REAL TIME CONTROL OF PLASMA PROFILES AT JET

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ABSTRACT

This paper describes the work that has been done in the recent past and the work in progress at JET regarding the control in real-time of current and temperature profiles. The possibility of achieving such control appears to be crucial in the high performance plasma regimes, where the reduction of the turbulence in the plasma leads to the onset of an Internal Transport Barrier (ITB). Maintenance of ITB regimes during tokamak operation is a critical issue: real-time control of both the safety factor q and of the pressure profile is needed. In this paper we present some experimental results obtained at JET and we briefly describe the next steps.

INTRODUCTION

In operating tokamaks real-time feedback control is mainly adopted in two contexts: *i*) for the control of the plasma current, position and shape by means of the poloidal field coils; *ii*) for the control of current, temperature and density profiles by means of the additional heating and current drive devices.

The control of the plasma current, position and shape has been widely studied and is well assessed. Different, more or less sophisticated, feedback controllers are used on all the operating tokamak machines. For this control, it is possible, in general, to use complex control algorithms since reliable mathematical models that describe how the variables to be controlled vary are available. This is a crucial point: most control techniques (the so-called *model-based* control techniques) rely upon the availability of a mathematical model of the process to control. If the model is reliable, then it can be used as the starting point of the controller design procedure. A complete survey on modelling and control of current, position and shape of axisymmetric plasmas can be found in [1].

Recently, many experiments on tokamaks have focused on the possibility of achieving high performance plasma regimes, potentially leading to steady-state operation. Generally, the reduction of the turbulence in the plasma leads to the onset of an Internal Transport Barrier (ITB), characterised by a reduced particle and heat transport. Consequently, these transport barriers have the feature of very steep pressure profiles. Maintenance of ITB regimes during tokamak operation is a critical issue: real-time control of both the safety factor q (parameter proportional to the ratio of the toroidal field over the poloidal field) and of the pressure profile is needed.

Design of sophisticated controller for the plasma profile control is much more complicated than for shape control since almost no reliable mathematical models describing how the profiles quantities behave in response to heating power variations are available. Indeed most of the codes adopted in this context can only be used to interpret past experiments and to predict just *qualitative* behaviours of future experiments. Therefore transport modelling cannot directly be used to obtain reliable models to be used to accurately simulate transient responses and internal transport barriers (ITB's). For this reason, for the plasma profile control the models that are usually adopted are identified from experimental data.

During last experimental campaigns of 2003-2004 at JET, a model-based design technique has been proposed and implemented [2,3] to control the profiles of q and of ρ^*_{Te}, a parameter linked to the electron temperature gradient [4], using the three heating and current drive systems. On the basis of experimental results, an algebraic mapping of the plasma response to the variation of the heating powers has been identified. Using this matrix, the parameters of a multivariable PID controller have been tuned. This controller has been experimentally validated, and it has shown to be able to keep the profiles close to the target ones.

In the next future, an improvement of the performance is expected to be achieved using dynamic plasma profile response models. The model identification and controller algorithms will first be tuned on the simulation results given by transport codes, and then refined on experimental results of dedicated discharges. The dynamic model will enable to explore the possibility of using a two-time scale control approach [5], based on the fact that the temperature profile response is faster then the current profile response.

This paper describes the methodology used in the past campaigns for the combined control of q and of ρ^*_{Te}, presenting some experimental results. Then we will briefly present how the dynamic model will be derived and how the future experiments of next JET experimental campaign will be designed.

