Real-time model-based plasma state estimation, monitoring and integrated control in TCV, ASDEX-Upgrade and ITER.

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Abstract:

To maintain a high-performance, long-duration tokamak plasma scenario, it is necessary to maintain desired profiles while respecting operational limits. This requires real-time estimation of the profiles, monitoring of their evolution with respect to predictions and known limits, and their active control to remain within the desired envelope. Model-based techniques are particularly suitable to tackle such problems due to the nonlinear nature of the processes and the tight coupling among the various physical variables. Physics-based, control-oriented models for the core plasma profiles in a tokamak are presented, formulated in such a way that powerful methods from the systems & control engineering community can be leveraged to design efficient algorithms. We report on new development and applications of these models for real-time reconstruction, monitoring and integrated control of plasma profiles on TCV, ASDEX-Upgrade and simulations for ITER.

1 Introduction

The radial distribution of plasma current density, particle density, pressure and momentum has a strong influence on plasma performance and stability in a tokamak. Simultaneous control of all these profiles requires a model-based approach, as the cross-coupling between processes, the distributed nature of the problem and shared effects of actuators make manual tuning of simple single-input-single-output controllers suboptimal, and sometimes infeasible. Also, in particular for long-pulse scenario in large tokamaks, supervision of the plasma discharge evolution becomes increasingly important [1]. To prepare for the operation of ITER, such monitoring schemes are being deployed and tested on various tokamaks. A model-based control design approach is presented to tackle these challenges, with application to control of plasma density and pressure on TCV, reconstruction and monitoring of profiles on ASDEX-Upgrade and hybrid scenario simulations for ITER. One advantage of such a model-based approach is that these tools are readily portable from one tokamak to another: parts of the model parameters may need to be adjusted to reflect the specific actuators and diagnostics on a given device, but the controller design procedure remains the same.

In this work, control-oriented models of the plasma are presented that are formulated in such a way that control engineering tools can be applied to them (Section 2). In particular we introduce the RAPTOR code, a real-time control-oriented tokamak profile simulator. Then a plasma state estimation algorithm, specifically an Extended Kalman Filter (EKF) is designed to estimate the plasma profiles in real-time (Section 3.1). An EKF merges information from various diagnostics with model-based expectations of the plasma behaviour. The EKF can also be used to detect discrepancies between expected and observed plasma evolution, providing useful input to plasma scenario monitoring algorithms. Experimental results are shown of model-based controllers for plasma β and density implemented in TCV (Section 3.2). An example of plasma monitoring on ASDEX-Upgrade is shown in Section 3.3. The rapid execution time of RAPTOR is also used for numerical optimization of plasma ramp-down scenarios in Section 3.4.

2 Physics-based, control-oriented modeling of tokamak plasma profile evolution

A control-oriented core profile evolution model is implemented in the RAPTOR (RApid Plasma Transport simulatOR) code [3], [4], which is capable of simulating the coupled evolution of current density and temperature profiles faster than real-time for present-day medium-sized tokamaks. RAPTOR solves the transport PDEs for poloidal flux and electron temperature, and contains the key nonlinearities of the coupled transport between magnetic and thermal profiles. Neoclassical Tearing Modes (NTMs) and sawteeth are also evolved self-consistently. In similar spirit, a model for the particle density was developed [5] that couples the 1D evolution of the particle density profile with particle reservoir models for the plasma wall and vacuum chamber inventory. Both models have been validated, after tuning of a limited number of empirical model coefficients, against measurements of

