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Simultaneous Real-Time Control of the Current and Pressure Profiles in JET: Experiments and Modelling

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INTRODUCTION

Real-time control of the plasma profiles (current density, pressure and flow) is one of the major issues for sustaining Internal Transport Barriers (ITB) in a high performance plasma, with a large bootstrap current fraction. Indeed, the controllability of the proposed advanced scenarii must be demonstrated to envisage steady state operation in ITER, and the control of advanced discharges in JET is an essential part of this program. Past experiments focussed on the separate control of the maximum normalised electron temperature gradient ρ^*_{Te} (see definition in [3]), on one hand [1], or of the safety factor profile on the other hand [2], in different discharges. A major challenge still remains to control both the current and pressure profiles that are non-linearly coupled and therefore mix up the resistive and confinement time scales in a non-trivial way. We have recently investigated the experimental and numerical aspects of the *simultaneous* control of the current and pressure profiles in JET ITB discharges. The current density and the electron temperature were successfully controlled via the safety factor profile (or via its inverse the *ι*-profile) and the ρ^*_{Te} profile, respectively. The results of these new studies will be presented here.

1. MODEL BASED PROFILE CONTROL TECHNIQUES

In order to cope with the coupled evolution of the pressure and current density profiles in ITB discharges a multi-variable model-based technique has been used [4]. It relies on the experimental determination of a linearized integral model operator identified from modulation experiments around a target steady-state. This approach has been already used in JET past experiments for the real-time control of the current density profile during a low [2] and high performance phase [4], but at that time the pressure was not simultaneously controlled and the method was applied to discrete values of the current profile at 5 given radii. Here, for the first time, the model retains the distributed nature of the plasma parameter profiles using an appropriate set of trial basis functions which allows a better approximation of those profiles [5]. Measurements constraints and physical considerations lead to control only part of the profiles. For q(x), with x representing the normalised plasma radius, the reconstructed real-time profiles from polarimetry data [6] are in poor agreement with the off-line numerical codes computing the magnetic equilibrium in the central region [0, 0.2]. As a consequence no accurate information can be used for $x<0.2$. Moreover, the q-value at the plasma edge $[x = 1]$ is proportional to the total plasma current and is independently controlled by the primary circuit of the tokamak. Therefore, the control of the q-profile has been restricted to the region $0.2 \leq \times \leq 0.8$. For ρ^*_{Te}, the control region has been reduced to $0.4 \leq \times \leq 0.6$ where an ITB was requested and also because the real-time electron cyclotron emission diagnostic provides no temperature measurements at the edge and in the core of the plasma. 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 (ai(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 (bj(x) j = 1…3) with knots at x = [0.4, 0.5, 0.6], [5].

A linearized Laplace transform model of the form **G**(s) = **K**(s) **P**(s) was then assumed around the reference plasma steady state, where **G**(s) is a [8×1] vector representing the variation of the profile coordinates in the chosen trial function bases, and **P**(s) is a (3×1) 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), $\mathbf{K}_{inv}$, 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 [4, 5] : $\mathbf{P}(s) = \mathbf{H}(s) \cdot \mathbf{G}(s) = g_c\ [1 + 1/(\tau_i \cdot s)]\mathbf{K}_{inv}\ \mathbf{G}(s)$ where g c is a proportional gain and (g_c/τ_i) is an integral gain. The related algorithms have been implemented in the JET control system, allowing the use of the three heating and current drive actuators (NBI, ICRH, LHCD).