CONTROL TECHNIQUE FOR PROFILE CONTROL AT JET

The control technique used at JET assumes that the plasma dynamics can be linearized around an equilibrium reference stationary state with an ITB. The observation of stable stationary conditions corresponding to the application of steady powers would in principle require pulse durations which are much longer than the current resistive time. However, by performing dedicated open-loop experiments in a regime sufficiently below maximum performance, and with pulse lengths in the range of 12–15 s, one can reach a steady plasma state which is assumed to be sufficiently close to an equilibrium to be used as a reference state. The current density profile is characterized by the safety factor profile $q(x)$, or its inverse, $\iota(x)$, related to the rotational transform. The coordinate x is a normalized radius, $x=r/a$, where r is the half-width of a flux surface in the equatorial plane and a is the minor plasma radius (half-width of the plasma in the equatorial plane), so that $x=0$ corresponds to the magnetic axis (plasma core) and $x=1$ to the separatrix of the plasma. The pressure profile is characterized by a dimensionless parameter $\rho^*_{Te}(x)$ which is the thermal Larmor radius normalized to the characteristic length of the electron temperature gradient. It has been used at JET to detect the emergence of an ITB and to measure its strength. A criterion for the existence of an ITB at radius x can be expressed on JET as $\rho^*_{Te}(x) \geq \rho^*_{ITB}$, where $\rho^*_{ITB} = 0.014$.

Measurements constraints and physical considerations lead to control only part of the profiles. The control of the q-profile has been restricted to the region $0.2 \leq x \leq 0.8$. For $\rho^*_{Te}(x)$, the control region has been reduced to $0.4 \leq x \leq 0.6$ where an ITB was requested. An optimised set of basis functions and nodes have been found for the profiles approximation. Following that study, the safety factor $q(x)$ profile was projected upon 5 cubic splines ($a_i(x)$, i = 1…5) with knots at x = [0.2, 0.4, 0.5, 0.6, 0.8], and the normalised electron temperature gradient $\rho^*_{Te}(x)$ profile was projected onto 3 triangle functions ($b_j(x)$ j = 1…3) with knots at x = [0.4, 0.5, 0.6].

Having defined the plasma parameters to be controlled, let us introduce the actuators used for the control: the heating and current drive systems. The JET tokamak is equipped with three additional heating and non-inductive current drive systems which we use as actuators for current and temperature profile control: lower hybrid current drive (LHCD), ion cyclotron resonance heating (ICRH) and neutral beam injection (NBI). The first two systems use electromagnetic waves to accelerate some classes of resonant ions (ICRH) or electrons (LHCD), which then collisionally heat the plasma and drive currents. The NBI injects high energy neutral particles which get ionized in the plasma. The resulting fast ions then deposit their energy through collisional slowing down – also driving currents if they are injected in a given toroidal direction – until they eventually thermalize.

A linearized Laplace transform model of the form **G**(s) = **K**(s) **P**(s) was assumed around the reference plasma steady state, where **G**(s) is a 8-by-1 vector representing the variation of the profile coordinates in the chosen trial function bases, and **P**(s) is a 3-by-1 input power variation vector. For the experiments described below, the steady state gain matrix **K**(0) was sufficient and was deduced from simple step power changes in dedicated open loop experiments. A pseudo inverse matrix of **K**(0), $\mathbf{K}_{\mathrm{inv}}$, was used to design a controller which computes the power inputs to be applied in order to minimize the error signals. A simple proportional-plus-integral feedback control with minimum (least square) steady state offset, was obtained by choosing the controller transfer function matrix **H**(s) as follows:

$$\mathbf{H}(s) = g_c\,[1 + 1/(\tau_i\, s)]\,\mathbf{K}_{\mathrm{inv}} \tag{1}$$

where g_c is a proportional gain and (g_c/τ_i) is an integral gain.

