Development of Integrated Real-Time Control of Internal Transport Barriers in Advanced Operation Scenarios on JET

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Abstract. An important experimental programme is in progress on JET to investigate plasma control schemes which, with a limited number of actuators, could eventually enable ITER to sustain steady state burning plasmas in an "advanced tokamak" operation scenario. A multi-variable model-based technique was recently developed for the simultaneous control of several plasma parameter profiles in discharges with internal transport barriers (ITB), using lower hybrid current drive (LHCD) together with neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH). The proposed distributed-parameter control scheme relies on the experimental identification of an integral linear response model operator and retains the intrinsic couplings between the plasma parameter profiles. A first set of experiments was performed to control the current density profile in the low-density/low-power LH-driven phase of the JET advanced scenarios, using only one actuator (LHCD) and a simplified (lumped-parameter) version of the control scheme. Several requested steady state magnetic equilibria were thus obtained and sustained for about 7s, up to full relaxation of the ohmic current throughout the plasma. A second set of experiments was dedicated to the control of the q-profile with 3 actuators (LHCD, NBI and ICRH) during the intense heating phase of advanced scenarios. The safety factor profile was also shown to approach a requested profile within about 5s. The achieved plasma equilibrium was close to steady state. Finally, during the recent high power experimental campaign, experiments have been conducted in a 3T/1.7MA plasma, achieving the simultaneous control of the current density and electron temperature profiles in ITB plasmas. Here, the distributed-parameter version of the algorithm was used for the first time, again with 3 actuators. Real-time control was applied during 7s, and allowed to reach successfully different target q-profiles (monotonic and reversed-shear ones) and different ITB strengths quantified by their normalized electron temperature gradient.

1. Introduction

The perspective of ITER and the need to optimize the tokamak concept for the design of an economical fusion power plant have motivated extensive international research on plasma transport and confinement in toroidal devices. These investigations have led to plasma regimes with improved confinement with respect to the one predicted by typical tokamak scaling laws, and to the concept of "advanced tokamak" operation scenarios [1]. In a large number of machines, experiments have demonstrated the existence of such regimes allowing access to a high confinement state with improved MHD stability and leading to a strong increase of the plasma performance quantified by the normalized energy confinement time, H, and plasma pressure, β_N. In such conditions a dominant fraction of the plasma current is self-generated by the neoclassical bootstrap mechanism, which alleviates the requirement on the externally driven non-inductive current for steady state operation. This is helped by the generation in the plasma of a so-called 'Internal Transport Barrier' (ITB) [2], a region where the plasma turbulence is almost suppressed, and can lead to a sustainable bifurcated plasma equilibrium. Many recent studies have shown the key influence, for the triggering of ITB's, of the safety factor radial profile, q(r) [3]. The magnetic shear, (r/q)(dq/dr), and/or the location of the magnetic flux surfaces where q is rational have been shown to be important for the emergence of ITB's [3-6].

An important experimental programme is in progress on JET to investigate plasma control schemes which could eventually enable ITER to sustain steady state burning plasmas in an "advanced tokamak" operation scenario. The triggering and subsequent controllability of ITBs are major issues for fulfiling this goal, and their study is therefore an essential part of this programme. Uncontrolled ITBs are generally not stationary, as often observed on JET, and the coupled evolution of the plasma parameter profiles in high performance non-inductive discharges often leads to the premature loss of the good confinement ITB regime, or alternatively to an overpeaking of the pressure profile, with major MHD events, sudden barrier collapse and/or abnormal plasma termination. Initial ITB control experiments in JET focussed on the simultaneous control of the maximum normalized electron temperature gradient, ρ_{Te}^* [7], with ion cyclotron resonance heating (ICRH), and of the neutron rate with neutral beam injection (NBI), and were quite successful [8]. But they did not cope with the adverse evolution of the current density profile on the resistive time scale, which eventually led to the loss of the ITB.

