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ABSTRACT.

Simultaneous control of the plasma shape, the magnetic and kinetic plasma profiles (such as the safety factor, q(x), and gyro-normalized temperature gradient, $\rho_{Te}*(x)$, respectively) and the boundary flux is being investigated on JET, and has potential applications in the operation of ITER steady state advanced tokamak discharges. The control of radially distributed parameters was achieved for the first time on JET in 2004 [1-4]. The controller was based on the static plasma response only. The approach newly implemented on JET aims to use a dynamical plasma model, all the available Feating and Current Drive (H&CD) systems, and the Poloidal Field (PF) system in an optimal way to achieve a set of requested magnetic and kinetic profiles. This paper describes the new model-based optimal profile controller which has been tested during the last 2007 experimental campaign. The controller aims to use the combination of heating and current drive systems - and optionally the PF system. First experimental results of current profile control obtained during the last 2007 JET campaign are presented.

1. STATE-SPACE PLASMA RESPONSE MODEL IDENTIFICATION

The structure of the model stems from a set of transport equations,

$$\mu_0 \frac{\partial j}{\partial t} = -\nabla\times\nabla\times E, \qquad \frac{\partial n}{\partial t} = -\nabla.\Gamma+S_n, \qquad \frac{3}{2}\frac{\partial(nT)}{\partial t} = -\nabla.Q+S_T \tag{1}$$

in which couplings are retained with no loss of generality. The system (Eq.1) is linearized around an equilibrium reference state so that it can ultimately be cast in the generic form of a state space model. In doing so, the state variables appear naturally to be the variations of the internal poloidal magnetic flux, Ψ, and of the temperature, T, and the state space model reads:

$$\partial\Psi/\partial t = A_{11}\,\Psi(t) + A_{12}\,T(t) + B_{11}\,P(t) + B_{12}\,n(t) + U.V_{ext}\,(t) \tag{2}$$

$$\varepsilon\partial T/\partial t = A_{21}\,\Psi(t) + A_{22}\,T(t) + B_{21}\,P(t) + B_{22}\,n(t) \tag{3}$$

with inputs $P = [P_{LH}, P_{NBI}, P_{ICRH}]$, the heating and current drive input powers, and V_{ext}, the surface loop voltage. The distributed variables $\Psi(x)$ and $T(x)$, where x is a radial coordinate, are projected onto a finite set of trial functions using a Galerkin scheme so that the original partial differential system of equations reduces to an ordinary linear differential system where U is known and $A_{i,j}$, $B_{i,j}$ are matrices of appropriate dimensions which are to be identified from experimental data. The small (constant) parameter, ε, represents the ratio between the energy confinement time and the characteristic resistive diffusion time ($\varepsilon \ll 1$).

2. TWO-TIME-SCALE APPROXIMATION

To take advantage of the small parameter ($\varepsilon \approx 0.05$ in JET), the control technique proposed here is based upon the theory of singularly perturbed systems and multiple-time-scale expansions [5]. We therefore seek two models of reduced orders, a slow model,

$$\partial\Psi/\partial t = A_s\,\Psi + B_s\,u_s \qquad \text{together with} \qquad T_s = C_s\,\Psi + D_s\,u_s \tag{4}$$

and a fast model ($\tau = t / \varepsilon$),

$$\partial T_f/\partial\tau = A_f\,T_f + B_f\,u_f \tag{5}$$

where $T = T_s + T_f$, and where u_s and u_f are the slow and fast components, respectively, of a vector, $u = u_s + u_f$, containing all the inputs (P, n and V_{ext}).

Having identified a set of relevant state variables, it can prove practical to apply the control to some output parameters which are more directly linked with MHD stability or internal transport barrier physics. The inverse of safety factor, ι (x), and gyro-normalized temperature gradient, ρ_{Te}*(x) [6], have been chosen and are thus introduced into the state-space model. As for Ψ((x)) and T((x)), a Galerkin approximation is used and in the following, the notations Ψ, T, μ and ρ will refer to the coefficients of the Ψ(x)), T((x)), ι((x)) and ρ_{Te}*(x) expansions, respectively. Noticing that ι ((x)) $\propto \nabla\Psi$((x)) and ρ_{Te}*((x)) $\propto$ ∇Te((x))/$\sqrt{}$Te(x)), linearizing these expressions, differentiating the basis functions and assuming that the time variations of factors such as the toroidal magnetic field and toroidal magnetic flux are not essential and do not depend intrinsically on the power inputs, it appears relevant to seek a model with direct matrix relations between the Galerkin coefficients Ψ and μ, on one hand, and between T and ρ on the other hand. Within the two-time-scale approximation, this yields:

$$\mu = C_{\mu,\psi}.\Psi \quad \text{and} \quad \rho_s = C_{\rho,\psi}\Psi + D_{\rho,\psi}\,u_s \quad (\text{or } \rho_s = C_{\rho,\mu}\mu + D_{\rho,\mu}\,u_s) \tag{6}$$

and

$$\rho_f = C_{\rho,T}.\,T_f \tag{7}$$

which complete the system (Eq. 4-5). The identified two-time-scale model is then used to construct and design a controller which can respond faster to rapid plasma events, while converging slowly towards the requested high performance plasma state (on the resistive time scale) [8].

3. EXPERIMENTAL RESULTS

The next step was to apply this controller to a real plasma discharge. In order to validate the controller, and as an intermediate step, we concentrated during the 2007 campaign on the control of the q-profile only. The main actuators were the LH, ICRH, NBI powers and the loop voltage. Open loop modulations of those actuators were performed around a reference state in order to identify the plasma model. A highly triangular ($\delta = 0.45$) configuration was chosen to perform both open and closed loop experiments with a toroidal magnetic field of 3T, a plasma current of 1.5MA and an average density of about $3.5\times10^{19}\,m^{-3}$.

Examples of such modulation of the heating and current drive actuators are given in Fig.1. As the q profile evolves on the resistive time scale, those modulations were relatively slow. In a same way, control of the loop voltage was possible due to the development of the JET Extreme shape controller [7, 9]. Comparison between the measured data and the reconstructed data using the identified model can be seen in Fig.2. Good agreement was found and feedback control experiments of the current profile were then performed. Control of q profile was performed over a period lasting more than 7s using the 3 H&CD systems while keeping the loop voltage at a constant value (see Figs.3 & 4), and for a shorter period with the loop voltage included in the loop (Fig.5). An important step has been made in demonstrating the validity of this new controller and the potential for controlling the safety factor profile.

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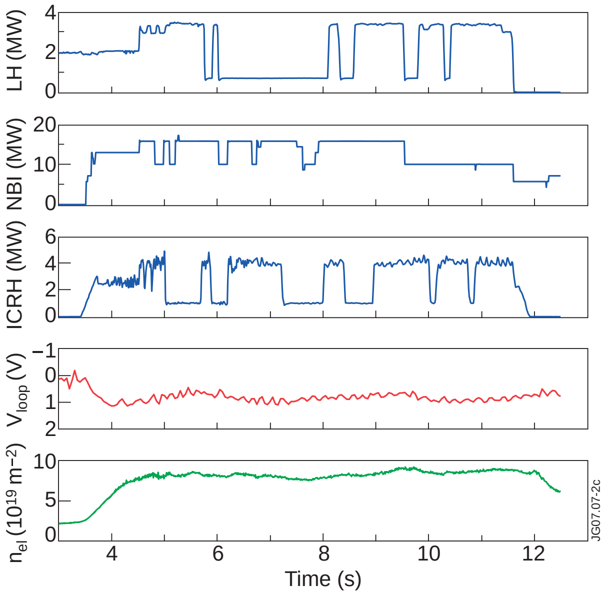

Figure 1: Input powers for modulated Pulse No: 67876, loop voltage and line integrated density..

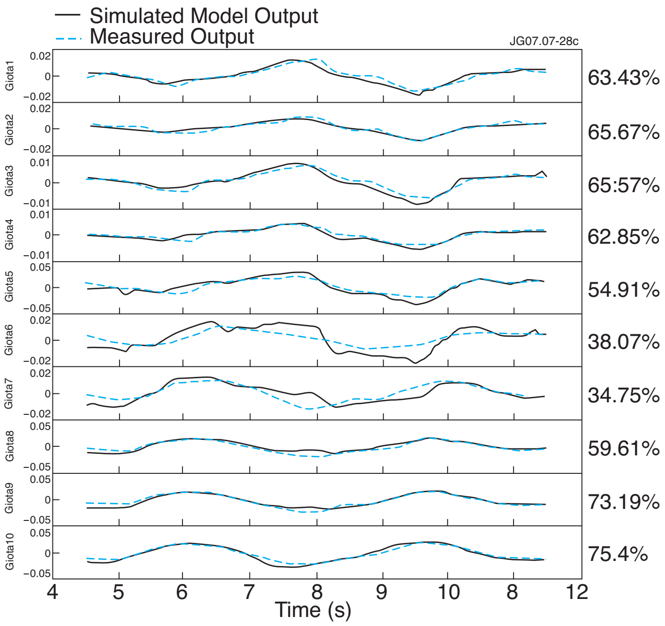

Figure 2: Comparison between reconstructed and measured iota profile for Pulse No: 67876 at 10 fixed normalized radii..