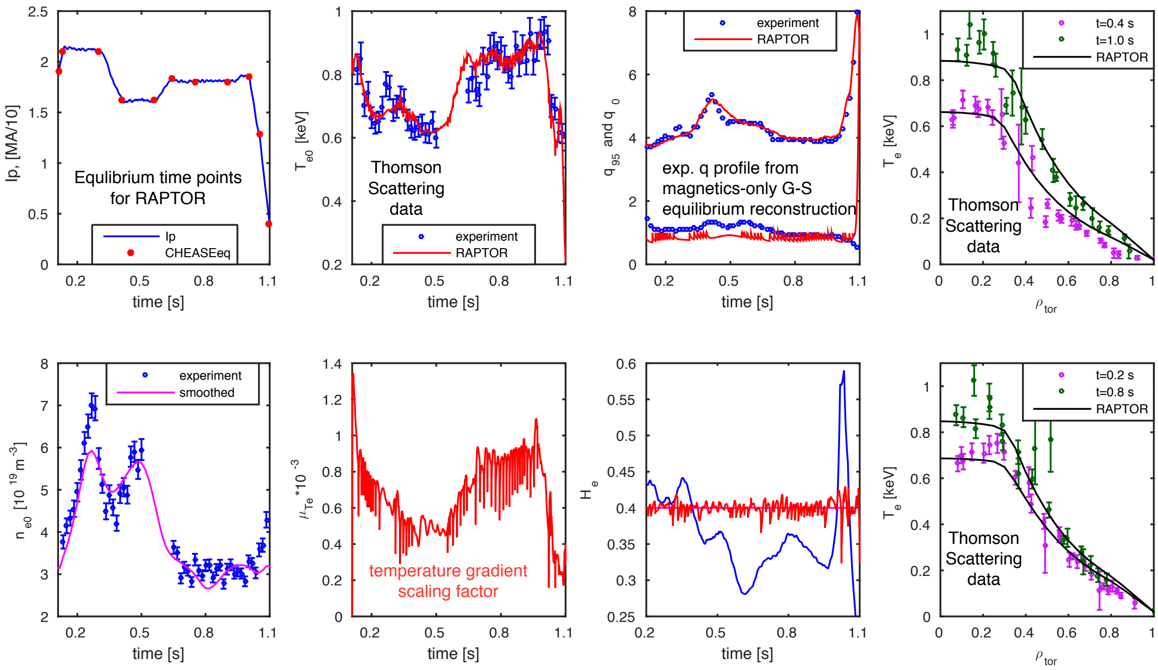

FIG. 1: RAPTOR simulation of Ohmic L-mode TCV discharge using the gradient-based electron heat diffusivity transport model [2]. The equilibrium geometry, particle density, H factor (H_e) and plasma current evolution are prescribed, and the simulation correctly reproduces temperature profiles and q profile evolution including sawteeth.

TCV and ASDEX-Upgrade plasmas as well as against higher-fidelity physics-based codes, and against predictive scenario simulations for ITER. A simulation of a TCV L-mode discharge using RAPTOR, and comparison with experimental measurements, is shown in Figure 1.

These control-oriented models are based on well-established and understood physics models as much as possible, but at the same time employ empirical or parametrized models where necessary for the sake of computational efficiency. For example, RAPTOR uses parametrized models for the power/current density profiles of various auxiliary heating systems. These actuator models can be constructed from off-line calculations of these profiles using more sophisticated and time-consuming codes. For the thermal transport, various options exist ranging from empirical models such as Bohm-gyroBohm or H-factor based models [2] to neural-network emulation of quasilinear gyrokinetic predictions of the thermal fluxes [6]. Particular effort is also placed on the numerical implementation of the PDE solver for the transport equations. The use of a fully implicit discretization scheme for the time evolution, with analytical evaluation of Jacobians, allows for relatively large time steps without sacrificing stability. Knowledge of the Jacobians is also useful for controller design and trajectory optimization [4].

3 Real-time plasma profile estimation, monitoring, and control

3.1 Estimators for the core plasma profiles

The real-time capabilities of the control-oriented models allow them to be run in real-time in parallel to the physical evolution of the plasma, in a scheme known in control engineering as a dynamic observer, in particular an Extended Kalman Filter (EKF). This enables a real-time data fusion of model predictions and various diagnostic measurements into a single, self-consistent estimate of the state of the plasma, in a form that is then independent of the specific diagnostics available on one machine [7]. This state estimate may then be compared in real-time to known operational limits to assess the proximity of the plasma to a disruption. Also, the state estimate may be compared to a real-time model-based prediction and unexpected differences can be flagged.