Recently, a multi-variable model-based technique was developed [9-11] for the simultaneous control of the current, temperature and/or pressure profiles in JET ITB discharges, using lower hybrid current drive (LHCD) together with NBI and ICRH. The control scheme relies on the experimental identification, and on a truncated singular value decomposition (TSVD), of a linearized integral model operator. The justification for using linear response models to design controllers for non-linear systems is that, if it works, the system should not depart largely from the requested equilibrium since the controller is to provide stability around it. Therefore a control matrix defined through linearisation can often provide an acceptable solution. The proposed technique retains the intrinsic couplings between the plasma parameter profiles, as well as their distributed nature by using an appropriate set of trial basis functions. The related algorithms have been implemented in the JET control system, allowing the use of three actuators (NBI, ICRH and LHCD), but they could be easily extended to an arbitrary number of input-output parameters and profiles. Efforts are being dedicated, gradually, to the implementation and validation of different versions of this technique with increasing degrees of completeness, and this paper reviews the progress achieved so far.

2. Control of the current density profile

The experimental investigations reported below were the first attempts at controlling the safety factor profile (rather than related integral quantities) in tokamaks. To start with, q(r) was simply characterized by its values at 5 fixed radii, considered an adequate set of discrete parameters to describe the system as a lumped-parameter system, prior to extending the method to the control of continuous profiles. The q-profile was calculated in real time using magnetic measurements together with data from the JET interferometer-polarimeter diagnostic which allowed a fairly accurate reconstruction of the magnetic equilibrium in real-time [12].

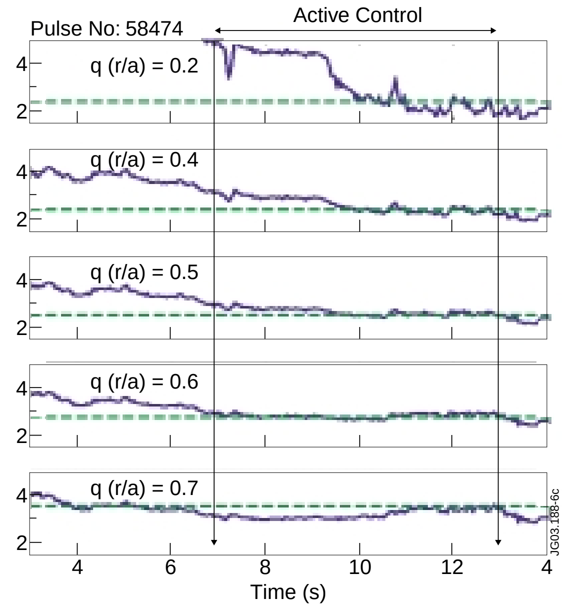

FIG. 1a. Time evolution of the safety factor at the five selected radii (pulse #58474, B_T = 3T, I_p = 1.8/1.5 MA). The setpoint values are indicated with dotted lines.

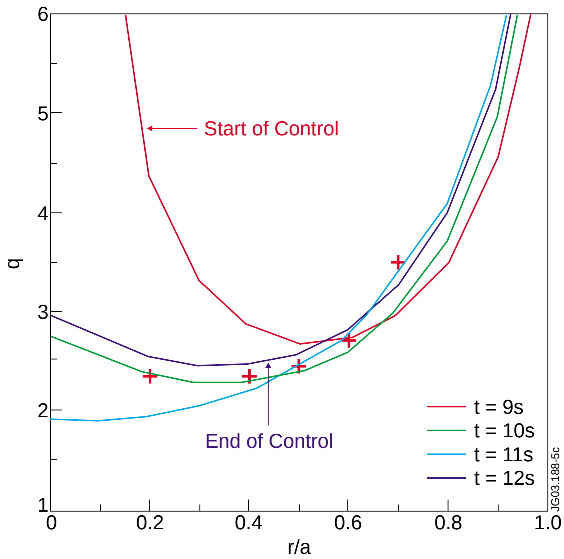

FIG. 1b. Real-time control of the q-profile using LHCD, NBI and ICRH (pulse #58474, B_T = 3T, I_p = 1.8/1.5 MA). The profile is shown at four different times between 7 s and 12 s. Pluses represent the 5 q-setpoints at r/a = [0.2 0.4 0.5 0.6 0.7].