Experimental results

The feedback control was applied in a 3T/1.7MA plasma during a maximum of 7 seconds, and allowed to reach successfully different target q-profiles - from monotonic to reversed shear – while simultaneously controlling the profile of the electron temperature gradient [2]. The detailed results of the applied feedback scheme is shown in Figure 1 for the JET Pulse No: 62160, (with a reversed shear target q and a target ρ^*_{Te} profile just above the ρ^*_{ITB} criterion) where the time traces of the profile values at the radial knots, and their corresponding targets (dotted line) are presented. The scenario and parameters of this discharge can be seen in Figure 2. An ion ITB appears at t = 8 s and the loop voltage is approximately 0.05 V, meaning that the plasma current was almost fully non inductively driven during the time of the control. To obtain this result the profile $1/q(x) = \iota(x)$, rather than $q(x)$, was controlled because it is directly proportional to the current density and therefore depends more linearly on the applied current drive power than $q(x)$.

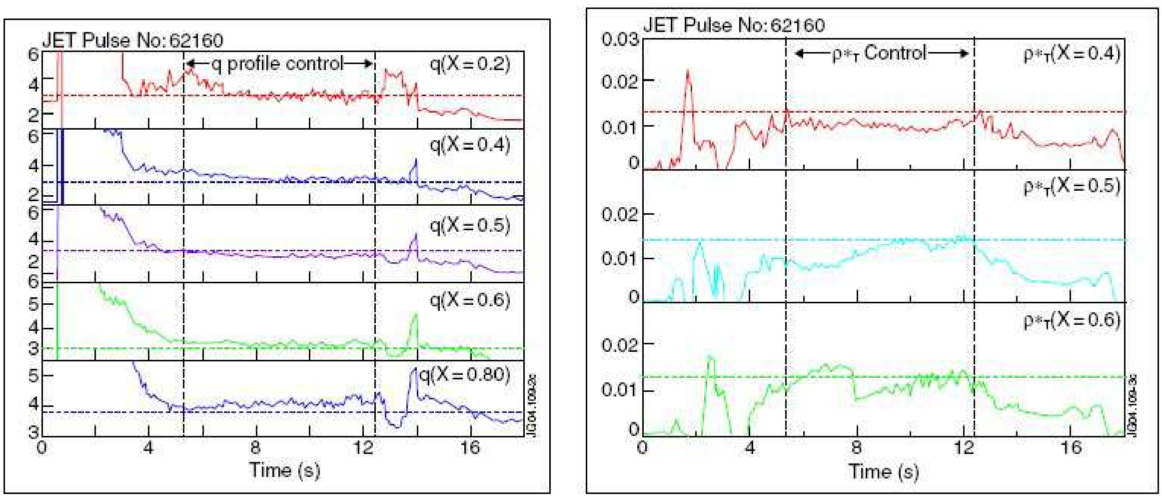

Figure 1: Time evolution of the measured and requested q values (a) at 5 radii and ρ^*_{Te} values (b) at 3 radii for a controlled pulse (Pulse No: 62160 B_T = 3T I_P = 1.7MA, current flat top starts at 4 s. Dashed lines are set point q and ρ^*_{Te} values. Control starts at 5.5 s and stops at 12.3 s.

IDENTIFICATION OF A STATE-SPACE MODEL

The procedure described in the previous section is based upon a static model of the plasma profile responses. The availability of a dynamic model would make it possible to tune the controller gains so as to have a desired transient response. For this reason a procedure has been set up to identify a dynamic linearized model. This state-space model is designed to best reproduce the response of the current and temperature gradient profiles (outputs $1/q$ and ρ^*_{Te}) to power modulations. The model is therefore in the standard state-space form

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \qquad (2)$$

where u and y are the model inputs and outputs respectively, and x is the model state. The identification procedure has consisted of the following steps (see also [6]):

- definition of the model inputs and outputs;
- choice of the model structure;
- choice of the input-output data to use for the identification procedure (*estimation data*);
- definition of the cost function to optimize in order to obtain the “best possible” model;
- validation of the model against suitable input-output data (*validation data*).

