

## Model-based design, simulation and testing of an electron temperature profile controller on ASDEX-Upgrade

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### Introduction

Model-based controller design is gaining increasing popularity also for design of controllers for tokamak plasmas, as this reduces the need for manual controller parameter tuning and permits extensive verification in simulation rather than experiments. In this work, we present the results of a model-based design, validation and experimental testing of a multi-input multi-output  $T_e$ -profile controller for ASDEX-Upgrade. The multi-input-multi-output (MIMO) controller uses two ECRH sources for which the power is controlled in real-time to maintain the  $T_e$  profile constant while neutral beam sources are switched between off-axis and on-axis sources.

To design the controller, we start with a control-oriented simulation of the target discharges using the RAPTOR profile evolution code [1], that reproduces the profile evolution from interpretative TRANSP simulations. A local linearization of the response of the profile to changes in the EC power, around a reference operating point, is automatically obtained from RAPTOR. A linear controller is designed based on an established control design technique for multivariable controllers: the principal input-output directions are computed by an SVD and each direction is controlled independently [2]. The controller is first tested in closed-loop simulations using RAPTOR as plasma simulator. It is then deployed on the ASDEX-Upgrade Discharge Control System (DCS) [3] for experimental testing. These steps will be explained further in the remainder of this paper.

### Experiment set-up

In order to facilitate analysis of the beam-driven current by on and off-axis NBI sources, it is desired that the temperature profile stays constant during the change of NBI deposition profiles [4]. In previous experiments, it was observed that using feedback control of the gyrotron power

\*See authorlist of "Meyer et al, Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution, accepted for publication in Nuclear Fusion"

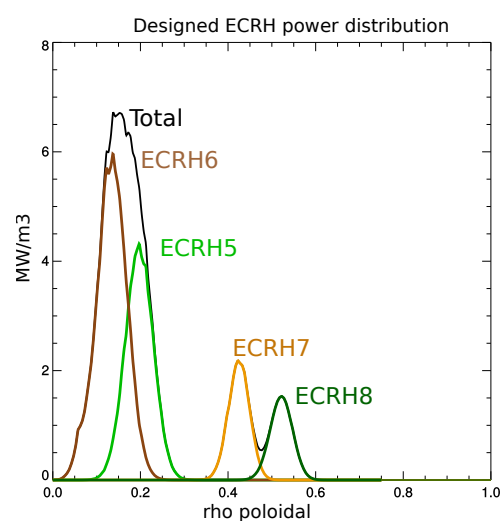
based on ECE measurements at a single radial position it was possible to maintain the  $T_e$  value fixed at a prescribed point, but the shape of the profile could change. The objective of the MIMO controller is to control more (in this case: two) parameters of the profile instead of one. To this aim, the EC launcher aiming was prepared to have one gyrotron (named ECRH5) depositing EC power close to the plasma center (near  $\rho_{tor} = 0.2$ ), and the second (ECRH7) depositing power near  $\rho = 0.4$ ). Power from other gyrotrons, which is controlled in feedforward, are also deposited in the center (to avoid core impurity accumulation) and off-axis (for NTM avoidance and stabilization purposes). The distribution of the EC sources can be seen in Figure 1.

Information about the real-time evolution of the  $T_e$  profile is obtained from the the RAPTOR-observer [5], which uses a dynamic state observer algorithm (Extended Kalman Filter) to merge ECE data with model-based predictions in real-time. This effectively filters ECE signals and provides a reliable way to reject outliers and unphysical measurements.

### Controller design and validation

A TRANSP reconstruction of the plasma profile evolution during a representative shot is used as a reference to tune a run of a RAPTOR simulation (offline). Source deposition profiles, density profile evolution,  $Z_{eff}$  profile and total plasma current are taken from TRANSP, which in turn uses various diagnostics inputs. RAPTOR predicts the evolution of  $T_e$ ,  $T_i$  and  $q$  profiles, using the empirical Bohm-gyroBohm transport model. This was observed to accurately reproduce the  $T_e$  and  $q$  profile evolution, with some offset in the  $T_i$  evolution which can be attributed to the simplicity of the transport model. Since we are interested in temperature profile control, this is not deemed a large problem.

Next, the simulation is repeated with the new designed EC deposition profiles (Figure 1) and expected NBI sources for the target experiment. One time slice of the simulation, with corresponding actuator powers and profiles, is chosen as the point around which to derive a local linear model. This model consists of a set of linear ordinary differential equations (ODEs) relating the variation of input powers (for the controlled gyrotrons numbers 5 and 7) to the variation in  $T_e$  profile values on a  $\rho_{tor}$  grid. As discussed in [1], a unique feature of RAPTOR is that it returns this local linear model automatically when solving the nonlinear PDEs of the transport equations, so no further simulations are necessary to obtain this model.