A first set of experiments was performed in the low-density/low-power LH-driven phase of the JET advanced scenarios. The current density profile, whose peaking was initially retarded by the application of a given amount of off-axis LHCD current drive during the plasma current ramp up phase, was subsequently controlled using LHCD as the only actuator. Several requested steady state magnetic equilibria were obtained and sustained for about 7s after full relaxation of the ohmic current throughout the plasma [10]. Then, more interestingly in view of high power operation, a second set of experiments was dedicated to the control of the q-profile during the intense heating phase of advanced scenarios where one expects high plasma performance due to the formation of ITB's. The safety factor profile was shown to approach a requested profile (again defined by its values at 5 radii) in the least square sense, within about 5 s. This is a reasonable time with regard to the full current diffusion time scale in these plasmas and it was of course achieved within the family of profiles which were accessible with the combination of the ohmic current and of the LHCD, NBI and ICRH driven currents, at the power levels available at the time of the experiments. Figure 1 shows the result of a closed-loop experiment in which the target q-profile had a weak magnetic shear in the plasma core (slightly reversed) and the control was applied between t = 7 s and t = 13 s, with initial powers at the start of the control phase of 2.5 MW for LHCD, 7 MW for NBI and 3 MW for ICRH. These values were chosen sufficiently below the power limits of the systems to possibly avoid hitting the saturation of an actuator during the closed-loop experiments. The achieved plasma equilibrium state was close to steady state. These were the first experiments using three heating and current drive systems to control the q-profile in an ITB tokamak scenario with a large fraction (70 %) of the plasma current driven non-inductively.

The success of these experiments provided a basis for starting preliminary investigations on the proposed integrated ITB control using the full distributed-parameter version of the proposed technique. This was done during the last high power experimental campaign where we started to address the simultaneous control of q(r) and $\rho_{Te}^*(r)$, two non-dimensional parameters which characterize the current density and electron temperature profiles, respectively. These two profiles are strongly coupled and believed to be essential ingredients governing ITB physics.

3. Integrated control of the current density and electron temperature profiles

For these experiments, the full control algorithm was implemented using 3 actuators (LHCD, NBI and ICRH), and 8 output parameters [normalizing r with respect to the plasma minor radius, a, the profiles are projected upon 5 cubic-spline basis functions for the inverse safety factor, $\iota(x)=1/q(x)$ with $x=r/a$, and 3 piecewise-linear functions for the normalized electron temperature gradient profile, $\rho_{Te}*(x)$]. Real-time control was applied during 7 seconds in a 3T/1.7 MA plasma, and allowed to reach successfully different target q-profiles (monotonic and reversed-shear ones), and different ITB strengths quantified by $\rho_{Te}*(x)$ in a radial window about half plasma radius. Two sets of trial basis functions, $a_i(x)$ and $b_i(x)$, were chosen to provide good approximations of the measured profiles [11]. The current density profile was controlled via the inverse of the safety factor, because, being directly proportional to the integrated current, it depends more linearly on the applied current drive power than q(x) itself. The ι profile was projected upon 5 cubic splines ($a_i(x)$, i=1…5) with knots respectively at x = [0.2, 0.4, 0.5, 0.6, 0.8]. In the case of the electron temperature, or more precisely of the $\rho*_{Te}$ profile, three triangular functions ($b_j(x)$, j=1…3) with knots at x = [0.4, 0.5, 0.6] were used.

