002 (Helsinki, Finland, 9–13 September 2002)

ABSTRACT.
WALLS has been used in JET plasma operations as a real-time active protection system supporting the plasma shape controller. Provided with real time information on the boundary location, plasma current and the additional input power, the code checks the distance of the plasma from the wall and then computes an energy state for a set of chosen locations of the plasma facing components. If this energy function exceeds a pre-set threshold then the pulse is promptly terminated. The JET divertor MKIIGB has recently been modified (MKIISRP) by replacing the septum with a tile that has very little power handling. This paper will principally focus on the code upgrade for the new divertor.

1. INTRODUCTION

H-mode high-density triangular plasmas, which show improved stability characteristics and longer confinement times, represent one of the most promising future scenarios. Therefore, in current-generation tokamaks the plasma shape is of primary importance for achieving better fusion performance. In JET the control of plasma shape relies on the digital Plasma Position and Current Controller (PPCC [1, 2]), a system that allows the Session Leaders to easily design and run extremely complex scenarios involving different plasma shapes. In normal operation conditions a large amount of power is discharged to the plasma facing components where the plasma boundary – defined as the last closed flux surface inside the vacuum vessel – intersects the first wall. In limiter configurations the plasma edge is directly in contact with a structure; in diverted plasmas, the presence of a magnetic *X*-point defines the boundary and particle and energy flow to the divertor along the separatrix legs.

A Wall Load Limitation System (WALLS) has been developed as a complement to PPCC, in order to protect the plasma facing structures from excessive power deposition. Furthermore, WALLS was designed to check the maximum heights of the strike points on the divertor side plates, in order to avoid depositing power away from the divertor region.

During the 2001 shutdown, the divertor septum has been removed and replaced with a Septum Replacement Plate (SRP) with limited power handling capability. In Figure 1, the geometry of the new divertor Mark II SRP is shown and compared with the previous Mark II GB. The new divertor will give the Session Leader larger freedom in strike point positioning and triangularity, hence gaining the possibility of designing new configurations in the *X*-point region. WALLS has consequently been modified in order to take into account the new needs arisen from the different structure.

2. THE PROTECTION SYSTEM

At JET, the location of the plasma boundary is specified in terms of positions along a set of lines poloidally distributed around the first wall (gaps) and directed inward, and four more curves in the divertor region (strikes). All these segments are highlighted in Figure 2. As a consequence, the computation of the plasma-wall distance is performed along a line.

WALLS checks in real-time the clearance along a chosen subset of the gaps and, when the gap clearance is smaller than a pre-set threshold, it is assumed that the additional heating power is transferred to the wall at that location, according to the following formula:

$$E_n(t) = \int_t P_{add}(\tau) \cdot W[D_n(\tau)] d\tau$$

where $P_{add}(\tau)$ is the total additional power, $W[D_n(\tau)]$ is a linear function from 0 to 1 weighting the distance along the n^{th} gap and $E_n(t)$ monitors the status of a first wall location. Each gap is rated with a maximum energy handling capability. When the energy accumulated reaches a value greater than this limit, the additional heating is promptly removed and the pulse is terminated by slowly ramping down the plasma while preserving the shape of the plasma (Soft Stop termination). Both the ohmic power and the internal energy variation are neglected in the energy computation, because their measurement is not available. Their values are relatively small and are taken in account by allowing some margin in the energy limits. The spread of the power on the wall is also not considered, so that the integrated energies are the worst case for the actual additional heating energy deposited on the first wall.

