Model-based Magnetic and Kinetic Control of ITER Scenarios

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1 Introduction

The development on ITER of hybrid and steady state operation scenarios with high neutron fluence implies the control of improved-confinement, high-β, high-bootstrap discharges. Such advanced scenarios are currently obtained in various tokamaks empirically [1-2], and most of the time transiently or for durations that do not exceed the resistive diffusion time. In this respect, *simultaneous magnetic and kinetic control of plasma profiles and parameters such as the current profile, the pressure profile (or the normalized pressure parameter, β_N), and the alpha-particle power* are essential. An integrated model-based plasma control strategy, ARTAEMIS, has been initiated on JET [3] and pursued on JT-60U and DIII-D [4], and closed-loop control of the poloidal flux, safety factor and β_N has been recently performed [5]. In this paper, the same approach is simulated on an ITER hybrid-mode scenario for the control of the poloidal flux profile and of two kinetic parameters, β_N and P_α, the alpha-particle power. For the time being, the control actuators are the ITER neutral beam injectors (NBI1, NBI2), electron cyclotron (ECRH), ion cyclotron (ICRH) and lower hybrid (LHCD) systems, and the plasma surface loop voltage (V_{ext}). The nonlinear plasma response to the actuators is modeled through the time evolutive METIS transport code which is a module included in the CRONOS suite of codes [6].

2 State-space structure and identification of the control-oriented ARTAEMIS models

In the ARTAEMIS approach [3-5], the strong linkage between the various magnetic and kinetic plasma parameters and profiles is assumed to be essential and is given more emphasis in the controller synthesis than the non-linearity of the system, at least for preliminary investigations. Nonlinear plasma phenomena are complex and yet too uncertain to be comprehensively integrated in a profile controller design which, if it were ideal, would regulate the plasma and maintain it close to its target state. Well identified nonlinearities may have to be taken into account in the future, if needed as a result of the ongoing investigations and simulations.

Thus, based on the structure of flux-averaged transport equations, a control-oriented grey-box plasma model is postulated to consist of a set of linearized but strongly coupled plasma response equations that only depends on the radius x and time t:

$$\frac{\partial\Psi(x,t)}{\partial t} = \mathcal{L}_{\Psi,\Psi}\{x\}\bullet\Psi(x,t) + \mathcal{L}_{\Psi,K}\{x\}\bullet X + L_{\Psi,P}(x)\cdot P(t) + V_{ext}(t) \tag{1}$$

$$\varepsilon\frac{\partial}{\partial t}X = \mathcal{L}_{K,\Psi}\{x\}\bullet\Psi(x,t) + \mathcal{L}_{K,K}\{x\}\bullet X + L_{K,P}(x)\cdot P(t) \tag{2}$$

Here, the poloidal magnetic flux Ψ(x, t) and a set of kinetic parameters or profiles such as density n(x, t), toroidal velocity $V_\Phi(x, t)$, β_N and P_α, represented by the vector X, are the output variables. The unknown linear differential operators $\mathcal{L}_{\alpha,\beta}\{x\}$ and row vectors $L_{\alpha,\beta}(x)$ depend on x but are independent of time t. The input vector $P(t)$ contains the heating and current drive powers (NBI1, NBI2, ECRH, ICRH, LHCD). The small parameter ε ($\varepsilon \ll 1$ and constant) represents the typical ratio between the characteristic time for the evolution of kinetic parameters and the resistive diffusion time. As the order of magnitude of ε is about 0.05 in present-day tokamaks and 0.001 in ITER, identification and control techniques that are based on the theory of singularly perturbed systems and multiple-time-scale expansions are used. The details concerning this approximation and the identification of a two-time-scale data-driven grey-box model from the measured response of the plasma to actuator modulations can be found in references [3, 4].

We consider an ITER hybrid scenario [7] with plasma current around Ip=12MA, magnetic field B=5.3T, and maximum powers NBI1=NBI2=16.5MW, ECRH=20MW, ICRH=20MW. The controlled parameters are the poloidal flux profile $\Psi(x, t)$, β_N and P_α. Based on the simulated response data to modulations from our 6 actuators obtained from METIS, a full, two-time-scale model was identified using the ARTAEMIS algorithm. Then this model was validated on different METIS simulation data. Given a set of modulation data and input/output parameters, ARTAEMIS maximizes a global fit parameter f which is defined in [4]. As an example, the comparison between the METIS simulation for $\Psi(x, t)$, P_α and β_N, and their prediction from the control-oriented model are shown, for NBI1 modulations, in Fig

(1a-b). The model response to NBI1 fits well with the METIS simulation data for $\Psi(x)$, P_α and β_N as the fits are 84%, 87% and 84% respectively.

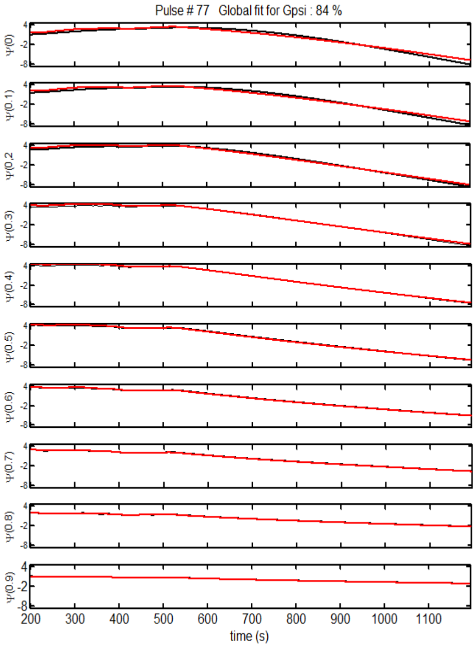


Fig (1a). Comparison between Ψ(x) data (Wb) at x=0, x=0.1, … x=0.9 from the ARTAEMIS model (red) and METIS simulation (black) from 200s to 1200s. The global fit parameter, f, is 84% .