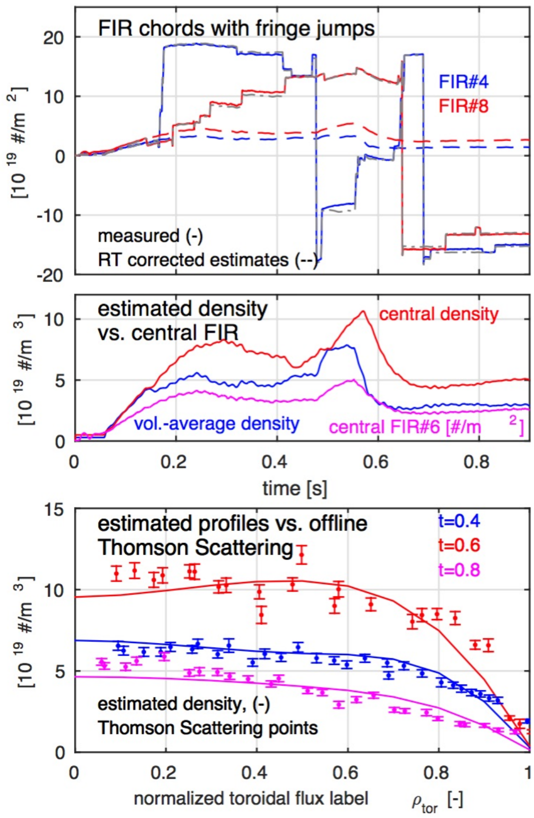

FIG. 2: Reconstruction of TCV plasma (#53095) particle density using a dynamic state observer.

Real-time profile estimation algorithms based on RAPTOR have been installed on TCV, ASDEX-Upgrade and RFX devices [8], [9]. On TCV and ASDEX-upgrade, RAPTOR uses flux geometry information from real-time equilibrium reconstruction codes. Apart from unavoidable differences in the models of actuators, diagnostics, and some (transport) model parameters, the methodology is practically identical on all devices. The profile estimation algorithms are inherently machine-independent and can be tailored to any available real-time diagnostics. Clearly, the quality of the reconstruction, and the resilience with respect to failure of individual diagnostics will increase the more diagnostics are added.

An example of real-time state estimation of the plasma density profile for TCV plasmas is shown in figure 2. An EKF algorithm is combined with the 1D control-oriented particle transport model, which is used to compute the one-step-ahead predicted measurements of 14 interferometer channels and compared in real-time to the true measurements. This facilitates the detection and correction of interferometer fringe jumps, which might otherwise disturb the profile estimate. The resulting profiles are in agreement with (off-line) data from Thomson Scattering measurements. The estimation algorithms runs every 1ms on the TCV control system, and the resulting profiles are used as input to real-time density controller using gas valve actuators.

3.2 Model-based control of plasma core density, pressure and q profiles

Feedback controllers for core plasma quantities can be derived directly from the control-oriented models, by model-based controller synthesis. These controllers receive the real-time estimated profiles from the state observer, and compute actuator signals to steer a quantity of interest to a set-point. Model-based control design has the advantage that it does not require manual tuning of controller gains and can deal with multi-variable systems where significant coupling is present. Multivariable controllers for the plasma thermal β and q profile using a combination of heating and current drive actuators have been developed for TCV using various approaches, ranging from passivity-based control [10] and adaptive control [11] to model based predictive control (MPC) [12]. Also, a model-based robust controller for the plasma density has been designed. The combined operation on TCV of the robust density controller (using the main fuelling gas valve) and a predictive controller for β (using two sources of Electron Cyclotron Heating) is shown in Figure 3. In this example, time-varying limits on the gyrotron power are taken into account. The plasma state used as input to the controllers in these experiments is estimated using two state observers: one state observer based on RAPTOR for the electron temperature profiles (giving β) and another observer for the density profile. These algorithms are implemented in the Simulink®block-programming language and automatically converted to C-code and compiled for the TCV control system [13].

