Optimization, real-time simulation and feedback control of tokamak plasma profiles on TCV

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Introduction

Control of plasma profiles is an essential ingredient in tokamak operation, in particular to access improved confinement regimes where the safety factor (q) profile plays a major role in determining plasma confinement and stability. This paper shows how physics models of profile transport can be used for improved plasma profile control methods. We show two distinct applications.

In the first, a physics model is used to aid in the real-time reconstruction of the q profile, providing spatial and temporal accuracy beyond the limits imposed by diagnostic hardware constraints. This paradigm has been implemented in the TCV tokamak real-time control system and is able to provide real-time estimates of the q profile every 1ms. The reconstructed profiles have then been used in a feedback controller for the internal inductance.

The second application is in determining the optimal time evolution (trajectories) of tokamak plasma actuators such as to reach a prescribed set of profiles at the final time while satisfying constraints during the transient. This technique is applied to determine the optimal trajectories of I_p and auxiliary power P_{aux} required to reach a stationary hybrid q profile at the end of a TCV plasma current ramp-up phase.

RAPTOR: a lightweight physics-based transport model

Both applications described above use a common, newly developed 1D profile diffusion code called RAPTOR (RApid Plasma Transport simulatOR) [1], developed specifically to be sufficiently complex to include the key physics yet sufficiently lightweight to be applicable in real-time. It solves the coupled nonlinear partial differential equations describing the radial evolution of poloidal flux $\psi(\rho,t)$ and electron temperature $T_e(\rho,t)$, written respectively as

$$\sigma_{||}\frac{\partial\psi}{\partial t} = \frac{R_0 J^2}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}(j_{BS}+j_{CD}), \tag{1}$$

$$V'\frac{\partial}{\partial t}[n_e T_e] = \frac{\partial}{\partial\rho}n_e\chi_e\frac{\partial T_e}{\partial\rho} + V'P_e. \tag{2}$$

It assumes time-invariant flux surface shapes chosen from a given (noncircular) MHD equilibrium, such that the profiles J, V', G_2 entering into (1) and (2) are fixed in time. This assumption is verified to have a small effect for a fixed plasma boundary, as long as the Shafranov shift does not excessively deviate from the chosen equilibrium. The neoclassical conductivity $\sigma_{||}$ and bootstrap current j_{BS} are modeled following [2] and the auxiliary current drive j_{CD} is modeled using a sum of gaussian deposition profiles. The boundary condition for (1) is prescribed by the total plasma current. The electron temperature diffusion (2) is modeled using an ad-hoc transport model for χ_e, similar in form to that used in [3]. The electron power input P_e is the sum of auxiliary and Ohmic power. The density profile is assumed fixed in this work.

Real-time simulation of plasma profiles

Traditionally, feedback control of the q profile is done relying on MSE-based real-time q profile estimates [4], [5]. Instead, we propose to use a real-time simulation of the current diffusion physics to reconstruct the q profile in real time. Internal measurements such as MSE can then be incorporated as additional constraints when available, but the overall spatial and temporal resolution is determined by the numerical properties of the algorithm and the available computational power, rather than the hardware constraints of the diagnostics. This concept is schematically illustrated in Figure 1, which illustrates how measurements available at discrete points in space and time are embedded in a physics simulation of a profile evolution model on a denser space and time grid. Importantly, the simulations allow prediction of the future plasma profile evolution.

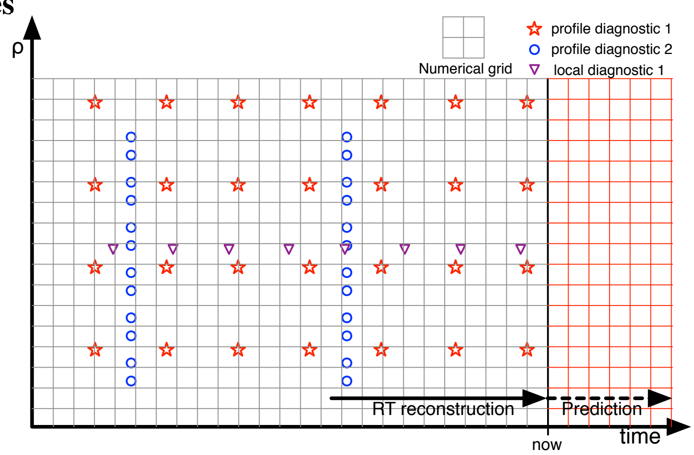

Figure 1: Schematic illustration of the RT simulation paradigm for better reconstruction of plasma profiles.

The use of real-time simulations in a Tokamak real-time control scheme is shown in Figure 2, illustrating possible applications in supervision, prediction, disturbance estimation as well as for providing accurate self-consistent estimates of the plasma (profile) state to advanced model-based controllers.

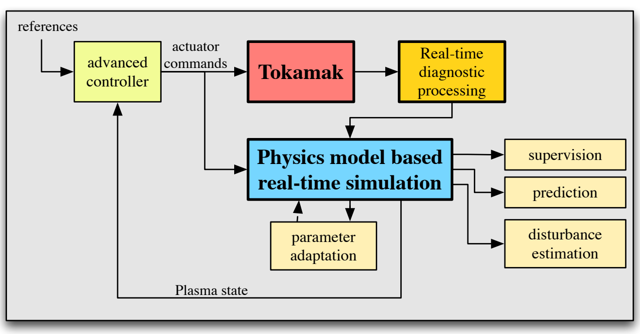

Figure 2: Real-time simulation embedded in a Tokamak real-time control scheme, from [1]

TCV implementation and use in feedback control experiments

A first practical demonstration of the real-time simulation paradigm has been made on the TCV tokamak. The lightweight RAPTOR transport model is used in real-time interpretative mode, where only the flux diffusion equation (1) is solved and the kinetic profiles T_e, n_e needed to compute the conductivity and bootstrap current are provided by interpretation of real-time diagnostic data. As no direct measurements of the q profile are available on TCV, the reconstruction is based entirely on the neoclassical current diffusion physics in this case.