2. EXPERIMENTAL RESULTS AND SIMULATIONS

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. The detailed results of the applied feedback scheme is shown in Fig.1 for the Pulse No: 62160, (with a reversed shear target q and a target ρ^*_{Te} profile just above the ρ^*_{ITB} criterion - equal to 0.014 in JET - which defines the existence of an ITB at radius x when $\rho^*_{Te}(x) \geq \rho^*_{ITB}$) 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 Fig.2. An ion ITB appears at t=8s and the loop voltage is approximately 0.05V, meaning that the plasma current was almost fully non inductively driven during the time of the control. A clear benefit of the control can also be seen on a global parameter such as the internal inductance li which is indirectly controlled through q(x). Fig.3 compares l_i on this pulse with l_i on the uncontrolled (open loop) reference pulse, and it indicates that the controlled pulse current profile was indeed more stationary. 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). It has been demonstrated [4] that the controller minimizes in the integral least square sense the difference between the target profiles and their respective real-time measurements. The minimisation of the relevant integral, i.e.

$$\int_{0.2}^{0.8} [\iota(x) - \iota_{setpoint}(x)]^2\, dx + \mu \int_{0.4}^{0.6} [\rho^*_{T}(x) - \rho^*_{Tsetpoint}(x)]^2\, dx$$

where μ is a constant scaling parameter, was indeed experimentally confirmed, as can be seen on Fig.4. Figure 5 shows the results for another controlled pulse where both the q and ρ^*_{Te} targets are reached (Pulse No: 62527 with another reversed shear target q and a target ρ^*_{Te} profile slightly decreased compared to Pulse No: 62160, but still above the ITB criterion), leading to a non monotonic profile while an ITB located at 0.2 in normalised radius is progressively displaced at mid-radius. In the control time window, the requested powers have been accurately delivered. The controller has also demonstrated some robustness in front of rapid plasma events such as MagnetoHydroDynamic (MHD) instabilities or strong ELM activity which gave rise to rapid modification of the pressure profile. The response and recovery from fast transient events such as spontaneous barrier emergence or collapse or large Type-I ELM's, which takes place on a confinement time scale, can be seen Fig.6.

Modelling of the current diffusion with the CRONOS code [7] indicates that stationary conditions were not totally reached, indicating that the heating and current drive powers may still have evolved, had the pulses been longer. The characteristic current diffusion relaxation time was found around 18s for such discharges. A large non inductive plasma current is found with about 30% from the bootstrap current, 40% from LHCD and 30% from NBCD (Neutral beam current drive), while a negative ohmic current is driven in the plasma core. The proposed control algorithms have also been simulated with the JETTO code on a longer time scale, using the Bohm Gyro-Bohm transport model. Closed-loop predictive modelling of the evolution of the density, electron and ion temperatures, plasma rotation and q-profile shows that the technique does achieve its goal provided that the linearized model operator is determined consistently with the non-linear transport model. Different q and r*Te target profiles have been reached on a time scale of the order of 20s, consistent with the chosen transport model and resistive time scale. Figure 7 shows the results of these simulations, where different q (monotonic and reversed shear) and ρ^*_{Te} profile targets (with and without an ITB) are successfully reached, again validating the proposed control algorithm in a fairly wide range of target q-profiles around the reference state, despite the use of a linearized steady state gain model for the controller design.

CONCLUSIONS AND PERSPECTIVES

A first successful demonstration of combined electron temperature and current density profile control in advanced tokamak regimes has been obtained in the JET tokamak. With only a limited number of actuators, the technique aims at minimizing an integral square error signal which combines the two profiles, rather than attempting to control plasma parameters at some given radii with great precision. The resulting fuzzyness of the control scheme allows the plasma to relax towards a physically accessible non-linear state which may not be accurately known in advance, but is close enough to the requested one to provide the required plasma performance. Closed loop experiments have allowed to satisfactorily reach different target q and ρ^*_{Te} profiles, and, to some degree, to displace the region of maximum electron temperature gradient. The control has also shown some robustness in front of rapid transient events like type I ELM's, and spontaneous emergence or collapses of the ITBs. Simulation of the feedback loops with the (non-linear) JETTO transport code confirms the effectiveness of the linearized, model-based algorithm in a wide range of target q-profiles around a given plasma state. An improvement of the proposed technique could consist in identifying a dynamical linear model which would allow to design a two-time-scale controller, perhaps more suited to control rapid plasma events while slowly converging towards a requested steady state.