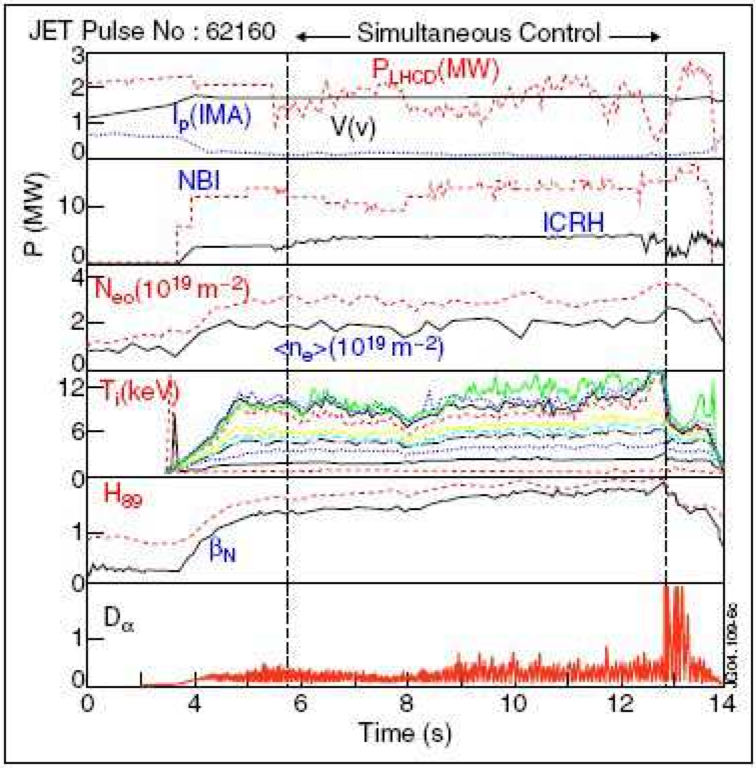

Figure 2: Time evolution of the LHCD, ICRH, NBI power waveforms, loop voltage, plasma current, central and mean density, T_i, H_{89}, β_N, D_α of a controlled pulse (Pulse No: 62160, $B_T = 3T$, $I_P = 1.7MA$).

This procedure has been applied making use of experimental data of JET past campaigns. The model has been identified making use of a so-called *black-box* approach [6]: all the coefficients of the matrices A, B and C are left free so as to allow the best possible fitting with the estimation data. No physical meaning of the state variable is retained. Once a satisfying model has been obtained using a trial and error procedure, it has been validated against other JET data. The validation has been carried out on discharges which were not included among the estimation data. Two different kinds of simulations have been considered: *i*) testing just the identified model taking as inputs the powers from the JET database (open-loop simulations); *ii*) testing the expected profiles behaviours closing the loop with the controller (1) (closed-loop simulations). Figures 3 and 4 show some results obtained for an open-loop and a closed-loop simulation, respectively. While the open-loop simulation gives satisfying results, in the closed-loop simulation, major discrepancies between the simulated traces and the experimental traces arise. The reasons for these differences need to be investigated in detail. Preliminary analyses have indicated some possible explanations: *i*) the time-window of the available experiments (~7 s) seems to be too short for identification purposes (the transient phase is not over yet); *ii*) besides the considered inputs u in (2), there are other variables that affect the profiles of q and ρ^*_{Te} that should be taken into account to improve the model performance.

DEVELOPMENTS AND PREPARATION OF FUTURE EXPERIMENTS

Alternative procedures in which the physical meaning of the state variables is retained and constraints are imposed on some elements of the matrices A, B and C are also under development [7], using simulated data and will be tested using experimental data. In the next experimental campaign of 2005-2006, it is foreseen to use a fully dynamic linearized model that takes into account the physical structure and couplings of the transport equations. This state-space model tries to predict the response of the current and temperature gradient profiles to power and loop voltage modulations. The outputs $1/q$ and ρ^*_{Te} evolve on different time scales: whereas $1/q$ is slow due to long current diffusion time (in absence of MHD activity), ρ^*_{Te} can be split in two components: a slow one $\rho^*_{Te\,slow}$ and a fast one $\rho^*_{Te\,fast}$ so that $\rho^*_{Te}=\rho^*_{Te\,slow}+\rho^*_{Te\,fast}$. The identification technique has been applied on data obtained from fully predictive and self-consistent simulations using the JETTO transport code: the plasma response to power and loop voltage modulations has been simulated and the inputs and outputs have been considered as experimental data. First, the state-space model is identified from a restricted training set of data. Then it has been checked that the model is able to reproduce with good agreement the outputs ($1/q$, ρ^*_{Te}) using a different set of inputs. 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]. This two-time-scale proportional-integral controller is designed using singular perturbation methods [5].