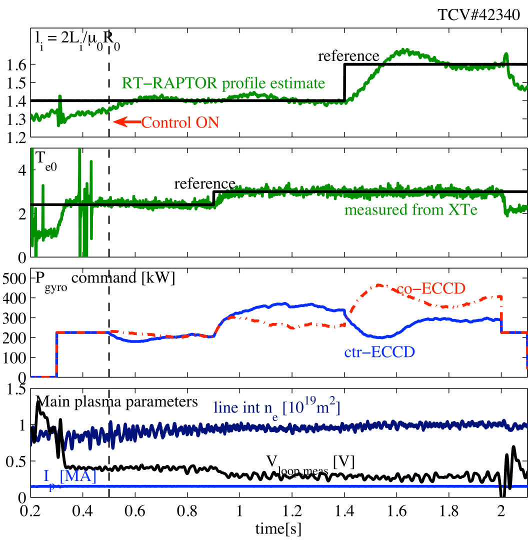

Figure 3: Demonstration of simultaneous feedback control of T_{e0} and l_i

The poloidal flux profile, as well as related quantities such as the q profile, current density profile, bootstrap current fraction, loop voltage profile and many other quantities are provided every 1ms, much faster than the TCV current redistribution time scale which is $\sim$ 150ms in heated plasmas. Profile estimates obtained in real-time compare favourably to results obtained off-line from interpretative transport modeling with the ASTRA code, supporting the validity of the approach [1]. First experiments have been performed using the real-time reconstructed ψ profile to control the normalized plasma internal induction l_i in real-time using two sources of EC current drive (ECCD). In this experiment, one ECCD source provides on-axis co-current drive while the other provides on-axis counter current drive. By varying the total power the central electron temperature T_{e0} is controlled, while the difference between the two powers governs the degree of central current peaking. T_{e0} and l_i are independently controlled using two PI controllers, as demonstrated in Figure 3.

Optimization of actuator trajectories

Another important application of the simplified transport physics model described is to compute the optimal plasma actuator trajectories required to reach a given plasma state. In particular, we have studied the optimal time evolution of $I_p(t)$ and $P_{aux}(t)$ required to reach a stationary hybrid-like q profile at the end of a current ramp-up phase for the TCV tokamak, while satisfying the constraint $q_{min} > 1.1$ and $V_{loop,edge} > 0$ at all times [6]. The problem is cast in the form of a nonlinear, constrained, dynamic, finite-horizon optimal control problem. The cost function to be minimized is formulated such as to reach a flat loop voltage, indicating stationary plasma profiles, while minimizing the flux consumption.

The predictive version of RAPTOR, solving the coupled diffusion of ψ and T_e modeled by the two of PDEs (1)-(2), has the unique property of returning the parameter sensitivities of the profile evolution trajectories. For example, let p be the amount of auxiliary power P_{aux} during a pre-specified time interval. Then the transport code provides $\partial\psi(\rho,t)/\partial p$ i.e. the first order derivative of the flux profile evolution in time with respect to this parameter. This information is incorporated in a nonlinear optimization routine to solve the optimal control problem described, avoiding the need to take finite differences for computing the required gradients.

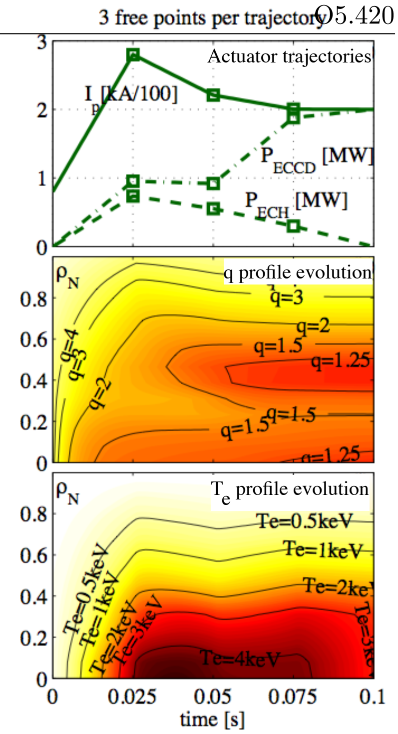

Figure 4: Optimal trajectories of I_p and auxiliary power [6]

The results are shown in Figure 4 where the optimization is run for the trajectories of I_p as well as off-axis ECCD $\rho_{dep} = 0.3$ and central ECH. The squares on the top panel represent the free points whose amplitude were varied by the optimization routine. The optimal trajectories feature an I_p overshoot similar to that which is experimentally found to be advantageous for obtaining hybrid scenarios in many tokamaks. The loop voltage profile at the final time $t = 0.1$s (not shown) is practically flat and the total flux consumption lower than for a set of simple, non-optimized actuator trajectories.

Conclusions

Real-time simulation, merging the fields of real-time control and post-shot interpretative transport modeling, has promising applications for improved profile control and prediction. Tokamak actuator trajectory optimization can provide the open-loop trajectory evolution for transient phases, and has advantages in scenario preparation and optimization as well as providing the basis references for subsequent feedback control. Further experimental validation of the proposed approaches is underway.

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