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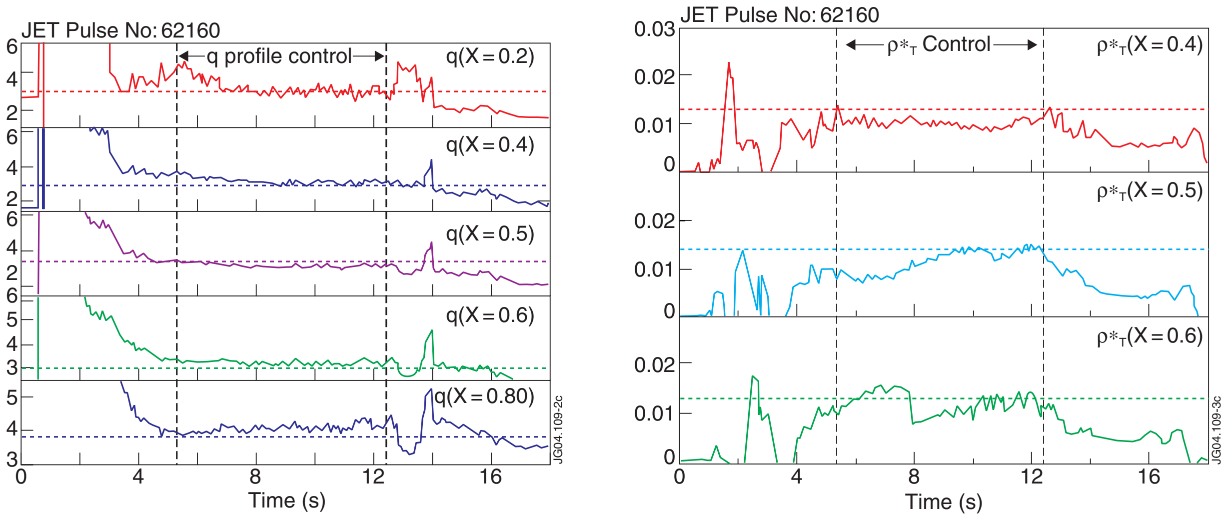
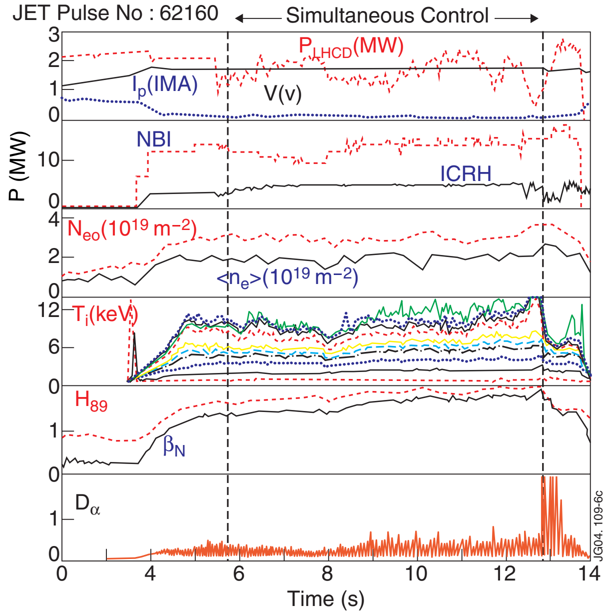


*Figure 1: Time evolution of the measured and requested q values (a) at 5 radii and ρ*T values (b) at 3 radii for a controlled pulse (Pulse No: 62160 $B_T = 3T$ $I_p = 1.7MA$, current flat top starts at 4s. Dashed lines are set point q and ρ^*_{Te} values. Control starts at 5.5s and stops at 12.3s.*