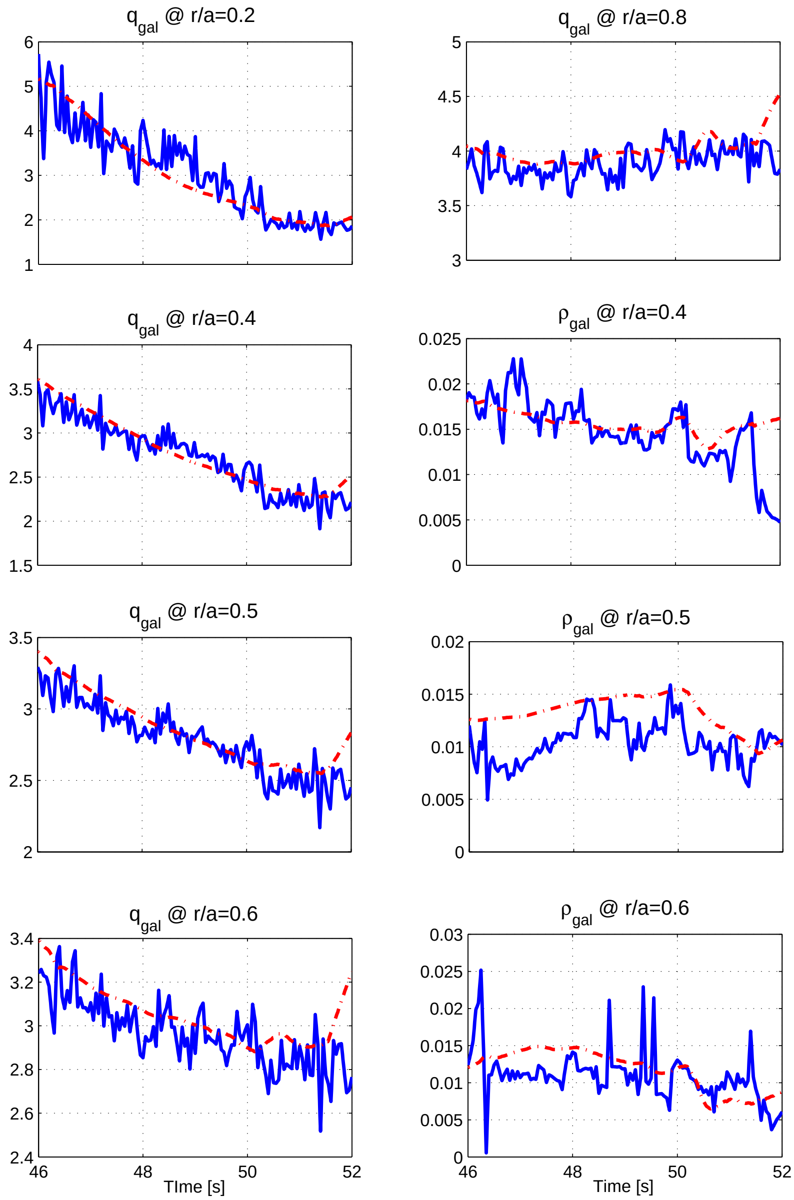

Figure 3: Time evolution of q and ρ^*_{Te} profiles as predicted by the identified model (1). The experimental traces are shown solid, the simulated traces dash-dotted. The simulation has been carried out in open-loop.