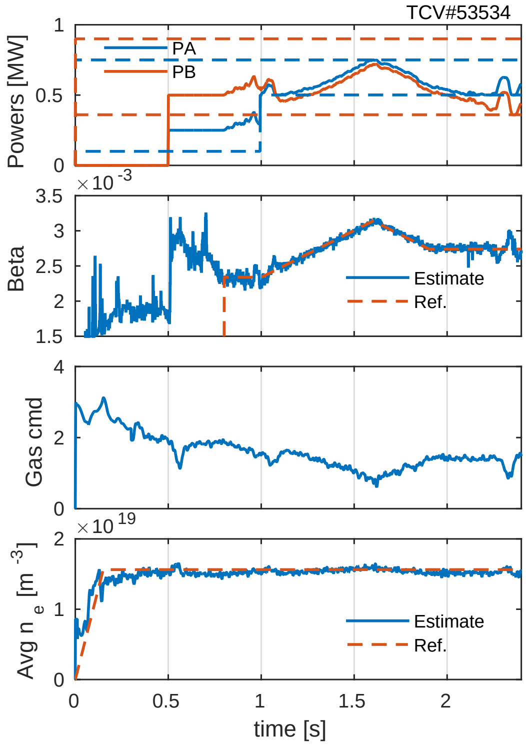

FIG. 3: Simultaneous control of plasma density and beta using model-based controllers on TCV. Two EC sources (P_A/P_B) are used for heating.

The model-based predictive q profile controller has also been used in simulations of profile control in a hybrid scenario in ITER [14] using the EC system. In these simulations, the MPC controller was aware in real-time of the amount of EC power available for current profile tailoring. Following a simulated appearance of an NTM, some EC power is redirected to suppress it (simulated self-consistently by evolving the Modified Rutherford Equation) while the controller uses the remaining EC power and a reduction of the plasma current to maintain the q profile above 1. The challenge of real-time actuator management for plasma heating systems, recently studied on ASDEX-Upgrade [15], has also been addressed by formulating the problem as a Mixed Integer Quadratic Programming (MIQP) problem. In this formulation, a set of sources (e.g. gyrotrons), targets (e.g.

locations in the plasma) and delivery systems (e.g. launchers) is defined, and prioritized requests for power allocations per target are specified. The desired properties of the allocation are condensed into a cost function, while a set of constraints defines the region of feasible allocations. An algorithm has been developed that can solve the optimization problem allocating 28 sources and 17 delivery systems to 5 targets, roughly the number of degrees of freedom available in ITER, in less than a second of computational time on a single CPU.

3.3 Plasma monitoring

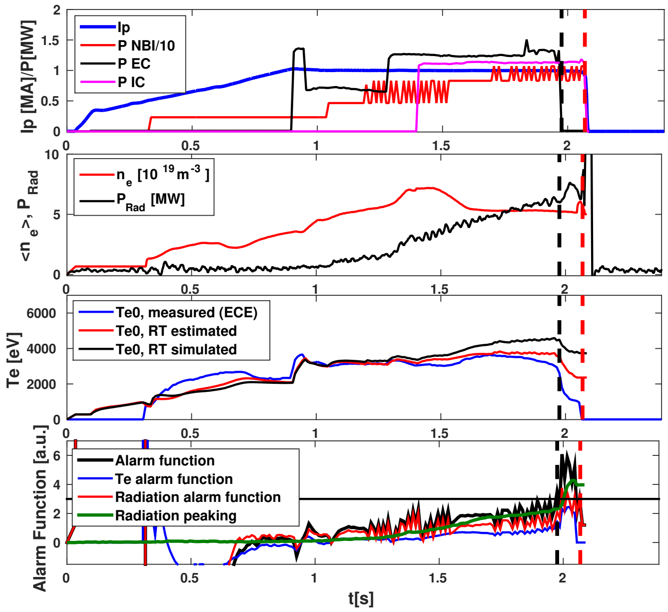

FIG. 4: Example of model-based plasma monitoring on ASDEX-Upgrade (#33627). Due to impurity accumulation, the plasma radiates more than expected, resulting in a discrepancy between the real-time predicted, reconstructed, and ECE measured temperature. This information can be used in the future as signal to a supervisory control system.

Real-time model-based predictions of plasma evolution can also be used for real-time scenario monitoring. Results from a real-time simulation of the expected plasma evolution with the known actuator inputs are compared to the reconstructed plasma state from the EKF, as well as directly to measurements. Discrepancies are flagged and can be used to trigger soft-stop or scenario recovery strategies. First results from a proof-of-principle plasma monitoring algorithm on ASDEX-Upgrade that uses this paradigm is shown in Figure 4. Impurity accumulation, which manifests itself as an increase of P_{rad} and radiation peaking, results in a discrepancy between the predicted, estimated and measured temperature. Signs of an excessive deviation are used to send an alarm signal. No recovering action was taken in this particular discharge, but future work will focus on integrating such an alarm in a higher-level scenario plasma monitoring algorithm for supervisory control.