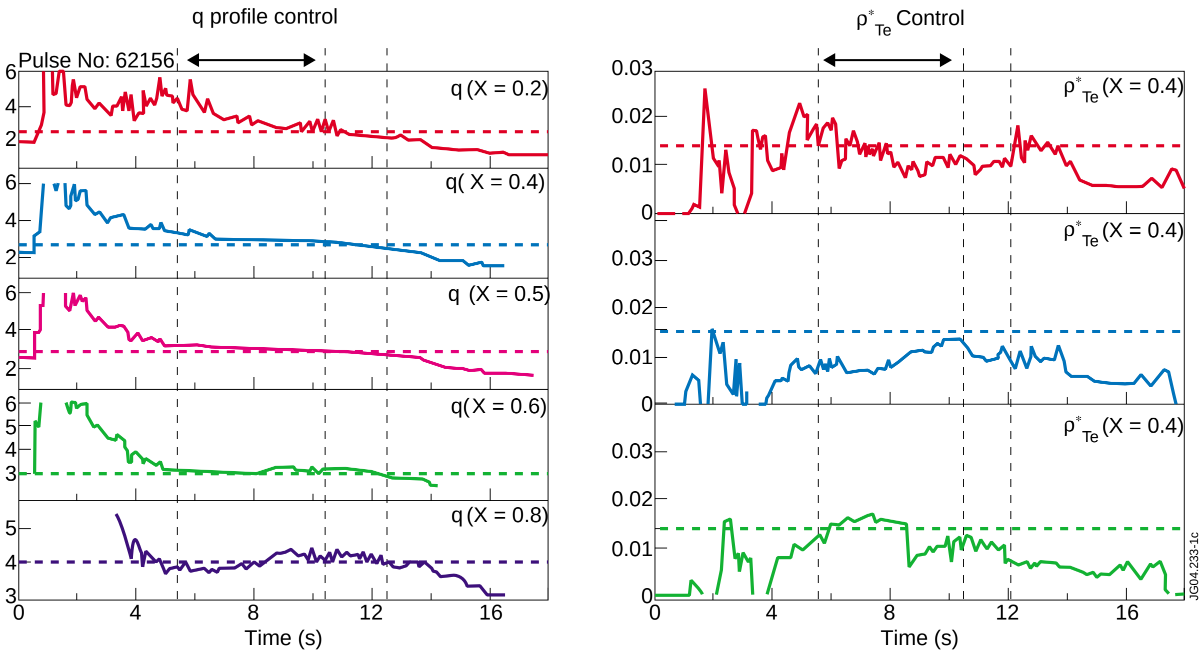

FIG. 2. Time evolution of the measured and requested (dashed lines) q values at 5 radii (left), and ρ_{Te} values at 3 radii (right) for a controlled pulse with monotonic q-profile (#62156 B_T=3T Ip=1.7MA). The current flat top starts at 4s. Control starts at 5.5s until 12.3s, but the ICRH power trips at 10.3s.*

In order not to overload the real-time controller, the number of trial basis functions was deliberately limited as well as the radial windows on which they operate. In fact, the accuracy of the real-time reconstruction of the q-profile from polarimetry data [12] was poor in the central region [$0 < x < 0.2$] so this region was excluded from the control window. In addition, the q-value at the edge is inversely proportional to the total plasma current which is constrained by the transformer circuit feedback loop, and therefore including the edge region in the q-profile control would have been redundant. Thus, the feedback control of the q-profile was restricted to the region $0.2 \leq x \leq 0.8$. For $\rho*_{Te}$, the region of control of the ITB was imposed by the real-time electron temperature measurements given by the electron cyclotron emission diagnostic which provided no measurement in the core of the plasma, nor near the edge in discharges with LHCD. The radial measurement window depends on the plasma configuration (in particular on the toroidal field and plasma current), but includes in all cases the region which extends from x=0.3 to x=0.7. Moreover, one of the goal of these experiments is to sustain an ITB at x > 0.4 in order to enhance the plasma performance, and the q-profiles which are accessible with the present heating systems on JET do not allow in general to sustain stationary ITB's at x ≥ 0.6. Thus, in these experiments the control region for ρ^*_{Te} was restricted to the window 0.4 ≤ x ≤ 0.6 where an ITB was expected and requested.

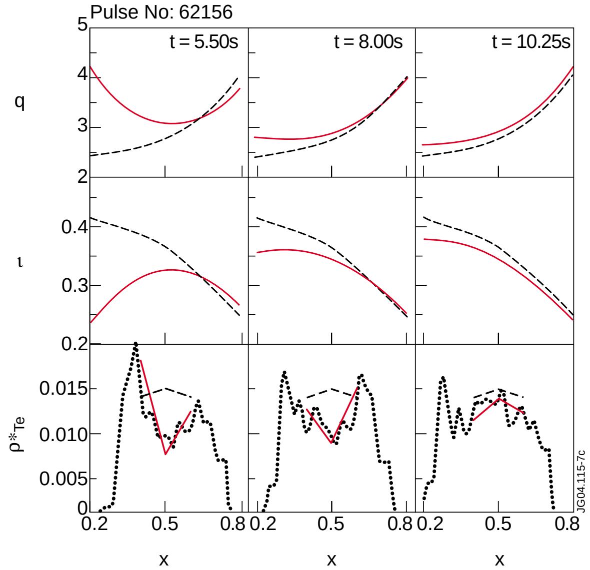

FIG. 3. Measured (solid) and target profiles (dashed) for q, ι and $\rho_{Te}*$ after projection on the basis functions, for pulse #62156 (B_T=3 T, I_P=1.7 MA, n_e=3x10^{19}m^{-3}). For $\rho_{Te}*$, the original profile is also shown (dotted).

