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Design, implementation and test of the XSC extreme shape controller in JET

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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 and without requiring a 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 $\Delta\beta_{\mathrm{pol}}$ up to 1.5 and Δl_{i} up to 0.5). The extreme shape controller (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.

Keywords: Shape control; JET; Tokamak; Feedback control strategies

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) [1], based on a philosophy similar to those adopted in ASDEX

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upgrade [2] and DIII-D [3], can only control a few plasma wall gaps or strike points. This, for strongly shaped plasmas, can lead to large deformations of the shape, mainly in case of large variations of poloidal beta β_{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 [4–6]. Its name is extreme shape controller (XSC), 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 β_{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 and without 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 β_{pol} ($\Delta\beta_{pol}$ up to 1.5) and/or l_i (Δl_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 [7].

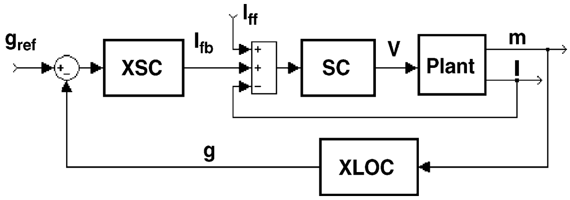

Fig. 1. JET XSC controller architecture.

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).

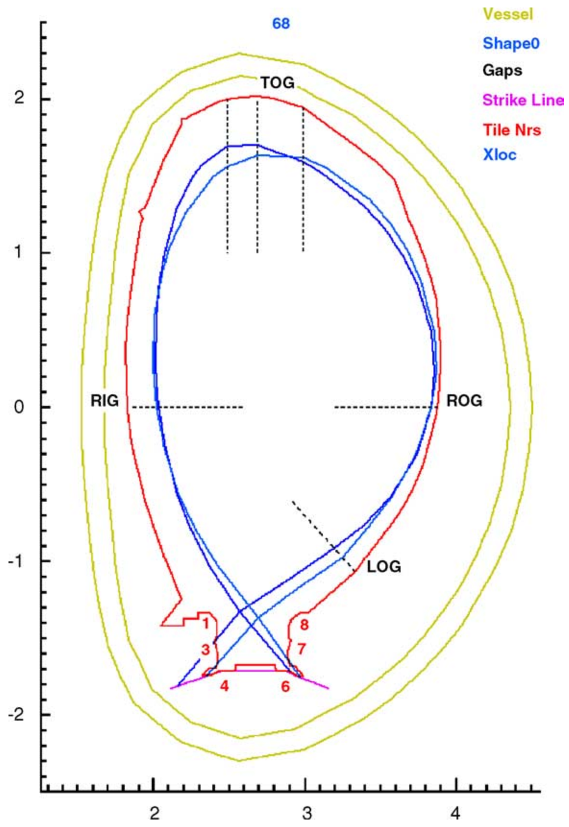

Fig. 2. Detail of the graphic window of JET XSC controller interface for the Session Leader, showing the gaps used by the old SC.

This model has been assessed on a set of JET pulses, carrying out current-driven open-loop simulations both in dry runs and in plasma shots [7].

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.

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 eight 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 eight 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 five or six directions (out of eight). The control algorithm [5] 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 internal module. This 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. As shown in Fig. 1, the XSC produces the current corrections that are summed to the feed-forward currents. The SC is used in full current mode, generating the voltage requests to the amplifiers. The plasma

