EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA-JET-CP(05)02-03

L. Laborde, D. Mazon, D. Moreau, M. Ariola, V. Cordoliani,
T. Tala and JET EFDA contributors

A Multiple-Time-Scale Approach to the Control of ITBs on JET

A Multiple-Time-Scale Approach to the Control of ITBs on JET

L. Laborde[1], D. Mazon[1], D. Moreau[1, 2], M. Ariola[3], V. Cordoliani[4], T. Tala[5]
and JET EFDA contributors*

[1] *EURATOM-CEA Association, DSM-DRFC , CEA-Cadarache, 13108, St. Paul lez Durance, France*
[2] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[3] *EURATOM/ENEA/CREATE Association, Univ. Napoli Federico II, Via Claudio 21, I-80125 Napoli, Italy*
[4] *École Polytechnique, Route de Saclay, 91128 Palaiseau, France*
[5] *EURATOM-Tekes Association, VTT Processes, FIN-02044 VTT, Finland*
** See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc.20 th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference,
(Tarragona, Spain 27th June - 1st July 2005)

1. INTRODUCTION

The simultaneous real-time control of the current and temperature gradient profiles could lead to the steady state sustainment of an internal transport barrier (ITB) and so to a stationary optimized plasma regime. Recent experiments in JET (Fig.1) [1, 2, 3] have demonstrated significant progress in achieving such a control: different current and temperature gradient target profiles have been reached and sustained for several seconds using a controller based on a static linear model. The current profile was controlled through the inverse safety factor profile, ι=1/q, and the temperature gradient profile was controlled through the profile of another non-dimensional parameter, ρ^*_{Te}, which characterizes internal transport barriers in JET (ρ^*_{Te} is the normalized electron temperature gradient introduced in [4]).

It's worth noting that the i profile evolves on a slow time scale (resistive time) while theρ^*_{Te} reacts on a faster one (confinement time). Moreover, these experiments have shown that the controller was sensitive to rapid plasma events such as transient ITBs during the safety factor profile evolution or MHD instabilities which modify the pressure profiles on the confinement time scale. In order to take into account the different dynamics of the controlled profiles and to better react to rapid plasma events the control technique is being improved by using a multiple-time-scale approximation. The paper describes the theoretical analysis and closed-loop simulations using a control algorithm that will be tested experimentally in JET during the forthcoming campaigns.

2. IDENTIFICATION OF A TWO-TIME SCALE STATE-SPACE MODEL

The identification of a fully dynamic linearized model has been addressed, taking into account the physical structure and couplings of the transport equations. 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 and loop voltage modulations (inputs P and V_{loop}). 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 ρ^*_{Te} slow and a fast one ρ^*_{Te} fast so that $\rho^*_{Te} = \rho^*_{Te\ slow} + \rho^*_{Te\ fast}$. The internal state variables X and Z represent magnetic and kinetic profiles, respectively. The state-space model takes the following form (noting _ as the ratio between the energy confinement and the resistive diffusion time scales):

$$\begin{cases} \begin{pmatrix} \dot{X} \\ \in\dot{Z} \end{pmatrix} = A \begin{pmatrix} X \\ Z \end{pmatrix} + B \begin{pmatrix} P \\ V_{loop} \end{pmatrix} \\ \begin{pmatrix} 1/q \\ P^*_{Te} \end{pmatrix} = C \begin{pmatrix} X \\ Z \end{pmatrix} + D \begin{pmatrix} P \\ V_{loop} \end{pmatrix} \end{cases}$$

The identification technique has first been applied on data obtained from simulations using the ASTRA [5] transport code: the plasma response to power and loop voltage modulations has been simulated with ASTRA 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 (P, V_{loop}) (Fig.2). The application of this identification method to data obtained from different semi-empirical models in another transport code, JETTO, and finally to experimental data is in progress. This approach differs from the identification of a current profile dynamic model [6] where different linear models for the various non inductive sources (external current drive systems and bootstrap current) have been used to identify the q profile.