Since SRP power load limitations are more stringent, additional heating operation with the strikes on the SRP has been disallowed. The energy computation will use only the ohmic power estimated empirically via a plasma current proportional law ($P_{OH} = 0.6 \cdot I_P$) and distributed unevenly between the inner and the outer leg of the separatrix (respectively 25% and 50%, accounting the rest as radiative power). The new structure has been studied with a finite element model so as to estimate how long it would take for a tile to reach the maximum allowed temperature (1800ºC), given a certain power level. The power is delivered to the divertor tiles in the positions determined by the strike points, and the power density depends on the size of the scrape off layer at these locations. This system is non-linearly affected by the power density levels and by the value of the angle $\vartheta_\perp$ at the strike points. $\vartheta_\perp$ is defined as the ration of the poloidal field component normal to the tile surface and the toroidal field. The particular dependence from $\vartheta_\perp$ is dictated by the chamfering on the edges of the tiles, which also limits the value for the angle to a maximum of 8.6º. In more detail the power density on the SRP is affected by an amplification factor at the chamfer equal to

$$M = \left[\frac{\sin(\alpha_{chamfer} + \vartheta_\perp)}{\sin\vartheta_\perp}\right]$$

where $\alpha_{chamfer}$ is the chamfer angle (40º). The scrape off layer (SOL) footprint on the SRP is estimated as λF with λ set equal to 5mm at the outer midplane and F (flux expansion) depending on the plasma current and the toroidal field

$$(F = \frac{B_\vartheta}{B_\varphi} \cdot \frac{1}{\tan\vartheta_\perp}$$

where B_ϑ and B_φ are respectively the poloidal and the toroidal field values at the outer midplane). To simplify, the flux expansion has been linked only to the field line angle as

$$F = \frac{0.3}{\tan\vartheta_{\perp}}$$

which is consistent with typical q values in usual plasma configurations.

By means of a best-fit procedure over the magnetic measurements, the XLOC algorithm ([3], [4]) provides real time information about the plasma boundary, the magnetic separatrix, the strike points and $\vartheta_{\perp}$. As the expected values for the angles are in the range of some degrees, the approximation introduced in linearising the arctangent function is acceptable, while being a better solution from the computational point of view. To check the validity of the assumptions, the SOL on the SRP is also calculated, following the flux line whose distance from the boundary measured at the outer midplane is equal to λ to the divertor plates, as shown in Figure 3.

In order to have a more realistic estimate of the temperature the replacement tile has been poloidally partitioned into eight segments. The program then integrates the power both on the segment that is covered by the strike point and on the next one outside. The power load limits of the tile is in fact expressed on a two-dimensional table as maximum allowed exposure time to a given plasma current and a given toroidal angle $\tau(I_P, \vartheta_{\perp})$. This quantity cannot be directly integrated, but if a linear relation between temperature and time is assumed, $T = \alpha(I_P, \vartheta_{\perp}) \cdot \tau$ (where T is temperature, τ is time), then it is possible to express the thermal state of a tile segment in terms of a time integral: $T = \int\alpha(I_P(\tau), \vartheta_{\perp}(\tau))d\tau$. The rate of temperature rise a can be obtained from the table with a simple expression: $\alpha(I_P, \vartheta_{\perp}) = T_{max}/\tau(I_P, \vartheta_{\perp})$. In WALLS the maximum temperature for each tile is not specified, instead the thermal state of the tile is expressed as a percentage of a maximum energy. The discrete time integration is performed with this formula: $E = \Sigma\tau_{sampling}/\tau(I_P, \vartheta_{\perp})$. The summed element $\tau_{sampling}/\tau(I_P, \vartheta_{\perp})$ is defined as the 'quantum' and represents the variation of the percentile energy every $\tau_{sampling}$ (10ms).

3. RESULTS OF SIMULATIONS

Simulations of the real time code have been extensively run on a PC using both data from last experimental campaign and data artificially modified in order to fully exercise the protection system. The results presented in the paper are relative to real data of pulse #54828, where during the divertor phase the plasma current was 2.2MA, and the ohmic power about 1.3MW. The strike points have been swept in and out of the SRP to assess its characteristics: a detail of the position assumed by the strikes is presented in Figure 4, superimposed on a schematic plot of the divertor region.

For the limited range of field line angles tested, the estimated SOL footprint dimensions on the target are in sufficiently good agreement with those calculated as discussed in Section 2 (Figure 5). The real time calculation of the actual scrape off layer could provide an improved accuracy, is under development.