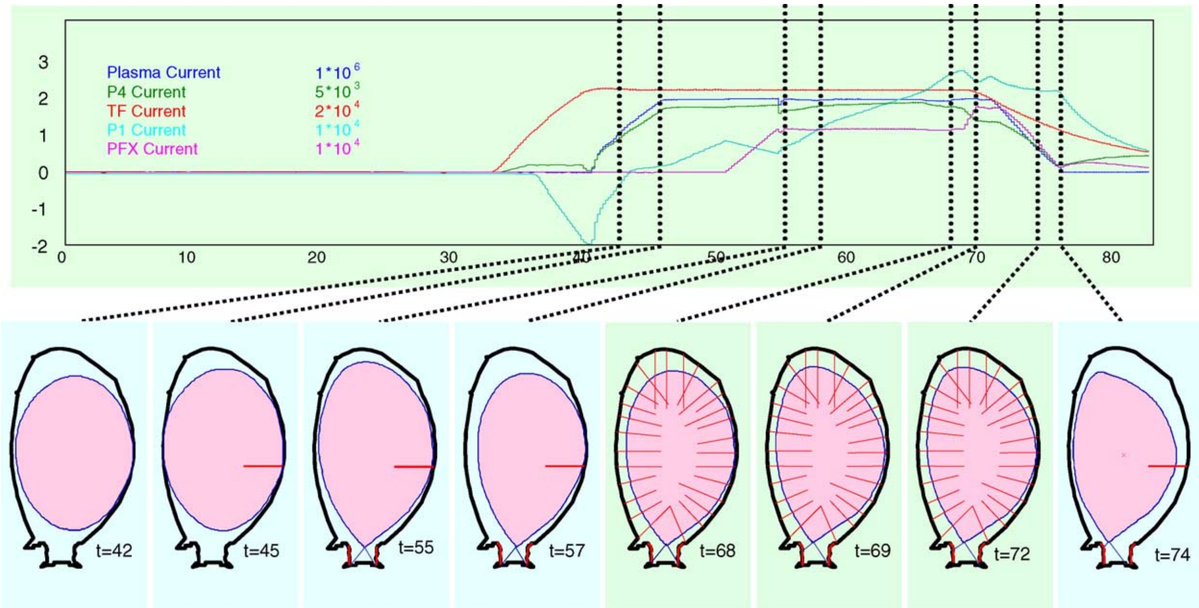

Fig. 3. JET pulse #61995. The XSC is activated in the time windows 68–72 s, and controls 32 gaps and 4 additional geometric descriptors representing the whole boundary shape. Before $t = 68$ s, SC controls the circuit currents and the radial outer gap only.

boundary is determined in real time from the magnetic measurements using XLOC.

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.

The transition time is limited by the time constant of the passive structures, by the frequency spectrum of the circuits taking into account the power supply limits, and by the possible interaction with the bandwidth of the vertical stabilization. As the circuits are equalized