3. TWO-TIME-SCALE CONTROLLER

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). This two-time-scale proportional-integral controller is designed using singular perturbation methods [7]. Requested powers and loop voltage are the sum of 2 components $P = P_{slow} + P_{fast}$ where (using the Laplace transforms in the time domain):

$$P_{slow}(s) = G_{slow}\,[1+1/(\tau_{slow}\,s)]\;E(q_{target} - q,\ \rho^*_{Te\ target} - \rho^*_{Te})$$

$$P_{fast}(s) = G_{fast}\,[1+1/(\tau_{fast}\,s)]\;E(\rho^*_{Te\ target} - \rho^*_{Te\ fast})$$

$$\tau_{fast} << \tau_{slow}$$

E is the error signal of each loop, the gain matrices Gslow and Gfast are determined using the state-space model matrices A, B, C and D according to an SVD technique described in [2]. Figure 3 indicates the scheme of the controller using the two control loops.

Simulation tests of this two-time-scale controller and comparisons with the technique used in previous experimental campaigns (simple proportional-integral control: $P(s) = G[1+1/(\tau s)]\,E(q_{target} - q,\ \rho^*_{Te\ target} - \rho^*_{Te})$) have already shown a faster control (Fig.4). In these first simulations, and for the purpose of the proof-of-principle demonstration, the closed-loop plasma response is assumed here to be given by the linear state-space model identified from the ASTRA data. The fast component ρ^*_{Te} fast of the ρ^*_{Te} output is also calculated - and will have to be estimated in the experiments - using the state-space model. Starting from the same initial conditions in terms of profiles and powers (not visible in Fig4(a) in reason of the instantaneous reaction of the inputs) the two-time-scale controller (red traces) reaches theρ^*_{Te} target profile faster thanks to the fast control loop while, as expected, the target 1/q profile is reached on the same resistive diffusion time scale as before. The new controller will be further tested using non-linear response models in the JETTO code similarly to what has been already done for the former technique [8].

4. DISTURBANCES ANALYSIS AND FEEDFORWARD COMPENSATION

In parallel with these studies, a detailed correlation analysis of the experimental data is in progress in order to identify parameters which perturb the measurements or the plasma evolution in a systematic way and could be taken into account in the controller design. For example, since the polarimetry is used in the real-time flux profile reconstruction [9], a change in the density profile has been found to affect the current density profile measurements while powers and loop voltage were nearly constant (Fig. 5). This analysis should lead us to take these parameters into account and design a correction in the controller through a conventional feedforward compensation.

CONCLUSIONS

In recent JET experiments, the real-time controller was sensitive to rapid plasma events (transient ITBs, MHD…). The identification of a two-time-scale state-space model allows a new controller to be designed. This identification technique will be further tested using simulated data obtained with semi-empirical transport codes and models (ASTRA, JETTO) as well as experimental data. Closed-loop simulations using the full dynamic - but linear - model used for the controller design to simulate the plasma response have demonstrated that this new controller allows r*Te target profile to be reached faster than the one used in previous experiments. The analysis in progress should also allow a feedforward compensation of some measurement disturbances to be included in the new controller. This controller will be implemented using a new Simulink® interface in the JET control system and will be tested in forthcoming experiments.

REFERENCES

[1]. Laborde L et al, 2005 Plasma Phys. Control. Fusion **47** 155.
[2]. Moreau D et al, 2003 Nucl. Fusion **43** 870.
[3]. Mazon D et al, EPS conference, Londres (2004).
[4]. Tresset G et al, 2002 42 520-526.
[5]. Pereverzev G, Yushmanov P N, Report IPP 5/98 (1998) Max Planck Institut fur Plasmaphysik, Garching, Germany.
[6]. De Tommasi G et al, "Identification of a dynamic model of plasma current density profile", this conference.
[7]. Kokotovi_ P V et al, 1986, Singular perturbation methods in control: analysis and design, Academic Press, London.
[8]. Tala T et al, 2005 To be published in Nucl. Fusion.
[9]. Zabeo L, Murari A, Joffrin E, Mazon D and Taliercio C, 2002 Plasma Phys. Control. Fusion **44** 2483.

