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

A new model-based plasma current and shape controller has been set up and tested on the JET Tokamak with the existing active circuits and control. The installation has been carried out without causing any interference to the plasma operation, or requiring long commissioning time. Eventually the new controller was used on really extremely shaped Internal Transport Barrier experiments at high poloidal beta and in the presence of quite large variations of the plasma current density profile (variation range $\Delta\beta_{pol}$ up to 1.5 and $\Delta l_i$ up to 0.5). The XSC controller architecture and philosophy also offer new interesting opportunities, e.g., the separatrix sweeping on the divertor plates without significantly affecting the overall plasma shape, and the possibility of improving the overall tokamak performance via combined control of plasma shape, current and profile. The adopted methodology constitutes also an important test bed for feedback control strategies of ITER relevance.

## 1. INTRODUCTION

Since in ITER the reference scenarios are planned to work at extreme plasma shape, JET operation will be progressively focused on the study of this kind of plasmas. The old JET Shape Controller (SC) can only control a few plasma-wall gaps at the same time. This, for strongly shaped plasmas, can lead to large deformations of the shape, mainly in case of large variations of poloidal beta $\beta_{pol}$ and/or internal inductance $l_i$. A new model-based plasma current and shape controller has been set up and tested in the JET Tokamak with the existing active circuits and control hardware [1-3]. Its name is XSC (eXtreme Shape Controller), as it is aimed at improving the performance of the present controller so as to allow the control of extremely shaped plasmas with higher values of elongation and triangularity.

The original aims of the project are the following:

- build a controller that maintains the plasma shape while $\beta_{pol}$ and $l_i$ are changing (for the first time at JET use all the poloidal currents to control the shape);
- test the ITER plasma magnetic modelling techniques on JET (the plasma response models are created directly from the equilibrium codes);
- use JET as a test bench for the ITER plasma control design methodologies, in order to validate them and improve them.

This new system was successfully installed on the JET machine during 2003 without causing any interference to the plasma operation, or requiring long commissioning time. Eventually the new controller was used on really extremely shaped Internal Transport Barrier (ITB) experiments at high poloidal beta and in the presence of quite large variations of $\beta_{pol}$ ($\Delta\beta_{pol}$ up to 1.5) and/or $l_i$ ($\Delta l_i$ up to 0.5). The quality of the model based controller design approach was also verified by a large sequence of plasma scenarios where extremely elongated shapes were achieved for the first time by using the controller without requiring any kind of tuning.

## 2. MODELLING

A linearized plasma model approach is used to design the XSC for JET single-null configurations. The plasma modelling tools CREATE-L and CREATE-NL code have been set up on the JET configuration, including an equivalent axisymmetric model of the iron core, also taking into account the eddy currents induced in the passive structures [4].

The input quantities are the poloidal field circuit currents (or voltages) and a number of parameters related to the plasma current density profile. The output quantities include the signals provided by the magnetic diagnostic system of JET (fields, fluxes and flux differences) as well as plasma current and shape (accurately described by a set of 32 plasma-wall gaps, the X-point position and the strike points on the divertor plates).

This model has been assessed on a set of JET pulses. First of all, neglecting the eddy currents in the passive structures (which is a valid approximation on a long time-scale, as compared with the decay time of the eddy currents), some current-driven open-loop simulations have been performed, both in dry runs and in plasma shots, showing a satisfactory agreement with experimental results [4]. Secondly, the equivalent eddy currents model has been validated by successfully comparing the predicted and measured growth rate in a number of shots terminated by a VDE [4].

The linearized plasma response model has also been successfully validated with closed loop simulations, hence providing a reliable starting point for the design and the assessment of a new current, shape and position control system developed on JET, as described in the following. Moreover, it has also allowed a deeper understanding of specific sets of experiments, namely the ones devoted to the successful detection of the neutral point for density limit disruptions [5], and the ones aimed at explaining the sudden jump of strike points in correspondence of ELMs [6].

## 3. CONTROLLER DESIGN

The shape is accurately described by 32 plasma-wall gaps, position of inner and outer separatrix strike points, radial and vertical location of the X-point. However only a limited set of actuators is available (only 8 poloidal circuits in JET). The problem is tackled by using a singular value decomposition (SVD) to identify the principal directions of the algebraic mapping between coil currents and geometrical descriptors. These principal directions identify 8 linear combinations of currents, each one influencing one linear combination of geometrical descriptors; in this way the original multivariable control problem can be solved using a set of separate PID controllers. To take in account the limits of the actuators, the SVD orders the principal directions as a function of the current to shape sensitivity and the XSC normally uses only the first 5 or 6 directions (out of 8). The control algorithm [2] tries to find a compromise between the effort of the actuators and the tracking error on the plasma shape. The price paid to obtain optimal performance is that different plasma response models and hence controller gains are needed for each plasma scenario.