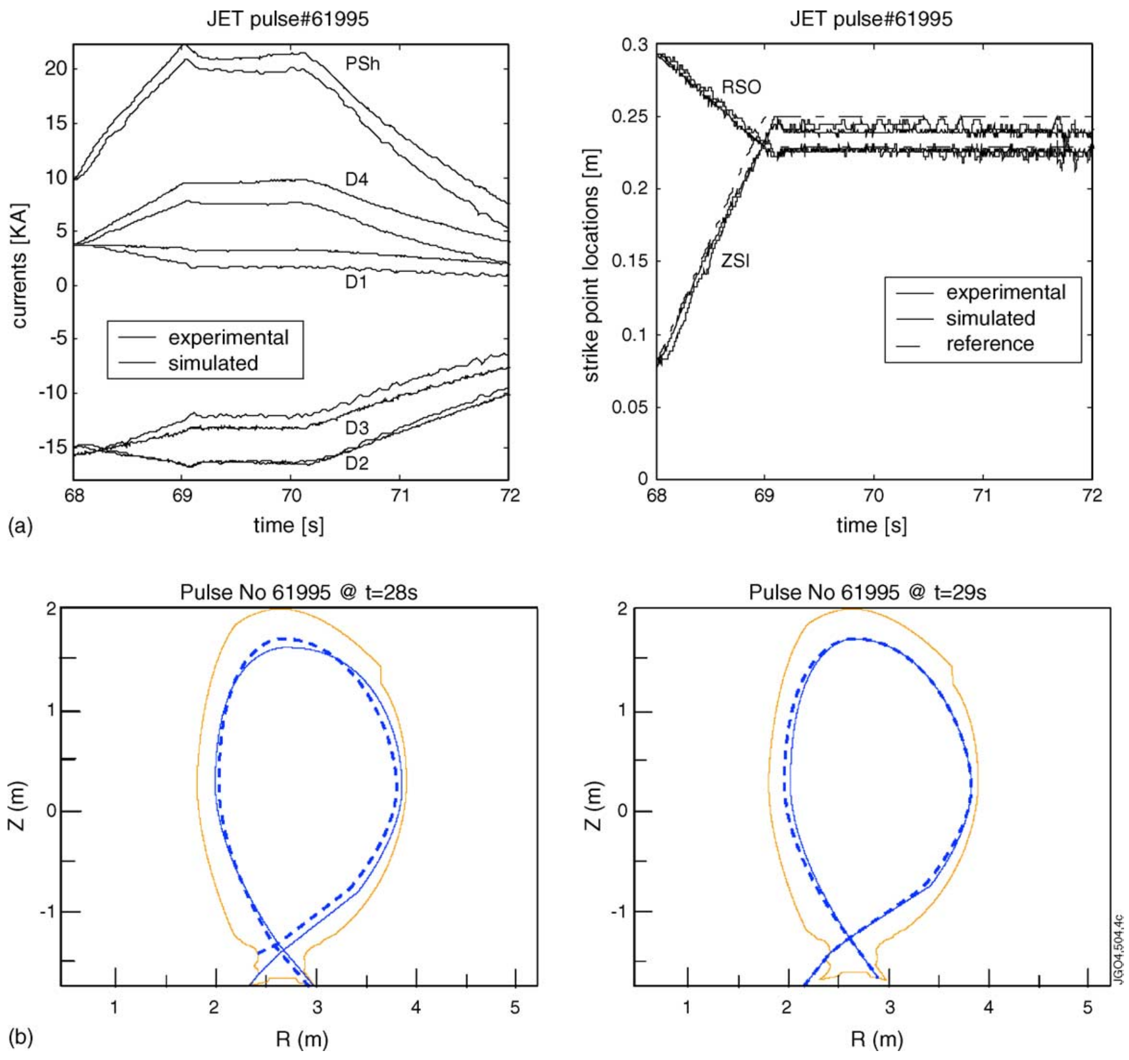

Fig. 4. JET pulse #61995, in which the XSC has been used from time = 68 s to the end of the pulse (I_p varying from 2 to about 1 MA; l_i varying between 1 and 1.5; $\beta_{pol} \sim 0.1$; transition time 1 s): (a) a priori prediction vs. experimental value of the current in one of the PF circuits and the radial position of the outer strike point; (b) experimental boundary (continuous line) vs. desired shape (dashed line) at beginning and end of transition time (t = time – 40 s).

via first order low 100 ms pass filters on each channel, the XSC operates reliably with a lower value of the transition time in the order of 250 ms.

The creation of a new XSC scenario takes about a hour, including definition of target configurations, derivation of linearized response models, selection of optimal controller gains, closed-loop simulations for testing controller performance, and transfer of relevant data to the interface for the Session Leader, who can interactively select a desired configuration (Fig. 2).

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 (Fig. 3).

Fig. 4 shows how the desired high triangularity has been kept within a RMS gap error of less than 2 cm even in the presence of wide excursion of I_p and l_i. Notice how the closed loop simulations are able to reliably predict the time behavior of currents and plasma shape.

In other pulses, the XSC has shown similar performance in the presence of wide variations of β_{pol} (Fig. 5) as well when tracking different shapes in various phases of the same shot, e.g., for pulse #62837.

In principle, the XSC can also be used from ramp-up till the end of a pulse, even if there are no stringent shape requirements in the phases, where the plasma is relatively cold. Obviously, this would require the selection of different target shapes in various time windows of the pulse with the use of different controller gains. In addition, a particular treatment would be needed in the transition from limited to diverted configuration, due to the strongly nonlinear response of some shape parameters in this phase.

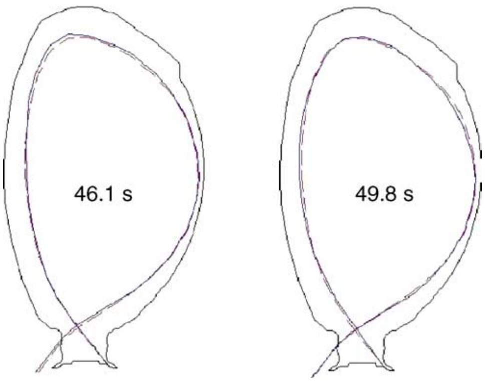

Fig. 5. JET pulse #62292, characterized by a wide ITB, in which the XSC has been used from 43.5 to 50 s. The desired shape (dashed line) is kept within a maximim error of 5 cm close to the upper and lower X-points in the presence of a wide β_{pol} excursion: $\beta_{pol} = 1.6$, $l_i = 0.8$, $I_p = 1.53$ MA at time = 46.1 s; $\beta_{pol} = 0.1$, $l_i = 1.0$, $I_p = 1.48$ MA at time = 49.8 s.

6. 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 experiments at high poloidal beta and in the presence of quite large variations of β_{pol} ($\Delta\beta_{pol}$ up to 1.5) and/or l_i (Δl_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.

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