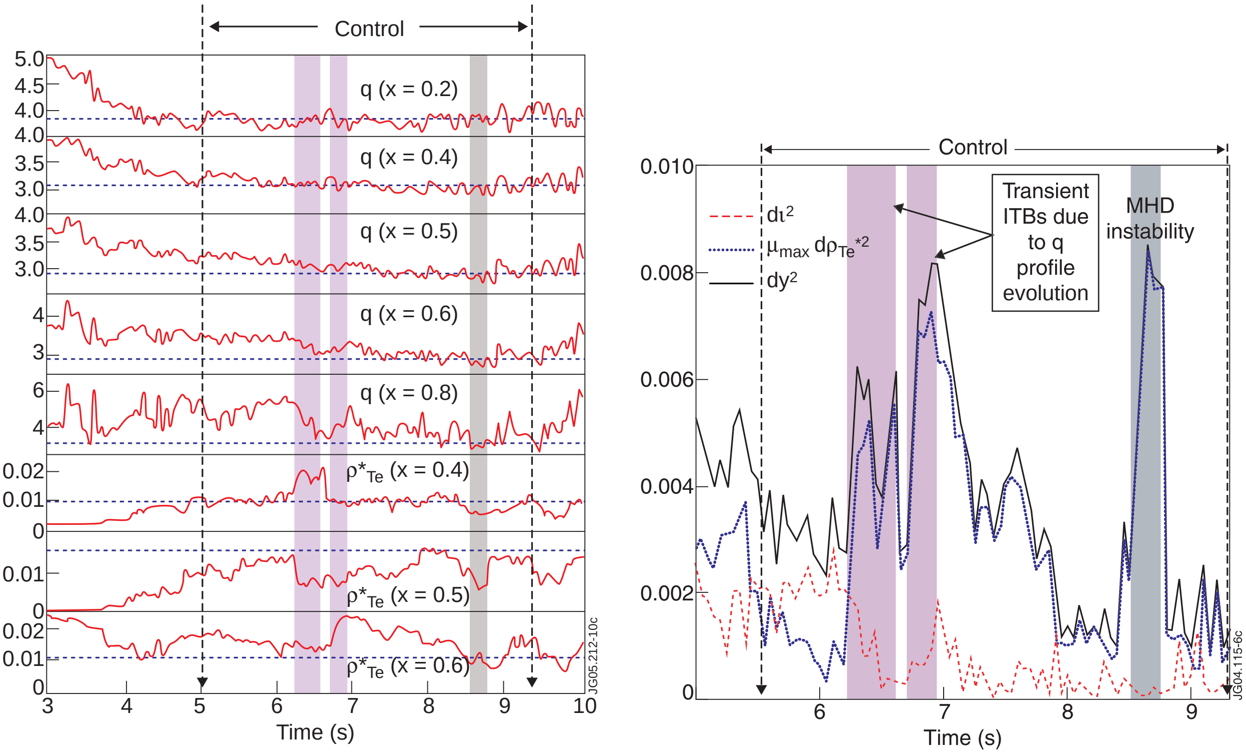

Figure 1: (a) Time evolution of measured and requested controlled values (q and ρ^{*Te}) at different normalized radii (x). (b) Time evolution of the squared distances (error on iota profile, normalized electron temperature gradient profile and the corresponding sum respectively $d\iota^2$, $\mu_{max} d\rho_{Te}{*}^2$, dy^2) between measured and requested profiles. Pulse JET No: 62527, $B_T = 3T$, $I_p = 1.7MA$. See [1] for details.