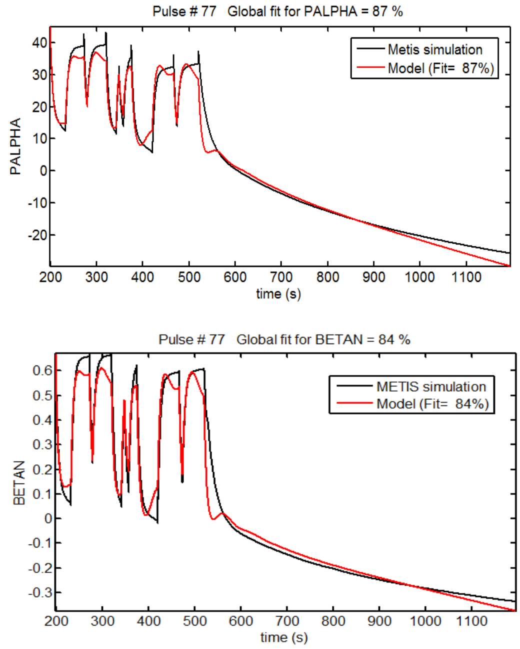
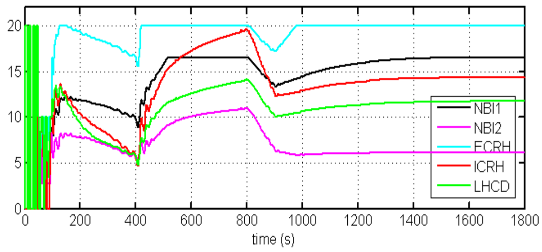


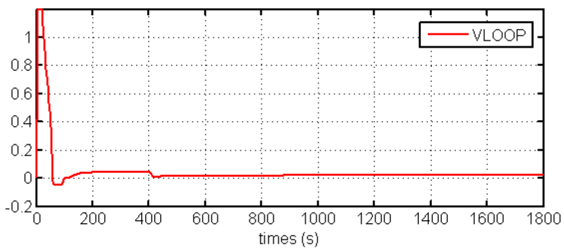
Fig (1b). Comparison between P_α and β_N data from the ARTAEMIS model (red) and from METIS simulation (black) from 200s to 1200s. The global fits are 87% and 84%, respectively.

3. Results of closed-loop control simulations with METIS/ARTAEMIS

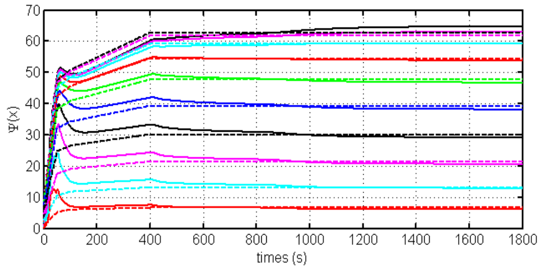
Control simulations were performed by inserting the METIS code at the output of the two-time-scale ARTAEMIS controller and feeding the appropriate error signals back into the controller, thus closing the loop. The near-optimal controller design parameters [3] were computed using the identified model, and the various weights in the controller cost function and in the steady state objective were adequately tuned. The evolution of the 6 actuators that are used in closed-loop control are shown in Fig (2a-b). Except for ECRH which is saturated in this example, all the powers are in the allowed limited range. $\Psi(x, t)$, P_α and β_N satisfactorily reach different preset target values at different times, as shown in Fig (3a-b). In these simulations the plasma density was given as well as many other plasma parameters. Plasma fueling could be added to the actuators for burn control. However, using only the heating and current drive systems in addition to the poloidal field system, integrated magnetic and kinetic plasma control could be achieved. The plasma model used in METIS is based on a 1.5D current diffusion model, 0D scaling laws and fixed power position profiles. As a result, these simulations can run in a CPU time which is close to real time. Further investigations with more comprehensive plasma simulators will be necessary to complete these studies.



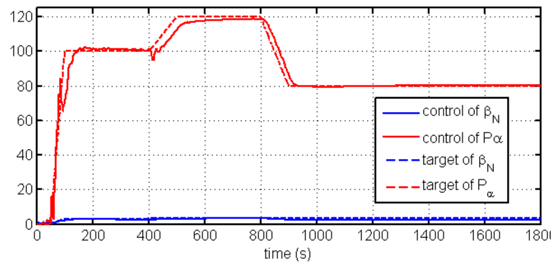
Fig(2a). Evolution of the a powers in the closed-loop simulation.



Fig(2b). Evolution of the loop voltage in the closed loop simulation.



Fig(3a). Control of the Ψ profile (solid line) at x from 0.1 to 0.9 using 6 actuators. Target values are represented by dashed lines.



Fig(3b). Control of the P_α (solid red line) and β_N (solid blue line) using 6 actuators. Target values for P_α and β_N are represented by dashed red line and dashed blue line, respectively.

4. Conclusions

The ARTAEMIS system identification procedure and integrated model-based control scheme have been applied successfully to ITER simulations. This work complements experimental investigations and tests that have been initiated on JET, JT-60U and are still ongoing on DIII-D. In the closed-loop simulations reported here, various target profiles for the poloidal flux have been obtained simultaneously with various levels of the normalized pressure parameter and of the fusion power. This shows that in a fusion device such as ITER, current profile control can be combined with kinetic control and burn control sharing a common set of dedicated actuators.

References

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