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** See annex of M.L. Watkins et al, "Overview of JET Results ", (Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006)).*

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ABSTRACT

This paper describes the results of recent experiments carried out at JET using a modified version of the XSC (eXtreme Shape Controller) including the control of the boundary flux. This new controller has been used in the experiments for the real time control of current profile and in the stationary hybrid scenario experiments.

INTRODUCTION

Advanced Tokamak (AT) scenarios [1] in JET have been developed to achieve steadystate operations, with high energy confinement and large fraction of noninductive plasma current. AT scenarios pose challenging control problems, requiring simultaneous achievement of ambitious plasma performance. Amongst these problems, both shape control and the active control of the internal pressure and current profiles play an essential role. The control schemes presently adopted on tokamaks [2] for pressure and current profile control make use of the additional heating devices available on the machine. The inherent, unavoidable coupling among the feedback loops, calls for a careful design of the various controllers. This paper presents an example of integration between two control loops performed at JET using the XSC (eXtreme Shape Controller) [3]: the plasma shape control and the boundary flux control. So far at JET the XSC in flux control mode has been used in three different kinds of experiments. In the first experiments, a preassigned flux reference is passed to the controller; this reference is either a ramp with a constant slope or a sequence of ramps with different slopes. The controller has shown a good tracking of the references; the time needed to reach the reference is about 1.5s. Then, in the second kind of experiments, the reference for the flux is calculated in realtime by another, external controller; in these experiments [4] the target is to demonstrate that the boundary flux can be used as an actuator for the control of the current and pressure profiles, in addition to the heating devices. Eventually, the boundary flux controller has been a key tool for the successful experiments on the stationary hybrid scenario (see [5]), lasting 20s.

2. CONTROL ARCHITECTURE AND CONTROLLER DESIGN

This section introduces the plasma boundary flux control system implemented at JET in 2006. Figure 1 shows the poloidal field coils of the Joint European Torus (JET) tokamak. The XSC controls the whole plasma shape, specified as a set of geometrical descriptors (typically 32), calculating the poloidal field (PF) coil current references. These current references are then tracked by the standard Shape Controller (SC), which is set in currents control mode [3]. The XSC design is based on a plasma linearized state space model [6], which relates the variations of the PF currents to the variations of the geometrical descriptors around a given equilibrium.

Embedding the boundary flux controller into the XSC architecture enables the simultaneous control of both the entire plasma shape and magnetic boundary flux φ_b. The actuator that has been chosen to control φ_b is the current in the P1 circuit, since it has been shown that the other circuits are much less efficient and therefore it is much worth to use them for the shape control. When controlling φ_b, the SC releases the control of the P1 current to the XSC. Thus when the XSC controls φ_b the plasma current is not feedback controlled. To design the boundary flux controller, it is necessary to have a SingleInputSingleOutput (SISO) model in the form

$$\delta\varphi_b W(s)\delta_{P1}(s), \quad (1)$$

with the transfer function W (s) of order as low as possible, to make the design easier. By means of a model order reduction a transfer matrix W (s) of the fourth order has been obtained. Based on model (1), a ProportionalIntegral controller has been designed using standard control techniques. When the XSC is controlling the flux, the plasma current is left floating between safe prescribed bounds; if it exceeds these bounds, a smooth termination of the pulse (softstop) is triggered.

3. SOME EXPERIMENTAL RESULTS

In this Section we present some experimental results obtained using the XSC with the boundary flux control.

In JET Pulse No: 67835, the boundary flux control has been used to perform plasma loop voltage modulations, as it is shown in Fig.2. This shot has been carried out with a nominal plasma current I_p = 1.5MA, while the available additional heating powers during the 10s plasma current flattop was about 15MW. In this case the slope of φ_{bref} (t) is varied so as to obtain different values of plasma loop voltage V_l. The plasma current Ip then was left floating between 1.0MA and 2.0MA. The results of the plasma loop voltage modulation experiment are in good agreement with the simulation carried out using the XSC Tools [7].