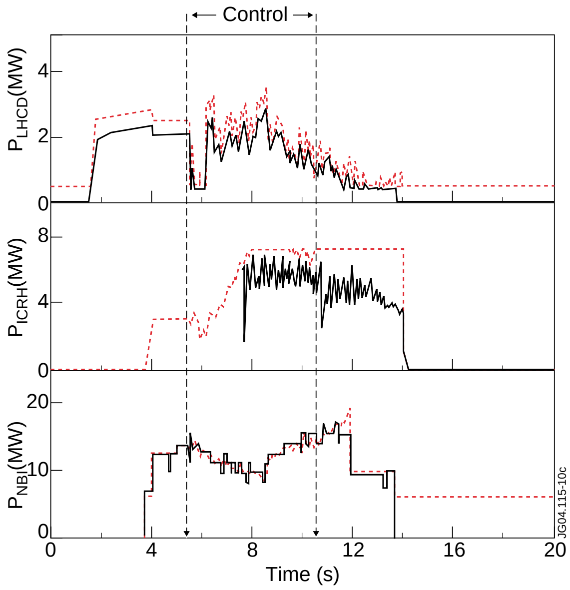

FIG. 4. Requested (dashed) and delivered powers (solid) during pulse #62156. Control starts at t=5.5s. At t=10.3s the ICRH power departs from the request and the control is ineffective.

The chosen reference scenario used a typical 1.7MA/3T reversed shear configuration obtained with 2.1MW of LHCD, 3MW of ICRH and 13.6MW of NBI, at a plasma electron density $n_e \approx 3 \times 10^{19}$ m^{-3}. These powers were carefully selected in order to get an ITB while staying well below the operational limits in order to have enough headroom both in open-loop power step experiments to identify the model and, later, in the closed-loop experiments. The Galerkin approximation of both profiles on each set of basis functions (five coefficients for ι and three for ρ^*_{Te}) were computed in real-time from the profile measurements and, every 10ms, a proportional-integral power request was sent by the controller to the different actuators. The control loop was applied during a maximum of 7 seconds and allowed to reach successfully different target q-profiles - from monotonic to reversed shear ones - while simultaneously controlling the profile of the electron temperature gradient. Figure 2 shows the result in the case of a monotonic q-profile target, and of a ρ^*_{Te}-profile target with a maximum slightly above the criterion for the existence of an ITB [7], at a fairly large radial location where ITB's are not easily achieved spontaneously. The effect of the controller is also shown in Fig. 3 where the requested and achieved q, ι and ρ_{Te}* profiles are represented at t=5.5s, 8s and 10.25s, and on Fig. 4 where the requested and delivered powers are shown. Both profiles were satisfactorily controlled. In this pulse, the ICRH system technically failed to deliver the requested power at around t=10.3s, and therefore the control phase duration was limited to 4.8 seconds.