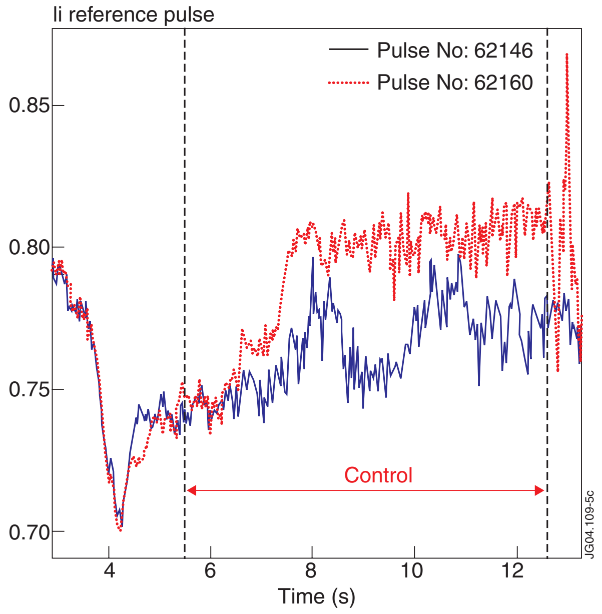
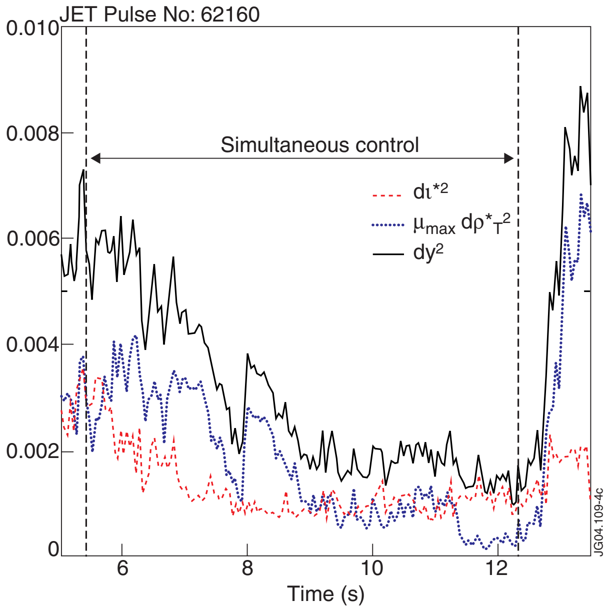


Figure 2: Time evolution of the LHCD, ICRH, NBI power waveforms, loop voltage, plasma current, central and mean density, Ti, H_{89}, β_N, Dα of a controlled pulse (Pulse No: 62160, $B_T = 3T$, $I_p = 1.7MA$).

Figure 3: Time evolution of the internal inductance of a feedback pulse (Pulse No: 62160, $B_T = 3T$, $I_p = 1.7MA$) compared to a reference pulse without feedback (Pulse No: 62146, $B_T = 3T$, $I_p = 1.7MA$)