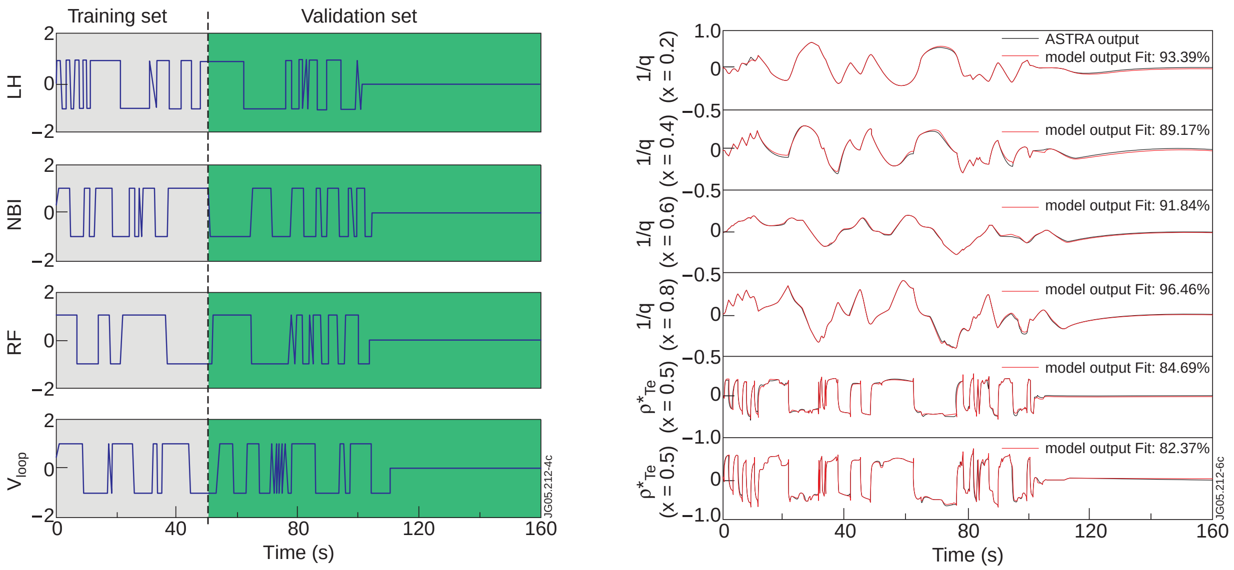

Figure 2: (a) Input powers modulations (from ASTRA code) used for identification and validation. (b) Comparison of outputs from ASTRA and from identified state-space model.

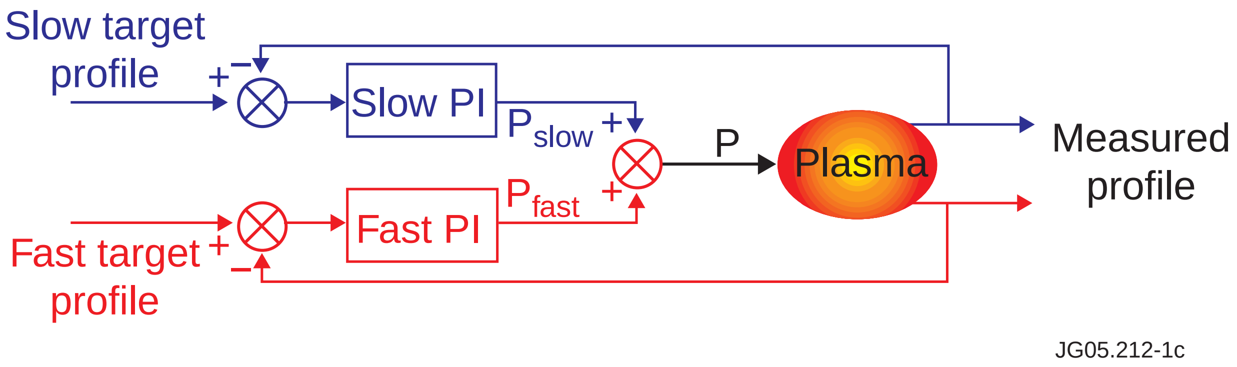

Figure 3: Scheme of the two-time-scale controller: the slow loop uses slow quantities (q and slow parts of ρ^*_{Te}) as inputs, whereas the fast loop uses fast ones (fast part of ρ^*_{Te}). This will be implemented using a new Simulink® interface in the JET real-time control system.