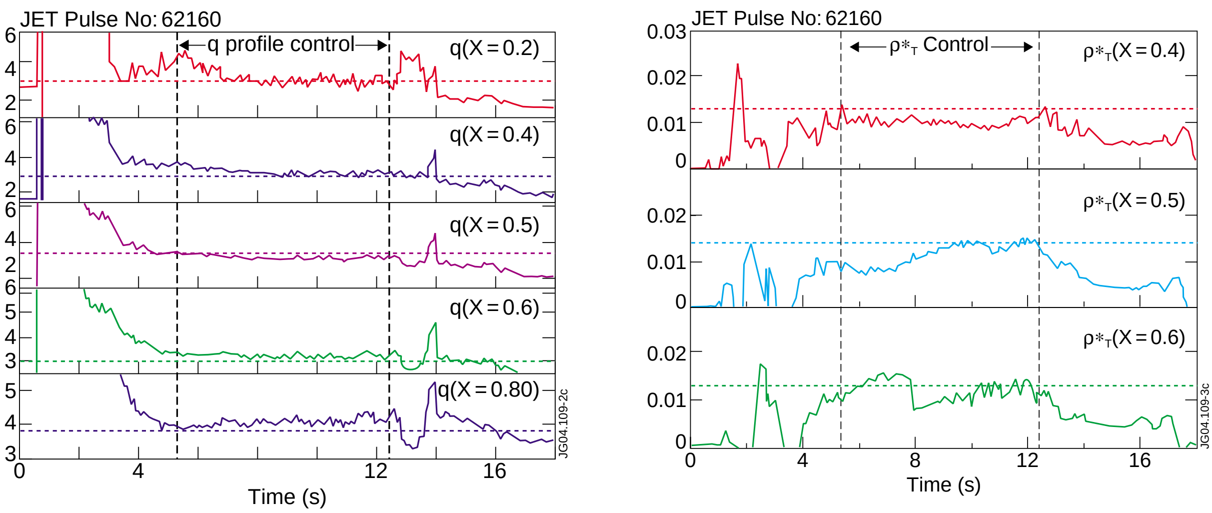

FIG. 5. Time evolution of the measured and requested (dashed lines) q values at 5 radii (left) and ρ_{Te} values at 3 radii (right) for a reversed-shear controlled pulse (#62160, B_T=3T, Ip=1.7MA, n_e=3x10^{19}m^{-3}). The current flat top starts at 4s. Control starts at 5.5s and stops at 12.3s.*

In a different discharge (pulse #62160) a non-monotonic target q-profile was requested, together with a target ρ^*_{Te} profile with a maximum above the ITB criterion but slightly lower than for the pulse #62156. Such a reversed-shear q-profile target was chosen in order to test the controller further away from the reference state. The control phase started at 5.5s and ended at 12.3s. The loop voltage was 0.05V, meaning that the plasma current was almost fully non-inductively driven during the control time window. Interestingly enough, both in pulse #62156 (t ≈ 8.5s) and #62160 (t ≈ 8s), a sawtooth-like relaxation is observed on ρ_{Te}* near x=0.6, and the controller nicely brings ρ_{Te}* back towards its target value. Such rapid phenomena where an ITB is lost are often observed in the ITB regime. The effect of the controller is shown in Fig. 5 (time traces) and also in Fig. 6 where the requested and achieved q, ι and ρ_{Te}* profiles are represented at t=6.95s, 8.4s and 9.15s.

Finally, as shown in Ref. [9], the controller was designed to minimize, in the integral least square sense, the difference between the target ι and ρ^*_{Te} profiles and their respective real-time measurements or, more precisely, to minimize the quadratic expression :

$$\int_{0.2}^{0.8}\left[\iota(x)-\iota_{setpoint}(x)\right]^2 dx + \mu\int_{0.4}^{0.6}\left[\rho^*_{Te}(x)-\rho^*_{Te\,setpoint}(x)\right]^2 dx \qquad (1)$$

where μ is a chosen parameter. This positive definite quantity, which will be referred to as the squared "distance" between the achieved and requested profiles, is plotted in Fig.7. The ι profile was reached faster than the target ρ_{Te}* profile which suggests that the selected weight factor, μ, was perhaps not optimised [μ was chosen equal to 1000 in order to give comparable weights to the squared ι term (about 10^{-1}) and ρ_{Te}* term (about 10^{-4}) in eq. (1)].

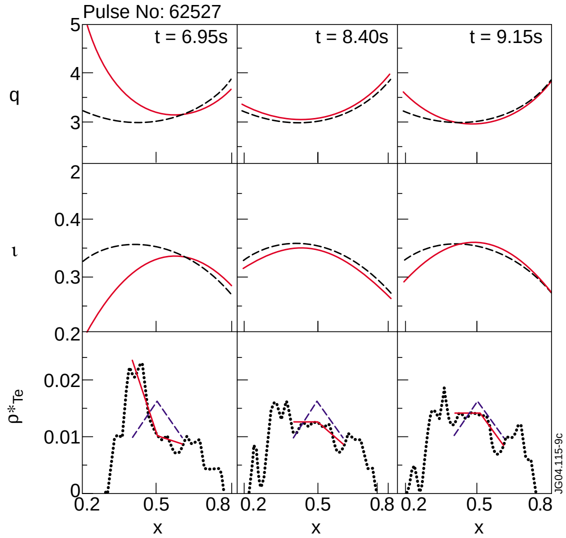

FIG. 6: Measured (solid) and target profiles (dashed) for q, ι and ρ_{Te*} after projection on the basis functions, for pulse #62527 (B_T=3 T, I_P=1.7 MA, n_e=3.5x10^{19}m^{-3}). For ρ_{Te*}, the original profile has also been plotted (dotted).