Moreover, the larger the SOL, the lower the field line angle, as predicted from the theory: the dependence from the poloidal field is inverse for the SOL dimension, while being direct for the line angle (Figure 6). As expected, the quantum is higher for the outer strike point and it shows the same behaviour as the field line angle (a quantization of the angle has been made for simplicity of implementation). This affects the growth of the energy states, as reported in Figure 7.

4. DISCUSSION

The protection of the limiter and of the gaps outside the divertor has shown to be quite effective in all tested situations, but the problem of which protection action to take in case of the SRP tile overloading is not fully resolved. The available link from Walls to the soft stop termination, used for the walls protections, is in this situation not usable, since by activating it, the code would instruct Shape Controller to keep the strikes in the same positions while the plasma is terminating and releasing all its internal energy. The solution, that is being developed, is to link WALLS also to the fast stop, which would cause SC to rapidly move the strike points outside the divertor.

While the new thermal energy calculations is probably adequate for the needs of WALLS, it would both be scientifically interesting and at the same time provide a more accurate protection action, if the thermal calculations would be performed using a more detailed physical model of the tiles.

ACKNOWLEDGEMENTS

This work is funded in part by the UK Department of Trade and Industry, and Euratom and has been performed under the European Fusion Agreement.

REFERENCES

[1] M. Garribba, R. Litunovsky, P. Noll and S. Puppin, The New Control Scheme for the JET Plasma Position and Current Control System, Proc. 15th SOFE Conf. (1993), Massachussets, pp. 33–36.

[2] S. Puppin, M.E. Angoletta, D.J. Campbell *et al.*, Real Time Control of Plasma Boundary In JET, Proc. 19th SOFT Conf., Lisbon (1996).

[3] F. Milani, Disruption Prediction at JET, PhD Thesis, University of Aston in Birmingham, 1998, pp.35–57.

[4] F. Sartori, A. Cenedese, F. Milani, JET real-time object-oriented code for plasma boundary reconstruction, Proc. 22nd SOFT Conf., Helsinki (2002), to appear.

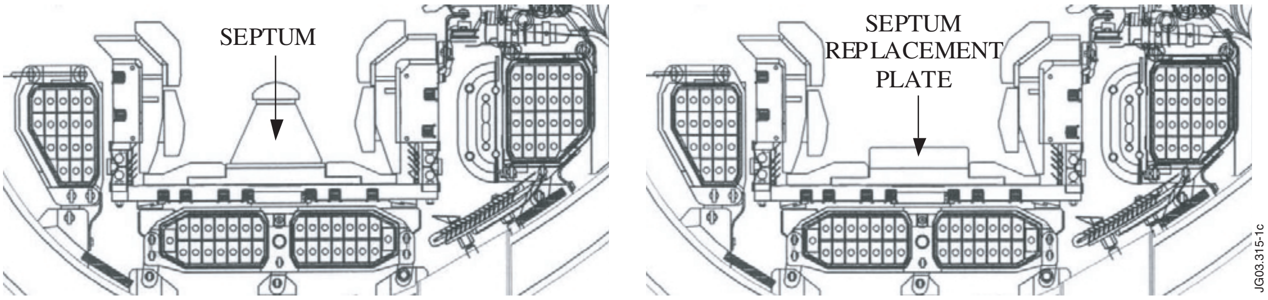

Figure 1: MKIIGB (on the left) and MKIISRP (on the right) divertor structures.