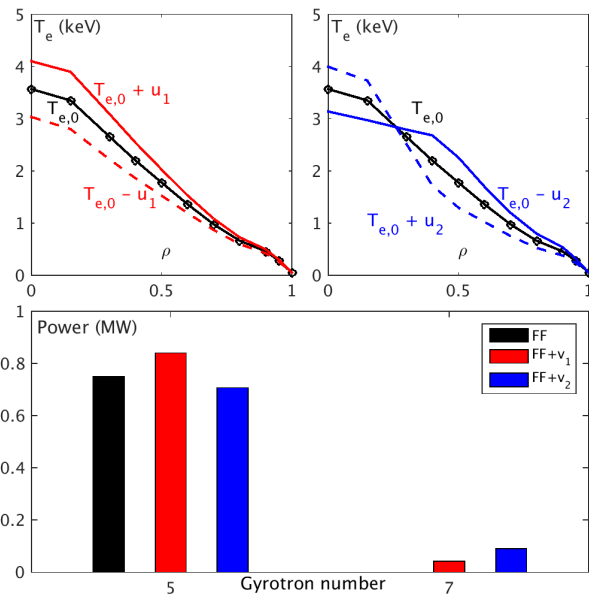
**Figure 1:** Designed distribution of EC deposition using TORBEAM. Power to gyrotrons 5 and 7 is controlled in real-time.

Once this linear model is available, the Singular Value Decomposition (SVD) of the steady-state response of the model to step-changes in the actuator power is used to compute the main controllable directions of the system. These directions are illustrated in Figure 2 and show, as expected, that the central temperature as well as the off-axis temperature can be controlled by variations of the on-and off-axis power. Obviously, this response model is based on an empirical transport model and may not be accurate in the magnitude of the profile deviation that can be obtained. However, this is compensated by designing the controller to tolerate changes in the amplitude of the response to a certain extent. A PID controller is designed for each controlled channel, with the gains chosen based on model simulations using the linear model including the delays that can be expected in the closed-loop.

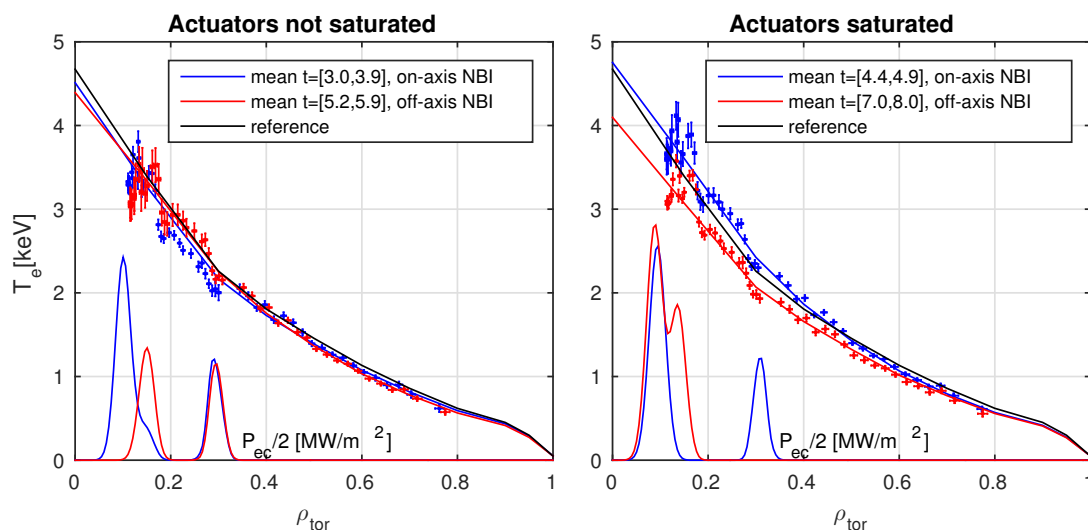
Finally, a further closed-loop simulation of the controller is performed using RAPTOR as a tokamak simulator. After verification that the controller performed adequately in this simulation, the controller matrices were implemented in the ASDEX-Upgrade DCS. Anti-windup compensation was included to handle saturation of the actuators.

## Results

Already during the first experimental trial, the controller was able to maintain a constant temperature profile during extended phases of the discharge, and showed a behaviour very similar to the off-line simulations. As can be seen in Figure 3, in periods when the actuators were not saturated, the controller successfully maintained the temperature profile despite a change of NBI deposition from off-axis to on-axis and back. In other time periods, the density had inadvertently increased and it was no longer possible to reach the reference profile without saturating the EC power in one or more of the sources, therefore the reference profile could not be tracked.



**Figure 2:** Graphical illustration of controlled directions for the MIMO profile controller. Temperature profile variation vs  $\rho_{tor}$  for principal directions  $u_1, u_2$  are shown in the top panels. Corresponding ECRH input variations  $v_1, v_2$  are shown in the bottom panel with respect to the equilibrium profile  $T_e^o$  and feedforward powers (FF) around which the linearization is performed (black).



**Figure 3:**  $T_e$  profiles estimated by RAPTOR-observer, and EC power density profiles, during on- and off-axis NBI power phases. Cases are shown where actuators were not saturated (left), as well as cases when actuators were saturated and control was not effective (right).

## Conclusions and Outlook

This work has shown a successful application of a model-based design and validation procedure to design a  $T_e$  profile controller, which showed successful control at its first experimental application. While this controller was designed for a specific operating point, real-time linearizations from the RAPTOR-observer combined with real-time calculations of the SVDs to adapt the controller in real-time could be used in the future. This would allow the controller to take into account changes of e.g. EC deposition location and density profiles. Also, more advanced and realistic transport models are in development [6] that would improve the physics fidelity of the RAPTOR simulation allowing one to design more aggressive controllers.

The  $T_e$  profile controller will enable several further physics applications such as control of the temperature gradient for transport studies. But most importantly, this experiment is a validation of model-based design techniques as will be increasingly important in ITER and other long-pulse devices where experimental time for manual controller tuning will be increasingly limited.

## References

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