An active feedback plasma profile control approach applied to TCV plasmas and perspectives toward ITER

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Abstract

In the advanced operation scenarios in ITER, such as hybrid or steady-state scenarios, active real-time control of plasma profiles is essential to achieve and sustain burning plasmas with sufficient performance. Among the developed plasma profile control approaches, a potentially robust plasma profile control approach for simultaneous control of plasma profiles has been applied to ITER discharge simulations [1] and has been demonstrated in KSTAR experiments [2]. We have extended this control approach to TCV to experimentally demonstrate the capability of q profile control. In this work, as a preparation of the experiment, we have performed simulations for simultaneous control of the ι (=1/q) profile and the plasma beta (β) using a transport simulator RAPTOR [3]. As actuator sharing is an important issue in ITER, the profile control approach has been combined with NTM control in ITER simulations.

Plasma response model

Static T_e and q profile response models [1] are developed using the simplified electron heat transport equation and the relation between q and plasma current density profile:

$$\frac{\partial}{\partial\rho}\left[V'\left\langle|\Delta\rho|^2\right\rangle\left(-\chi_e n_e\frac{\partial T_e}{\partial\rho}\right)\right]=V'Q_e,\quad q=\frac{V'^2F\left\langle 1/R^2\right\rangle\left\langle|\Delta\rho|^2/R^2\right\rangle}{4\pi^2\mu_0\int_0^\rho V'\left\langle 1/R\right\rangle j_{pl}\mathrm{d}\rho}. \tag{1}$$

Assuming linearity and time-invariance during each control time step, one can estimate the variance of T_e and ι as functions of the change of power, ΔP, and the control matrices (C_e, C_ι). Using the pseudo-inverse of the control matrices, the required ΔP to approach the targets can be derived as

$$\mathbf{\Delta P}=\begin{bmatrix}\omega_e\mathbf{C_e}\\ \omega_\iota\mathbf{C}_\iota\end{bmatrix}^+\begin{bmatrix}g_e & 0\\ 0 & g_\iota\end{bmatrix}\begin{bmatrix}\omega_e\Delta\mathbf{T_e}\\ \omega_q\Delta\iota\end{bmatrix}. \tag{2}$$

The new actuator power is estimated adding ΔP to the power from the previous step. For β and ι control, the control matrix for β (C_β) is derived using C_e and ΔP can be obtained in the same way as Eq. (2). These control matrices can be updated in real-time as the plasma state evolves, thus no database or pre-simulation is required. In this model, only auxiliary heating powers are considered as actuators. I_p is assumed to be separately controlled and unchanged during the flat-top phase. Note that the control model does not intend to provide an optimum feedforward path for each actuator but to give the best possible solution at each control time step.

Simultaneous control of β and ι profile control in TCV

For the preparation of the TCV real-time control experiment, simulations have been carried out for simultaneous β and ι profile control. As actuators, EC powers with positive (EC-A) and negative (EC-B) current drives are deposited at the plasma centre. An I_p of 120kA is kept during the flat-top phase. Feedforward EC wave forms are applied until feedback (FB) control begins at 0.2s. With the prescribed maximum and minimum actuator powers, the new estimated power goes to zero if it is smaller than the minimum and has the maximum value for the opposite case. Using this set-up, RAPTOR simulations have been performed to test the controller with time-varying β and ι targets. The simulation result using the achievable targets is shown in Fig. 1. As seen in Fig. 1a), the controller modifies the EC powers to match the target values. At 0.3s, EC-A (co-CD, blue) and EC-B (counter-CD, red) are switched to decrease ι value while keeping a similar β value. The targets are varied again at 0.6s and the controller brings the correct command of required powers for each EC beam. The computed ι profiles in Fig. 1d) show good agreement with each target profile. Note that we choose 4 points, [0.1, 0.3, 0.5, 0.7] in $\rho_{tor,N}$, for ι profile control.