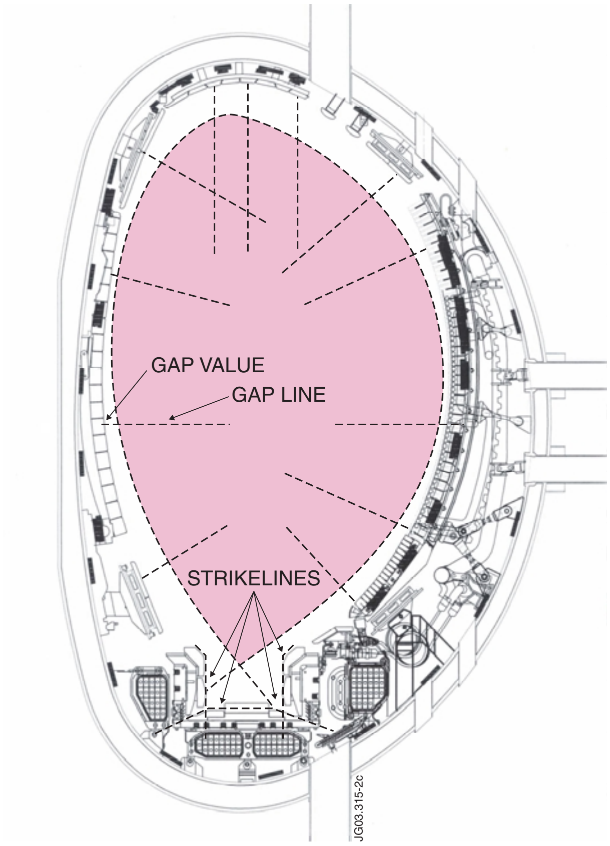

Figure 2: JET cross section with gaps and strikes.

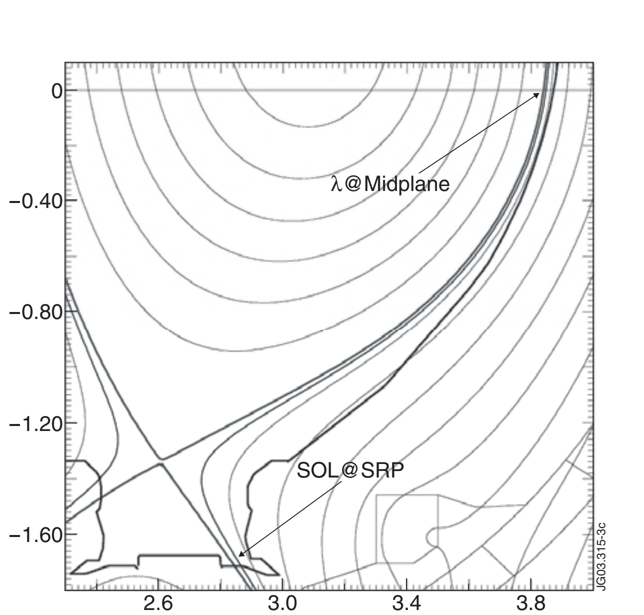

Figure 3: Plot of the flux lines showing the relation between the λ at the outer midplane and the scrape off layer at the SRP.

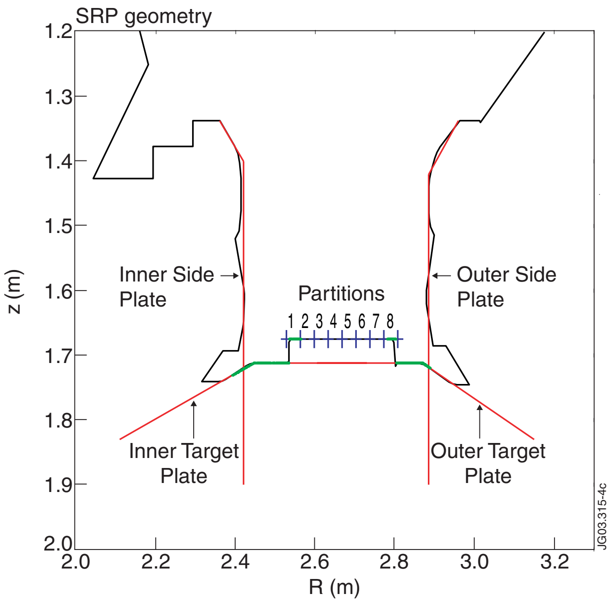

Figure 4: Position of the strikes during the discharge (Pulse No: 54828).