## 4. IMPLEMENTATION

So far, the project has required some limited hardware and software modifications of JET present system, mainly because the XSC has been implemented as a Shape Controller (SC) internal module that, when activated, substitutes its outputs to the reference to the existing SC in its proportional current control configuration. This method allowed the introduction of the new functionality without major changes to the code architecture and at the same time minimizing the required commissioning time because the internal diagnostic and protection actions were left untouched (Fig.1). The desired plasma boundary is selected interactively among a family of admissible shapes using a model-based tool and the controller works by minimizing the difference between the actual plasma boundary and the desired shape described as a set of co-ordinates. When the XSC is activated, it internally produces waveforms to linearly move from the current plasma shape to the desired one in a given *transition time*. The XSC also provides the current feed-forward waveforms ramping between the plant currents and the scenario reference.

## 5. EXPERIMENTAL VALIDATION

The first version of XSC has run on JET in a set of dedicated experiments. The modified control management algorithm was able to smoothly switch from SC to the new controller and back. These tests have also demonstrated that the modifications to the control management logic of the controller can adequately cope with current limitation and excessive control error events.

Then, the XSC has successfully been used in a number of JET sessions, controlling the plasma in Standard Fat configurations and during High Poloidal Beta and High Triangularity experiments (see Figs.2-3).

For instance, Fig.4 shows how the desired high triangularity has been kept within a tolerance of 2 cm even in the presence of wide excursion of $I_p$ and $l_i$. In other pulses the XSC has shown similar performance in the presence of wide variations of $\beta_{pol}$. Notice how the closed loop simulations are able to reliably predict the time behavior of currents and plasma shape.

## CONCLUSIONS

The XSC controller was installed on the JET machine during 2003 and successfully used to achieve and maintain really extremely shaped Internal Transport Barrier (ITB) experiments at high poloidal beta and in the presence of quite large variations of $\beta_{pol}$ ($\Delta\beta_{pol}$ up to 1.5) and/or $l_i$ ($\Delta l_i$ up to 0.5).

The XSC controller architecture and philosophy also offer new interesting opportunities, e.g., the separatrix sweeping on the divertor plates without significantly affecting the overall plasma shape, and the possibility of improving the overall tokamak performance via combined control of plasma shape, current and profile.

A new JET enhancement, which is in fact the second phase of the XSC project, has started. Its main objective is to investigate the possibility of improving the overall performance of the plasma shape and profile control by integrating the two separate control systems so as to account for the interactions between them. The attention will be focused on test cases devoted to the control of the safety factor profile and of the plasma loop voltage.

## ACKNOWLEDGEMENTS

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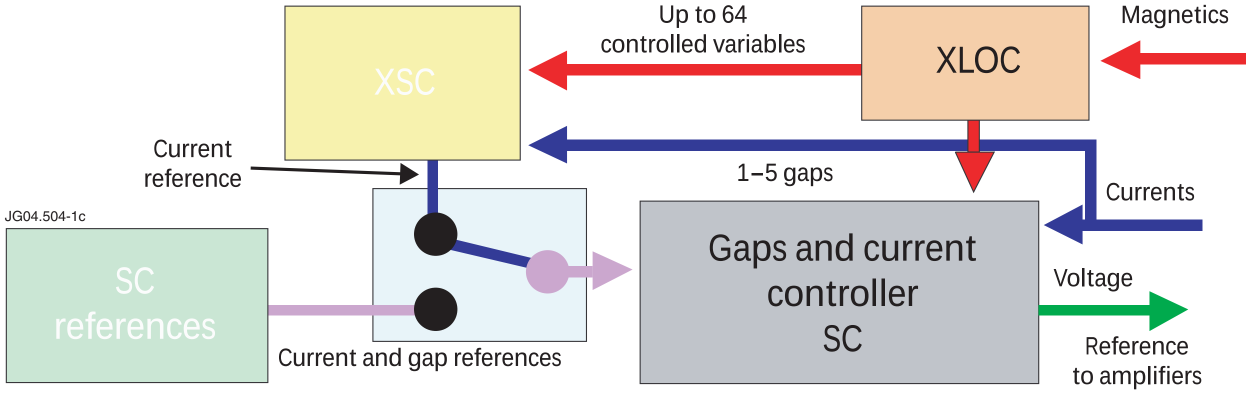