3.4 Numerical optimization of the plasma ramp-up and ramp-down

The availability of a fast control-oriented model such as RAPTOR allows to carry out many simulations of plasma evolution and use optimization techniques to explore ways to improve plasma discharges. This was studied for TCV and ITER ramp-up scenarios [4], [16], showing that current overshoot during the ramp-up is beneficial for obtaining stationary current density profiles early in the flat-top. Recently, these tools have been applied to compute actuator trajectories during ramp-down to terminate the plasma while remaining away from stability boundaries. This is achieved by well-timed reduction of the plasma elongation, heating and current, aimed at ramping down the plasma current in the shortest time. Figure 5 shows a demonstrative example of such an optimization for an AUG-like plasma. Constraint on the maximum $\beta_N < 2.8$, minimum $q_0 > 1$ and $l_{i,3} < 1.5$ are successively added. The plasma current and elogation time evolutions are optimized, assuming (in this example) only one degree of freedom for trajectory, with fixed start and end values. A satisfactory trajectory is found that features a simultaneous reduction of plasma current and elongation to stay within the limits. Adding more constraints and more degrees of freedom should allow further optimization.

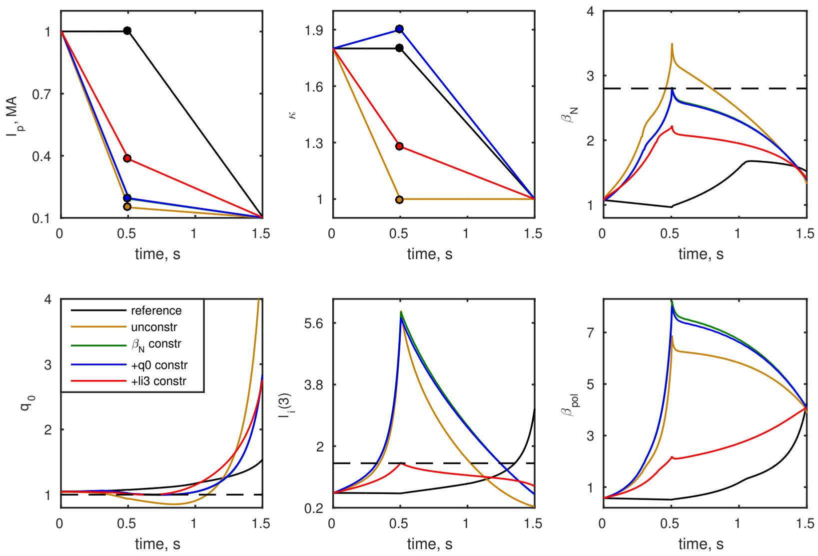

FIG. 5: Example of ramp-down optimization for an AUG-like plasma. Constraints on β_N, q_0 and l_{i3} are successively added, leading to different time-trajectories for plasma current and elongation.

4 Outlook

In the near future, the physics fidelity of the transport models used in RAPTOR will be improved further by including more transport fluxes and realistic transport coefficients based on neural network emulations of linear gyrokinetic codes [6], greatly enhancing the predictive capability. Model-based controllers will continue to be developed and integrated in the plasma control systems of TCV and other tokamaks. Real-time plasma monitoring applications will be extended to monitor as many known and well-understood physics and actuator limits as possible. Further work will also focus on plasma scenario supervision, developing algorithms that allow the plasma control system to react to unexpected events and take the appropriate action to either recover the plasma or terminate it in a controlled manner. Owing to the generic nature of the control-oriented models that form the cornerstone of this work, the developed solutions are readily portable across various devices including (but not limited to) RFX, JET, WEST, and ITER, as the monitoring and control algorithms are formulated in terms of the physics quantities, not in terms of the particular set of diagnostics that is available.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work is also supported by the Netherlands Organisation for Scientific Research (NWO) via the Innovational Research Incentives Scheme.

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