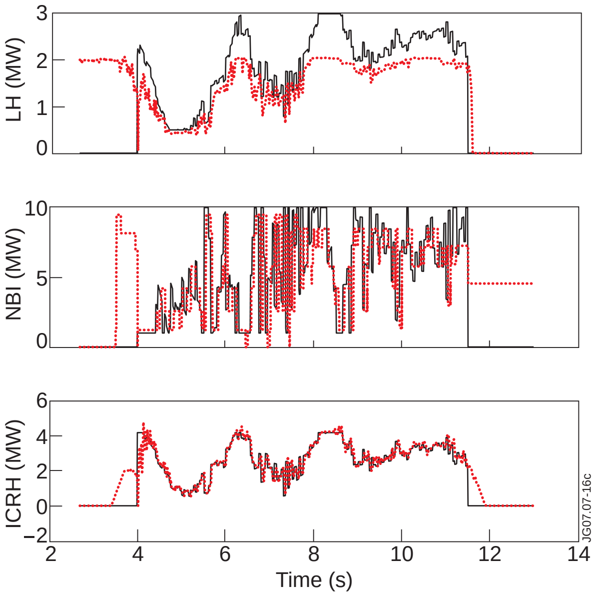

Figure 3: Requested and delivered powers (LHCD, NBI, ICRH) for the controlled Pulse No: 70395.

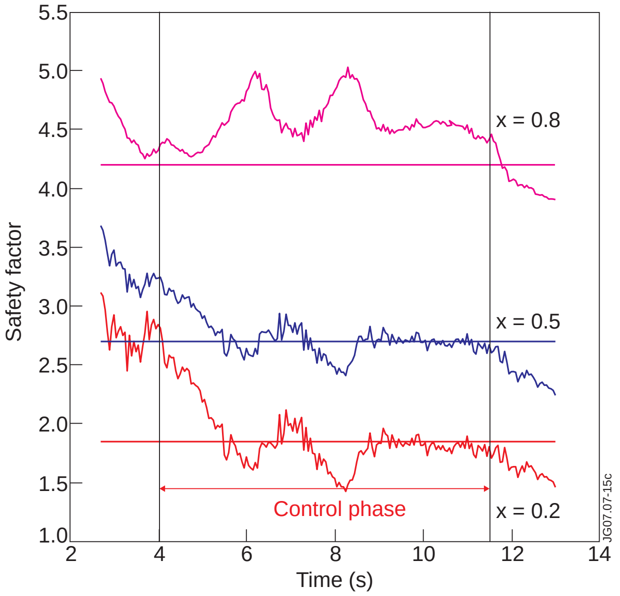

Figure 4: Control of the safety profile at 3 normalised position using the 3 H&CD actuators.Pulse No: 70395. Vloop constant (32 mV/rad).

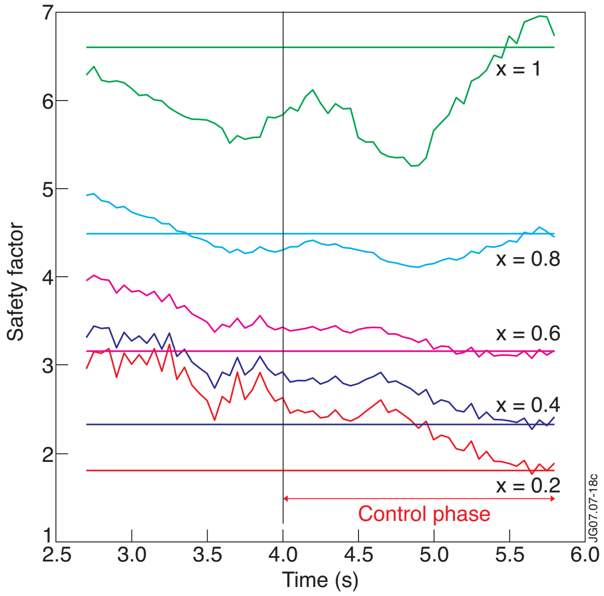

Figure 5: Control of the safety profile at 5 normalised position, x=1 (green), x=0.8 (cyan), x=0.6 (magenta), x=0.4 (blue), x=0.2 (red) using the 3 H&CD actuators. Pulse No: 70395.