*Figure 1: JET XSC controller architecture.*

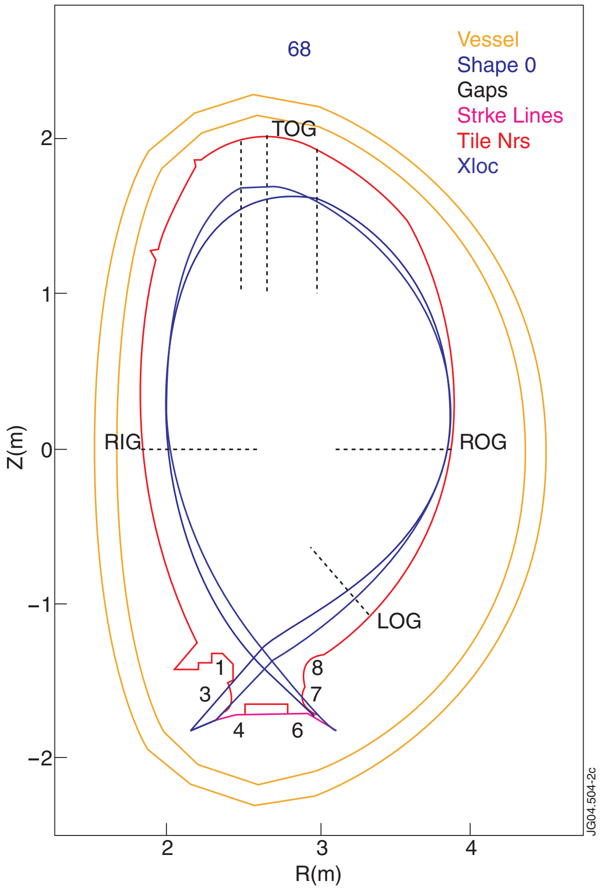

*Figure 2: Detail of the graphic window of JET XSC controller interface for the Session Leader.*

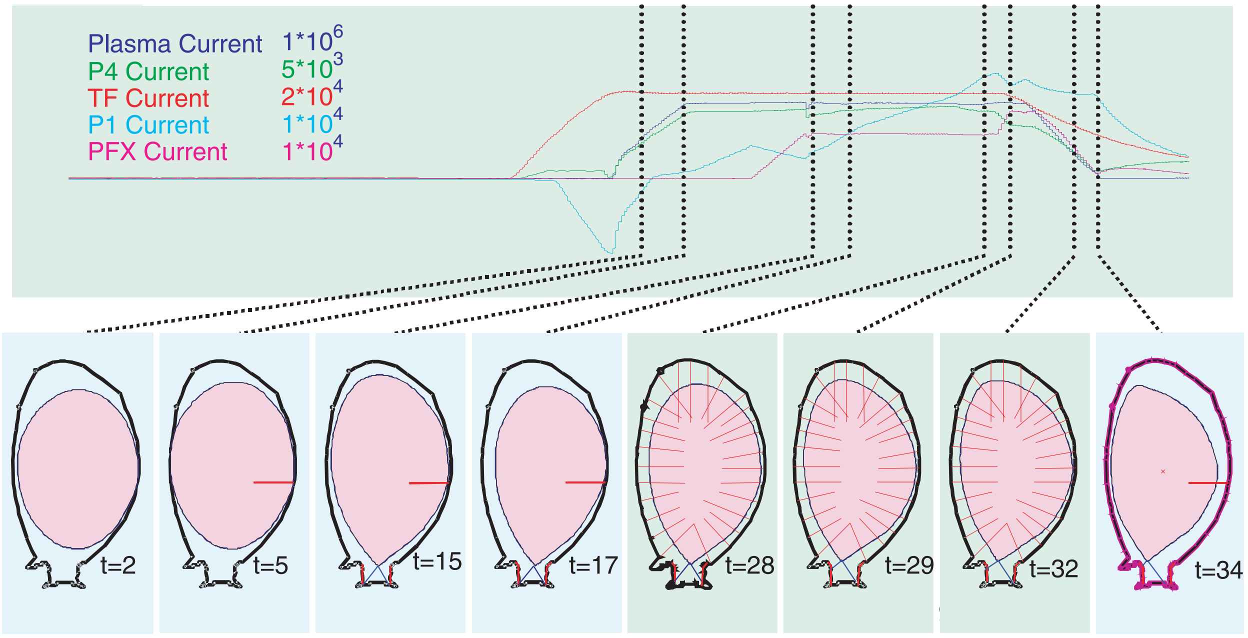

*Figure 3: JET Pulse No: 61995. The XSC is activated in the time windows 28-42s, and controls 32 gaps and 4 additional geometric descriptors representing the whole boundary shape. Before t = 28s SC controls the circuit currents and the Radial Outer Gap only.*