CONCLUSIONS

In this paper some recent results obtained at JET on the control of current and pressure profiles have been presented. Moreover, the next steps that are under preparation have been outlined. Up to now a static model of the plasma profile responses has been employed to design the feedback controller. In the near future a dynamic model, identified from dedicated discharges, will be used. This model will exploit the fact that the current and the temperature profiles evolve on different time scales. The profile control problem will then be tackled using singular perturbation methods [5].

"Advanced tokamak" operation scenarios in ITER require the availability of reliable and routine control of the plasma profiles. Therefore obtaining effective and routine profile control in an operating machine is an essential step.

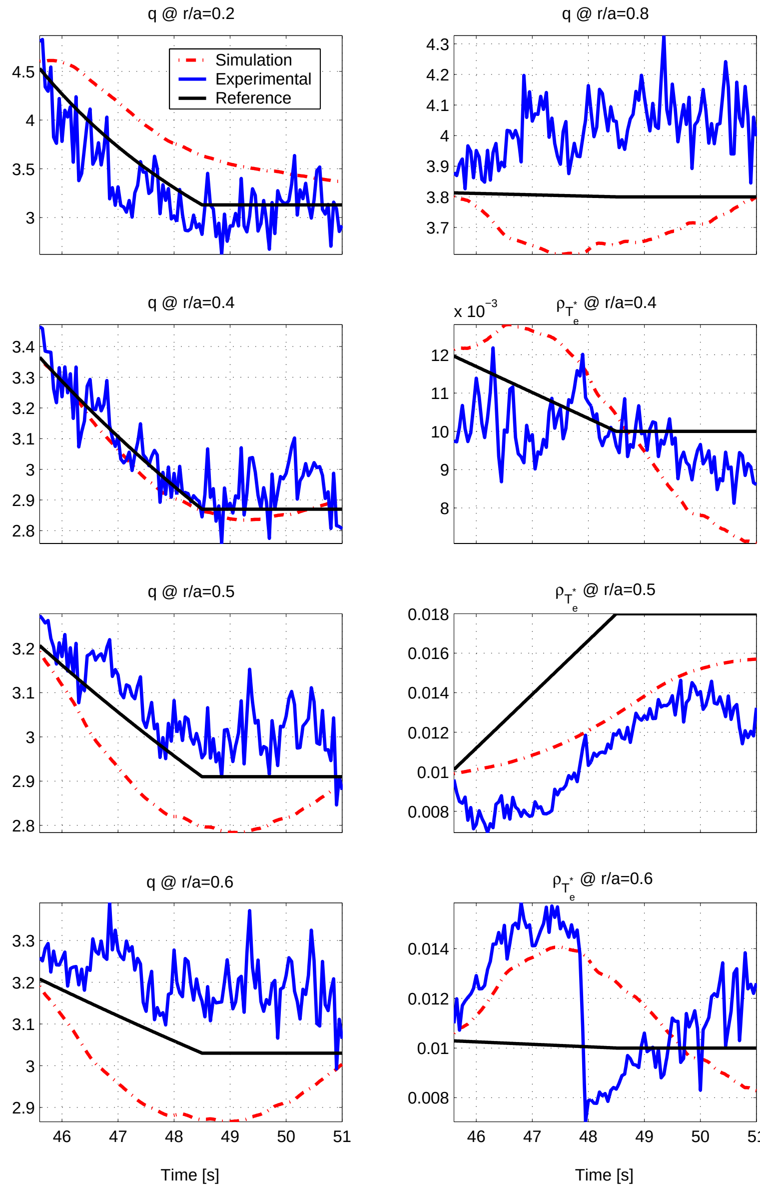

Figure 4: Time evolution of q and ρ^*_{Te} profiles as predicted by the identified model (1). The simulation has been carried out in closed-loop

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