In Fig.3, we show the experimental results obtained in JET Pulse No: 70404, where it was attempted to use 4 actuators, the 3 H&CD systems and the loop voltage, to control the safety factor profile in five positions. In this experiment, the XSC boundary flux controller was requested to track a reference generated by the external, profile controller. The profile controller is designed using a modelbased approach [4]. The integration between the boundary flux controller and the profile controller still needs to be assessed and optimized; the ongoing research efforts are concentrated on this topic.

CONCLUSIONS

A new version of the eXtreme Shape Controller has been developed, including the control of the boundary flux. This new controller has been used in different kinds of experiments at JET. This work was supported in part by Italian MiUR (PRIN grant #2006094025) and CREATE.

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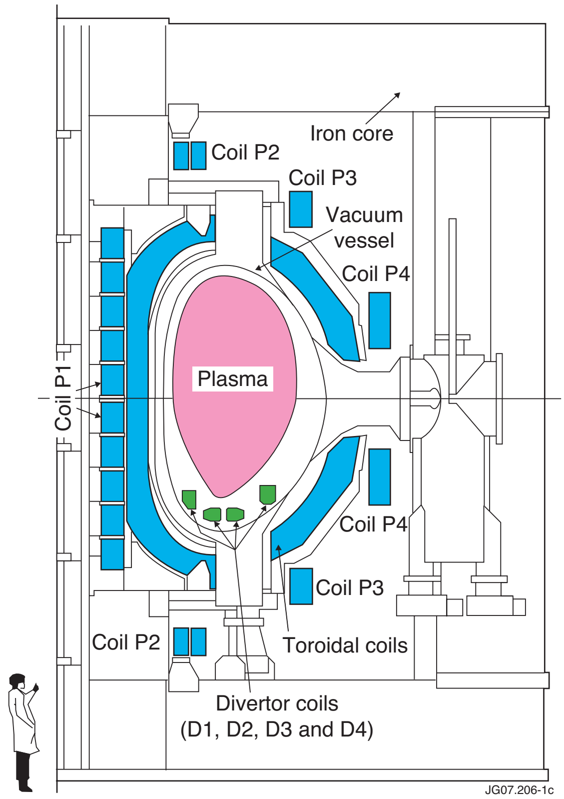

Figure 1: Cross section of the JET tokamak. Constant poloidal flux lines are shown inside the vacuum vessel. The plasma boundary is shown in red. The poloidal coils (P1P4 and D1D4) and the toroidal coils, which surround the plasma ring, produce the required magnetic field for plasma confinement. (Courtesy of EFDAJET)