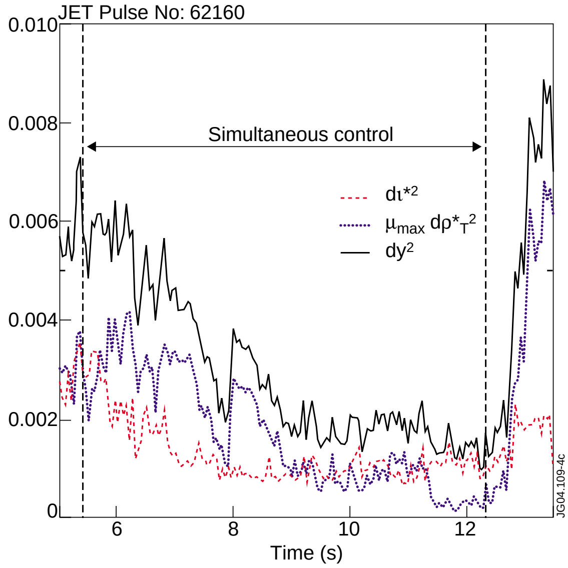

FIG. 7. Squared difference between the target ι-profile (red), the ρ_{Te}(x) profile (blue), and their respective real-time measurements for pulse #62160. The sum is shown in black and is indeed minimum at the end of the control phase.*

4. Conclusions and perspectives

A model-based multi-variable scheme has been implemented in the JET tokamak for the real-time control of distributed plasma parameters such as the current density, temperature, and/or pressure profiles. First experiments using the simplest lumped-parameter version of the proposed algorithm have demonstrated that the technique was efficient in obtaining and holding a pre-requested q-profile shape. Recently, further experiments were performed in a plasma regime with an internal transport barrier to control the ITB by controlling simultaneously the current density and electron temperature profiles. These profiles were characterized by the inverse safety factor, ι(r/a)=1/q(r/a), and the normalized temperature gradient, ρ_T*(r/a), respectively, using a distributed-parameter control algorithm. The proposed technique includes the identification of a distributed-parameter model with two different sets of appropriate basis functions for q(r/a) and ρ_{Te}*(r/a), and using the Galerkin method for projecting the measured profiles onto the trial function bases. The ITB temperature gradient control was restricted to the plasma region where an ITB was expected (and requested) to emerge once a given setpoint q-profile has been chosen. The technique amounts to the minimization of 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 evolve towards a physically accessible non-linear state which may not be accurately known in advance, but is the closest to the requested one, and therefore provides the required plasma performance. These experiments have shown that it is possible to obtain different target q and ρ_{Te}* profiles in a controlled way, with only a limited number of actuators.

The present controller was designed from the only knowledge of the static linear response model, **K**(0). The experimental identification of a fully dynamic linear model, **K**(s), is now under investigation in preparation of the 2005-06 experimental campaigns. This should make it possible to construct a two-time-scale model and design a controller which may respond faster to rapid plasma perturbations (MHD events, spontaneous emergence or collapse of ITB's) while converging slowly towards the requested high performance plasma state. Numerical modelling could be used in the longer term to identify linear, or piecewise-linear, response matrices. It was found, however, that present state-of-the-art plasma transport modelling was not yet accurate enough to do so (especially in transient regimes), although it was quite useful for a qualitative assessment of the control algorithms [13].

Future plans also include the integration of the ion temperature and plasma density in the controlled profiles as well as other actuators such as gas/pellet injection. Preliminary studies show that the transformer primary flux can also be integrated in the scheme together with the heating and current drive systems for driving the plasma towards a target stationary state which has the required profiles and is at the same time compatible with continuous tokamak operation (constant flux, i.e. zero loop voltage). Finally, experiments under additional feedback loops on the heating systems (e.g. ICRH) to simulate alpha-particle heating in a burning plasma need to be undertaken. This should be possible in JET with the availability of a new ITER-like ICRH antenna and burning plasma diagnostics. Because of the additional coupling between the fusion power yield, the pressure profile and the bootstrap current, such experiments will represent an important step before the ultimate challenge of developing controlled, reactor relevant, steady state scenarios in ITER.

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