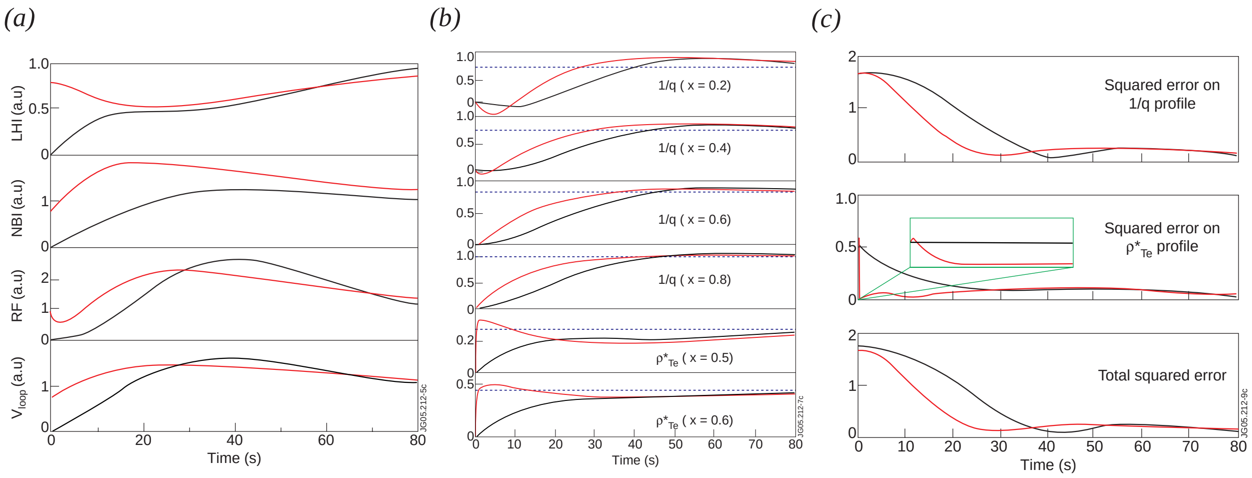

Figure 4: Comparison of inputs (a), outputs (b) and squared error (c) in closed-loop simulations: the new controller (red) allows to reach the targets (blue) before the previous controller (black) that was used in Fig. 1 experiments. This can be observed in the green window (on the right middle plot) which is a zoom between t=0 s and t=1 s.

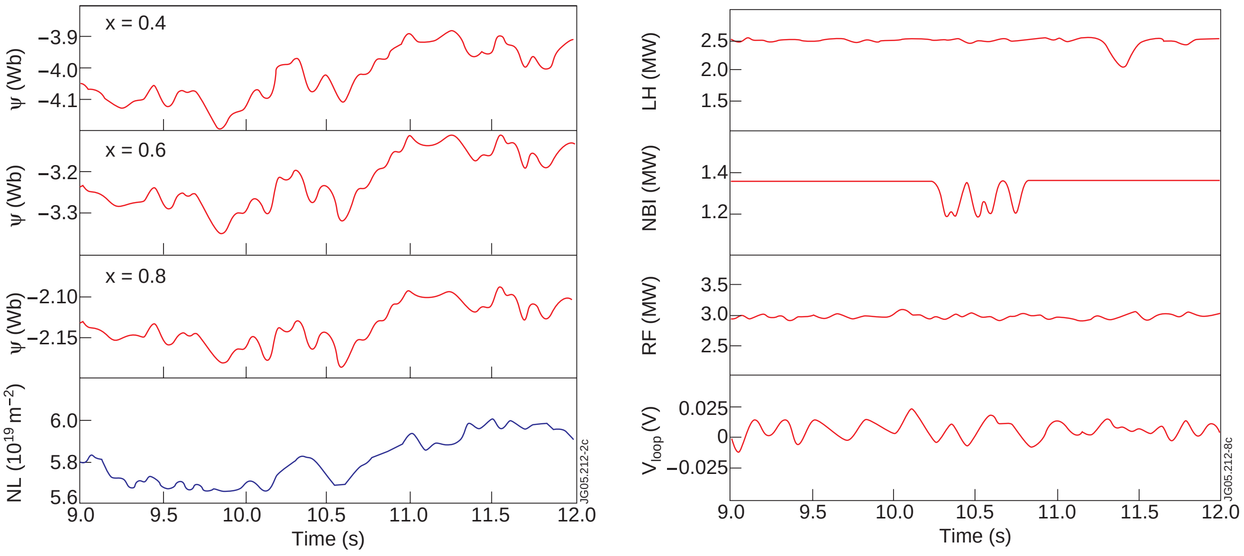

Figure 5: (a) Correlation between variations of poloidal flux at different radii (red) and a chord of line integrated density (blue). (b) Powers and loop voltage are nearly constant. Pulse JET No: 62149, B_T = 3T, I_p = 1.7MA