(a) *Plasma boundary flux $\varphi_b(t)$.* (b) *Plasma current $I_p(t)$.*

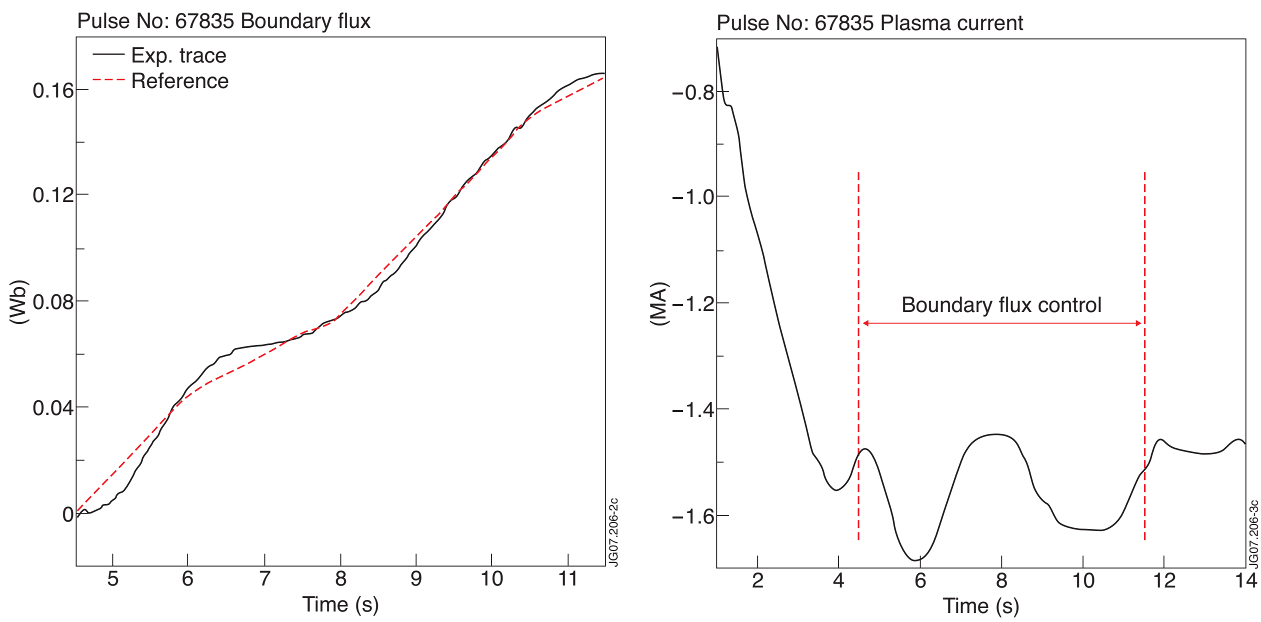

Figure 2: JET Pulse No: 67835 (B_t = 3.0T, I_p = 1.5MA) The boundary flux control is active between t = 4.5s and t = 11.5s.

(a) *Safety profile.* (b) *Requested (blue) and delivered powers.*

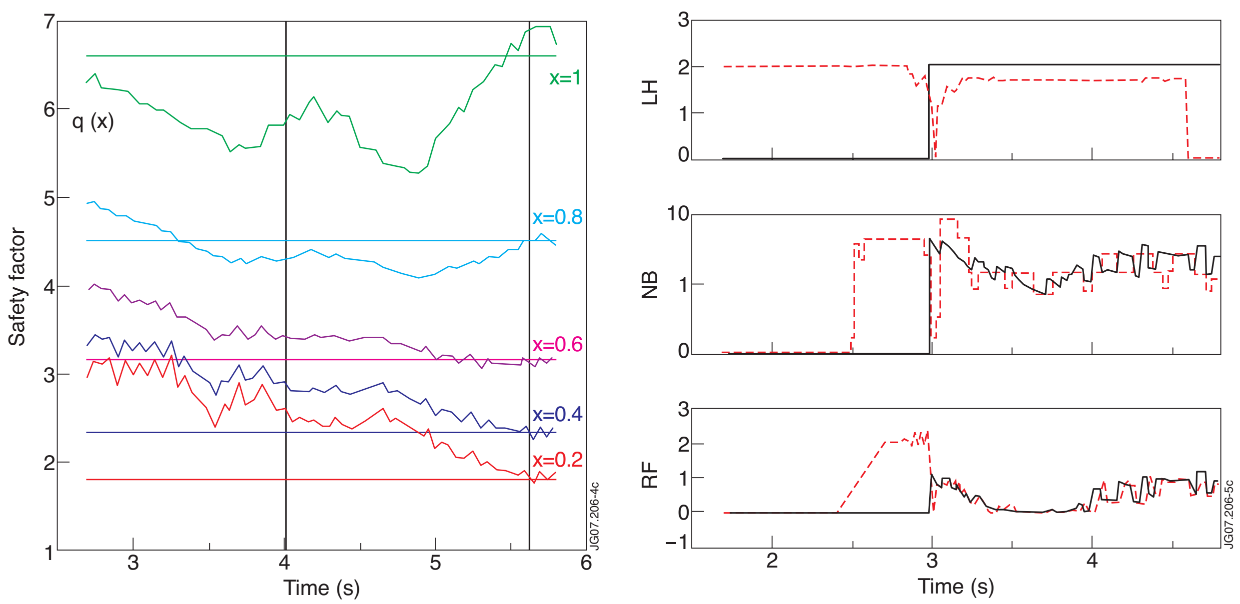

Figure 3: JET Pulse NO: 70404 (B_t = 3.0T, I_p = 1.5MA) Control of the safety factor profile at 5 normalised position, x = 1 (green), x = 0.8 (cyan), x = 0.6 (magenta), x = 0.4 (blue), x = 0.2 (red) using the 3 H&CD actuators and the loop voltage (not shown on the plot).