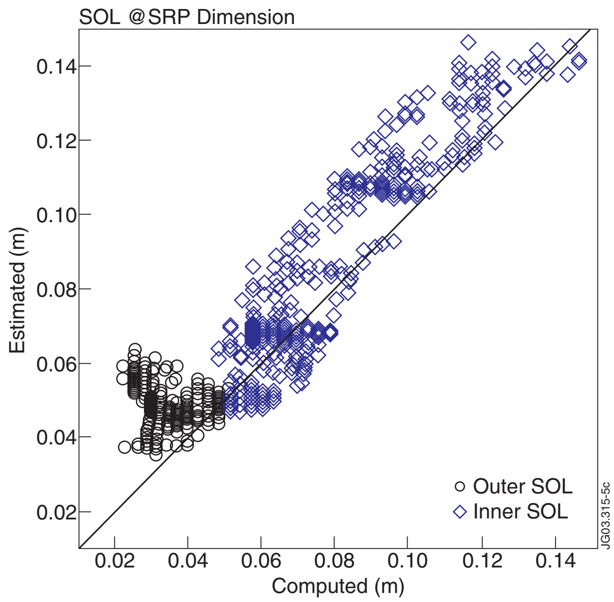

Figure 5: Computed and estimated SOL target footprint dimension (Pulse No: 54828).

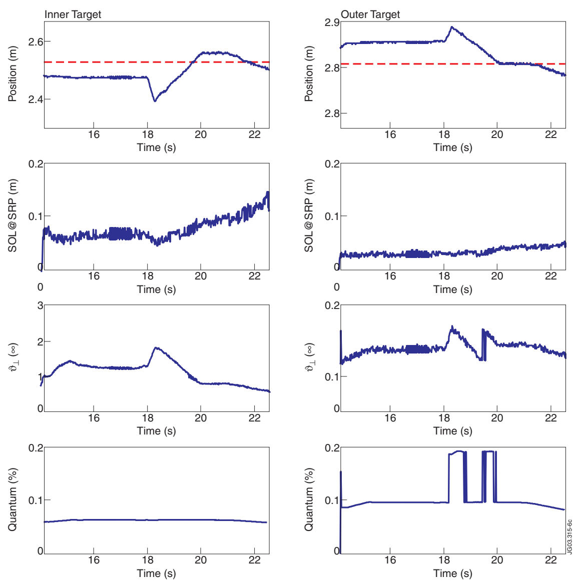

Figure 6: Strike characteristics (Pulse No: 54828).

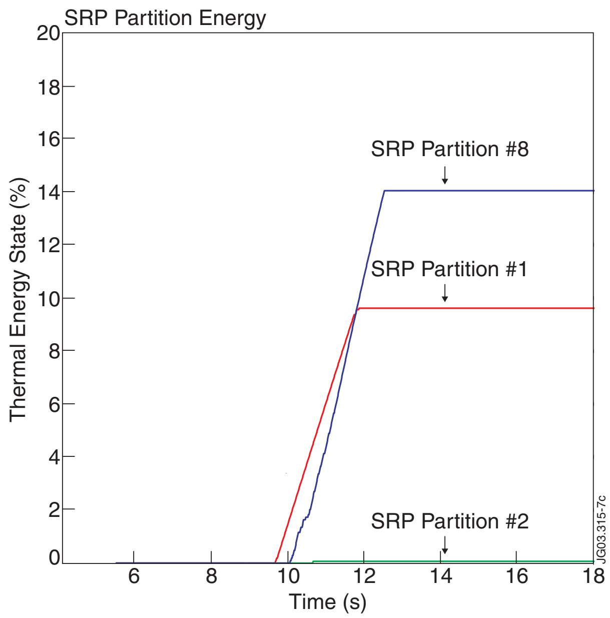

Figure 7: Energy status of the illuminated partitions (Pulse No: 54828).