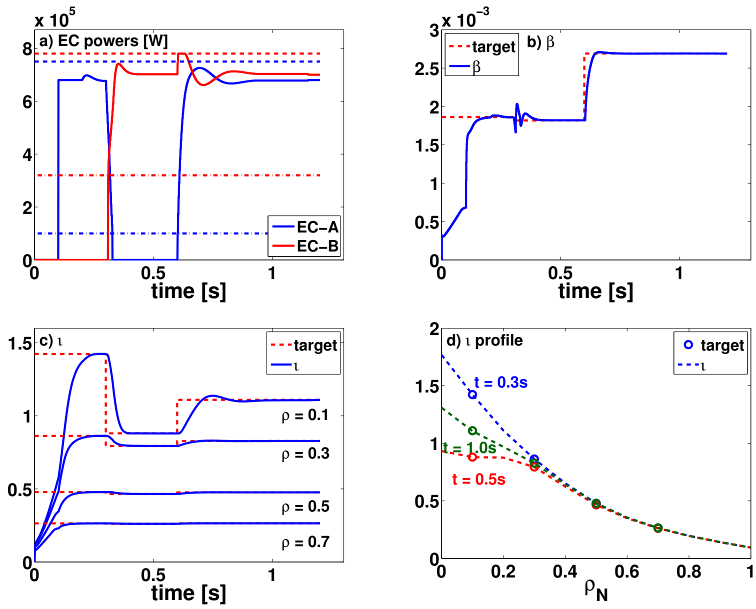

Figure 1: *FB controller correctly estimates a) the required power to reach the target b) β and c) ι values. The maximum (dashed) and minimum (dashed-dot) powers are indicated in a). d) ι profiles show good agreement with the time-varying target profiles.*

Application to ITER scenario

RAPTOR simulation setting is adjusted to reproduce the baseline ITER 15MA H-mode scenario obtained from CORSICA [4] and is modified to provide a hybrid-like scenario (I_p = 12MA, lower n_e, flat q profile ≥ 1, $\beta > 1.8$). Two NBH/CD, one ICH and three ECH/CD from equatorial launcher (EL) are used as actuators to control T_e and ι profiles at [0.0, 0.2, 0.4, 0.6, 0.8], [0.1, 0.3, 0.5, 0.7] in $\rho_{tor,N}$, respectively. All the actuators are assumed to have at least 1MW.