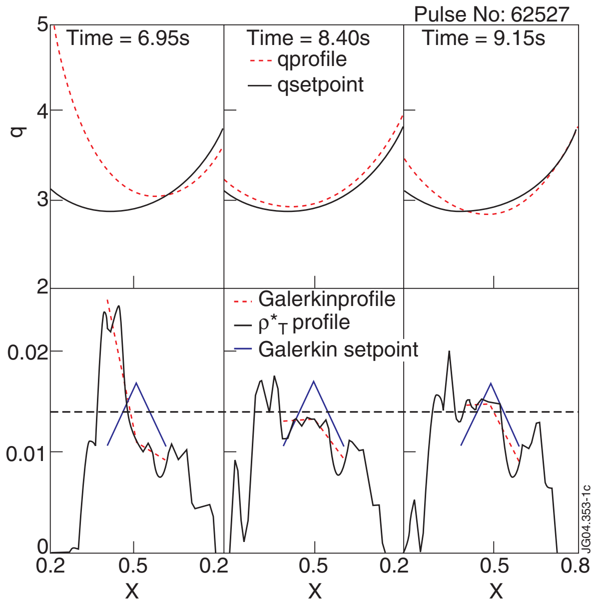
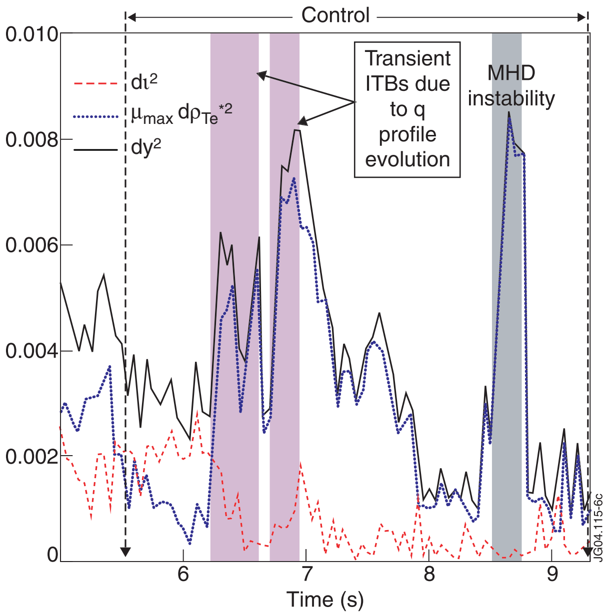


*Figure 4: Least square minimisation of the difference between the target ι-profile (red curve) and its real time measurement (respectively the ρ*T(x) profile (blue curve)). The sum is given by the black curve.*

*Figure 5: Time evolution of measured (red) and required (blue) q-and ρ*T profiles for a controlled pulse (Pulse No: 62527 $B_T = 3T$, $I_p = 1.7MA$). Control starts at 5.5s and stops at 9.15s. The black curve represents the measured ρ*T profile and the dotted line the JET criterion to get an ITB*



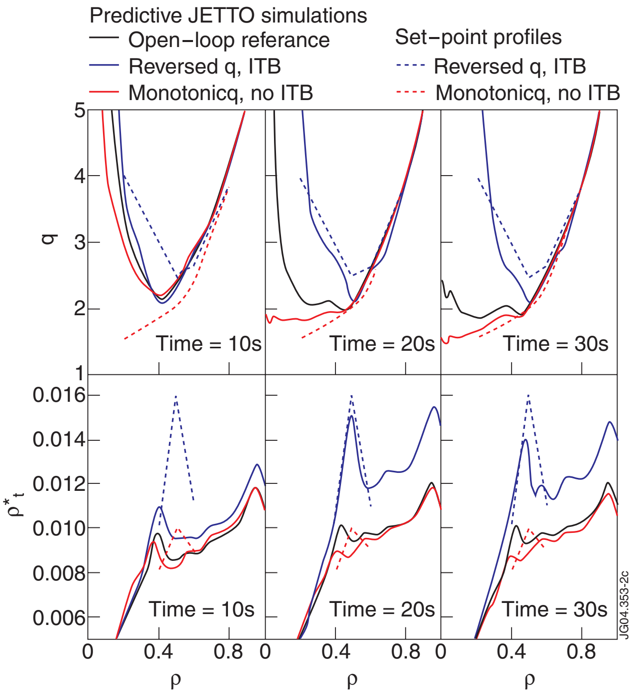


*Figure 6: Least square minimisation of the difference between the target ι-profile (red curve) and its real time measurement (respectively the ρ*T(x) profile (blue curve)). The sum is given by the black curve.*

Figure 7: Comparison of two closed loop simulations with JETTO for different target q and ρ^*_{Te} profiles. The picture shows also the open loop reference simulation.