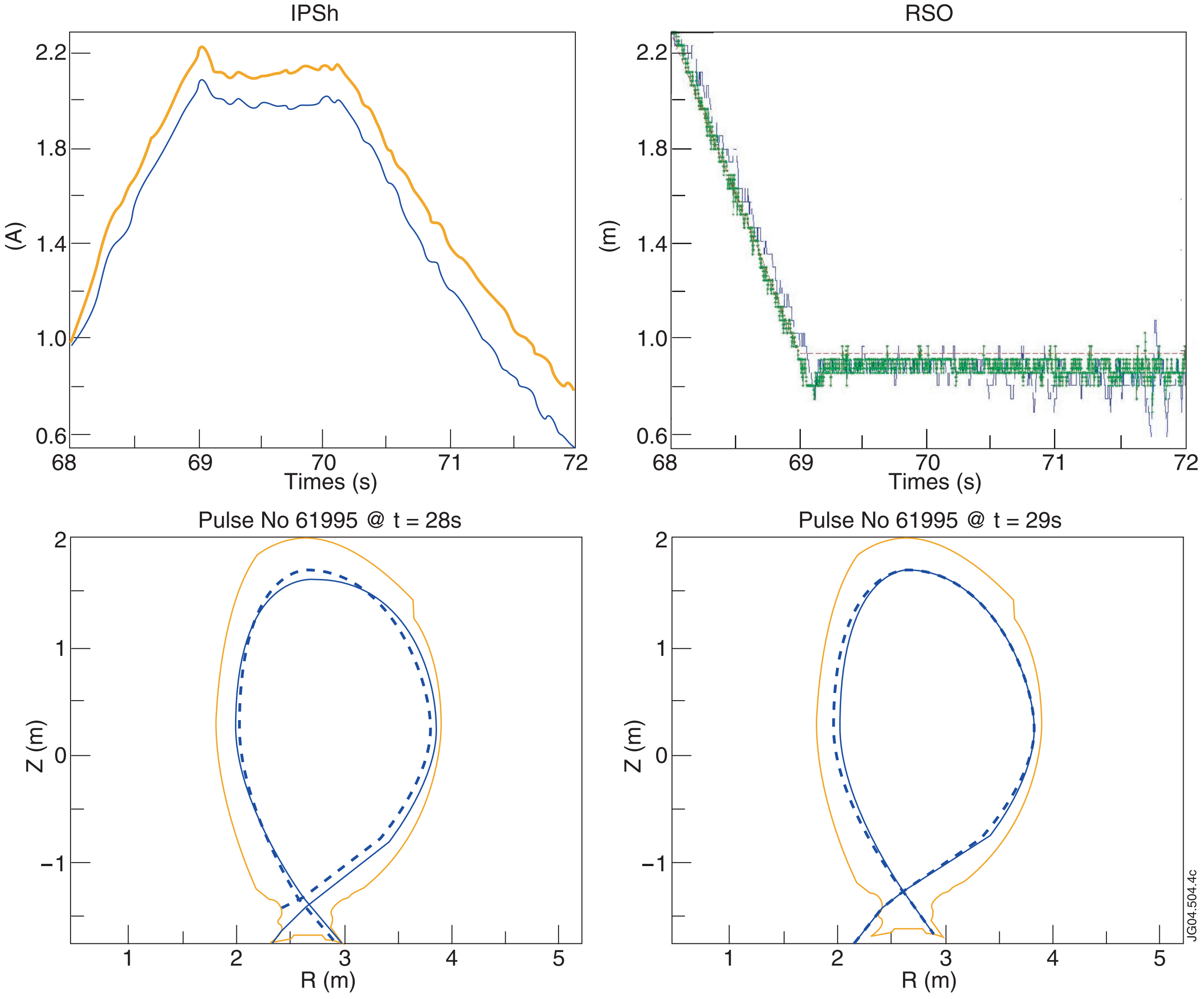

*Figure 4: JET Pulse No:61995, in which the XSC has been used from time = 28s to the end of the pulse ($I_p$ varying from 2 to about 1MA; li varying between 1 and 1.5; $\beta$~ = 0.1; transition time 1 s): a) a priori prediction vs. experimental value of the current in one of the PF circuits and the radial position of the outer strike point; b) a priori prediction (continuous line) and experimental boundary (dashed line) vs. desired shape(dotted line) at beginning and end of transition time.*