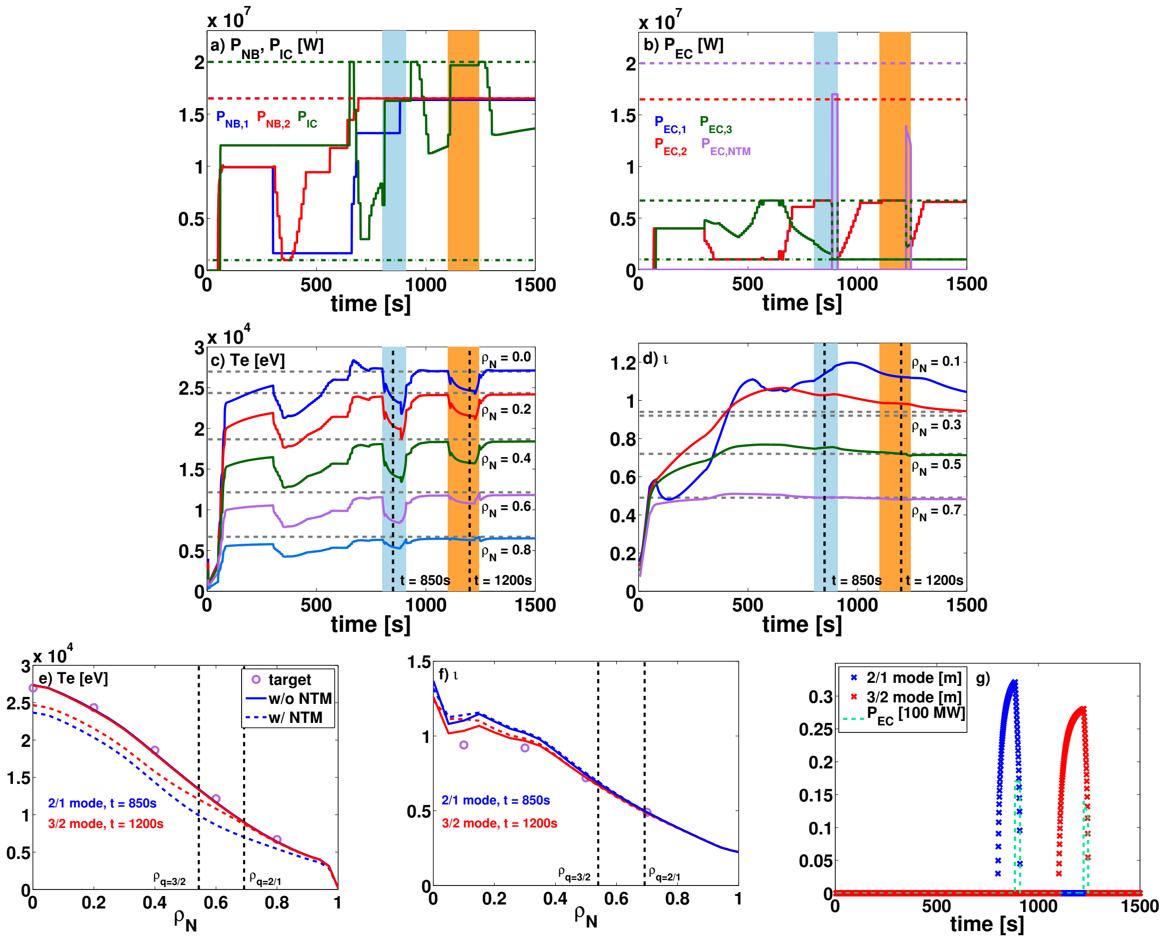

Figure 2: *Time trace of a) NB, IC, b) EC powers with the maximum (dashed) and minimum (dashed dot) power limits and c) T_e and d) ι profiles with target (dashed). The coloured boxes indicate the appearance of NTMs (light blue - 2/1 mode, orange - 3/2 mode). e), f) T_e and ι profiles are shown in comparison with those without NTM. The island size of each mode and applied EC power are presented in g).*

FB control runs every 10s from 300s and NTMs appear at 800s and 1100s (2/1 and 3/2 modes). For stabilising NTMs, the EC beams from the upper launcher (UL), as an additional actuator, are deposited at the mode location when the island size exceeds a certain level (32cm, 28cm for 2/1 and 3/2 modes). The required power P_{NTM} is estimated to satisfy $j_{EC}/j_{BS} \geq 1.2$ [5] (the max. power is set to 17MW) and the EC beams from EL share the rest power (20MW $- P_{NTM}$). Note that in this simulation, we deliberately let the island grow up to the given level to test the profile controller in the presence of NTMs. It is expected that ITER diagnostics, such as ECE, are capable to detect smaller islands and concomitant action for NTM stabilisation follows.

The simulation results presented in Figs. 2a) and b) show the estimated actuator powers and the time trace and profiles of T_e and ι are displayed in c), e) and d), f), respectively. Island sizes of each mode are shown in g). In $a) - d$), the appearance of each mode is indicated as coloured box (light blue for 2/1 mode and orange for 3/2 mode). At 300s, FB control begins and modifies actuator powers to match both T_e and ι profiles to the target values. T_e profile reaches the target around 700s while ι is still evolving. Since the current diffusion time is much longer than the confinement time, ι reacts much slower than T_e. However, ι starts to decrease following the control command (except at $\rho_{tor,N} = 0.1$). The first 2/1 NTM appears at 800s accompanied by T_e drop. Despite the increase of IC power, the controller cannot raise T_e to the target value. As shown in Fig. 2e), T_e in the central region with and without NTMs have the same ∇T_e while in the core region ∇T_e drops around the mode location when NTMs appear. Due to the stiffness in the core region, ∇T_e is not changed much by external heating [6]. Thus T_e cannot reach the target values in the presence of NTMs. As seen in f), the effect of NTM on ι is relatively small but ι is also affected as the combination of actuators changes. When island is bigger than the given level, EC power of maximum 17MW is deposited to stabilise the mode. While EC from UL is on, the maximum powers of the rest EC beams are reduced. Once the mode is stabilised, T_e is recovered and ι evolves close to the target value. This is repeated at 1100s with the emergence of a 3/2 mode. In this simulation, although the target values cannot be achieved due to the presence of NTMs, the profile controller acts to find the best possible solution to keep matching the targets. The sharing of EC powers for profile and NTM controls works well but more detailed study, such as using realistic actuator management, will be required.

Summary and future work

In this work, an active real-time plasma control approach which is essential to the ITER burning plasma operation has been applied to TCV and ITER simulations. The applied feedback control approach correctly computes the required power for β and ι profile control in TCV simulations. This will be experimentally demonstrated with different control cases, e.g. combine with NTM control. The applicability of the control approach to T_e, ι profiles control in the presence of NTMs is also tested for ITER. T_e and ι profiles are well matched to the target values without NTMs but cannot reach the target when NTM is triggered although the controller tries to give the best possible solution. For more realistic simulation, a more sophisticated actuator management algorithm will be applied as well as more detailed calculations of island size and growth rate using realistic EC beam conditions.

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