EUROFUSION CP(15)05/32

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Simultaneous Control of Plasma Profiles and Neoclassical Tearing Modes with Actuator Management in Tokamaks

(22nd June 2015 – 26th June 2015)
Lisbon, Portugal

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.

Simultaneous control of plasma profiles and neoclassical tearing modes with actuator management in tokamaks

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Introduction

Tokamaks require a plasma control system (PCS) to help ensure that physics goals are met while remaining within operational and machine limits. Especially in future long pulse devices (e.g. ITER), several control tasks need to be executed simultaneously that share a limited set of actuators, where the priority of control tasks and the availability of actuators may change suddenly due to plasma or hardware events [1].

PCS architectural design has recently gained much attention in the literature in view of future long pulse tokamaks (e.g. ITER [2] and Tore Supra WEST [3]) and currently operational tokamaks (e.g. AUG [4]). In the PCS design, actuator management is needed to resolve the conflicting requests of multiple control tasks that share a limited set of actuators [1].

Actuator management for the Electron Cyclotron (EC) beams at AUG is considered in [5], where gyrotrons are optimally allocated to low level controllers for gyrotron power and launcher steering, based on higher level power requests with corresponding importance and effectiveness.

In this work we show simultaneous control of plasma profiles and suppression of neoclassical tearing modes (NTMs) by using a shared amount of available EC-power that is often used for each of these individual control tasks. The proposed PCS architecture contains a high level actuator management layer that allocates resources to the profile and NTM-controller before execution of these control tasks. As such, an intelligent profile controller can be used to ensure satisfaction of (time-varying) operational limits, which would be impossible if calculated actuator commands would be modified afterwards.

Control architecture

Based on the existing (quite similar) PCS architecture designs in [2, 3, 4], we propose a control architecture to facilitate the simultaneous control of profiles and NTMs, that can be extended to more tasks. The control architecture is presented in Figure 1.

A central decision layer sets control task priorities based on the state of plasma and status of hardware (top). These priorities are used by the high level actuator management layer to allocate a limited set of resources to each control task, such that these controllers are aware of their resources. The NTM controller provides the actuator input for the next step and the desired allocated power for the next step is given back to the high level actuator management. The MPC controller computes at every time instant the future optimal control inputs for 120 time steps ahead, based on profile evolution models such that a q-profile reference is tracked and actuator and operational limits are satisfied [6]. The MPC controller could also provide profile predictions and warnings for expected constraint violations back to the central decision layer (not in this work). The inputs as given by the NTM and MPC controllers are in this work simply joined with feedforward inputs in the low level actuator management block, whereas functionality in this block could be extended based on the work in [5]. Finally the actuator inputs are given to the plasma transport simulator RAPTOR [7].

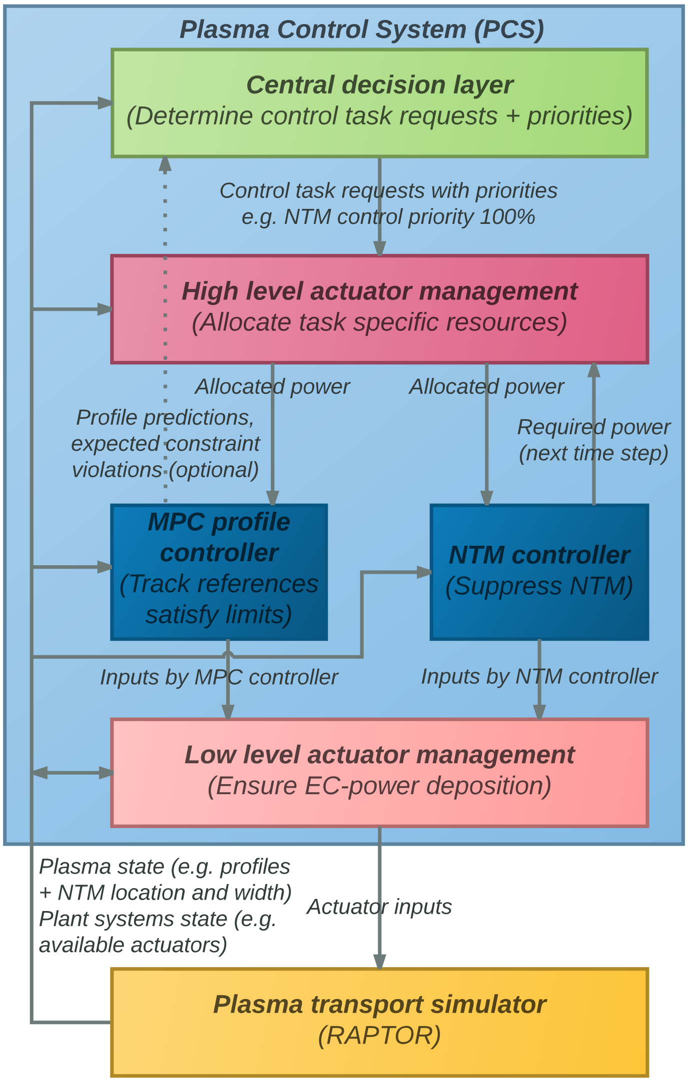

Fig. 1: PCS architecture for control of NTMs and profiles.

Simulation results

A simulation environment is built in Simulink [8] containing the designed PCS, connected to RAPTOR. RAPTOR has been extended to include the effect of NTMs on the plasma profiles, where the local heat transport is enhanced proportional to the island width, while the island width evolution is modeled by the Modified Rutherford Equation [9]. An ITER Hybrid scenario simulation in RAPTOR as described in [10] has been modified and has now a nominal flat top current of $I_p = 12$ MA, 33 MW NBI, and 25.7 MW EC. Actuator trajectories are optimized to achieve stationarity of profiles at the beginning of the flat-top (100 s) using the method

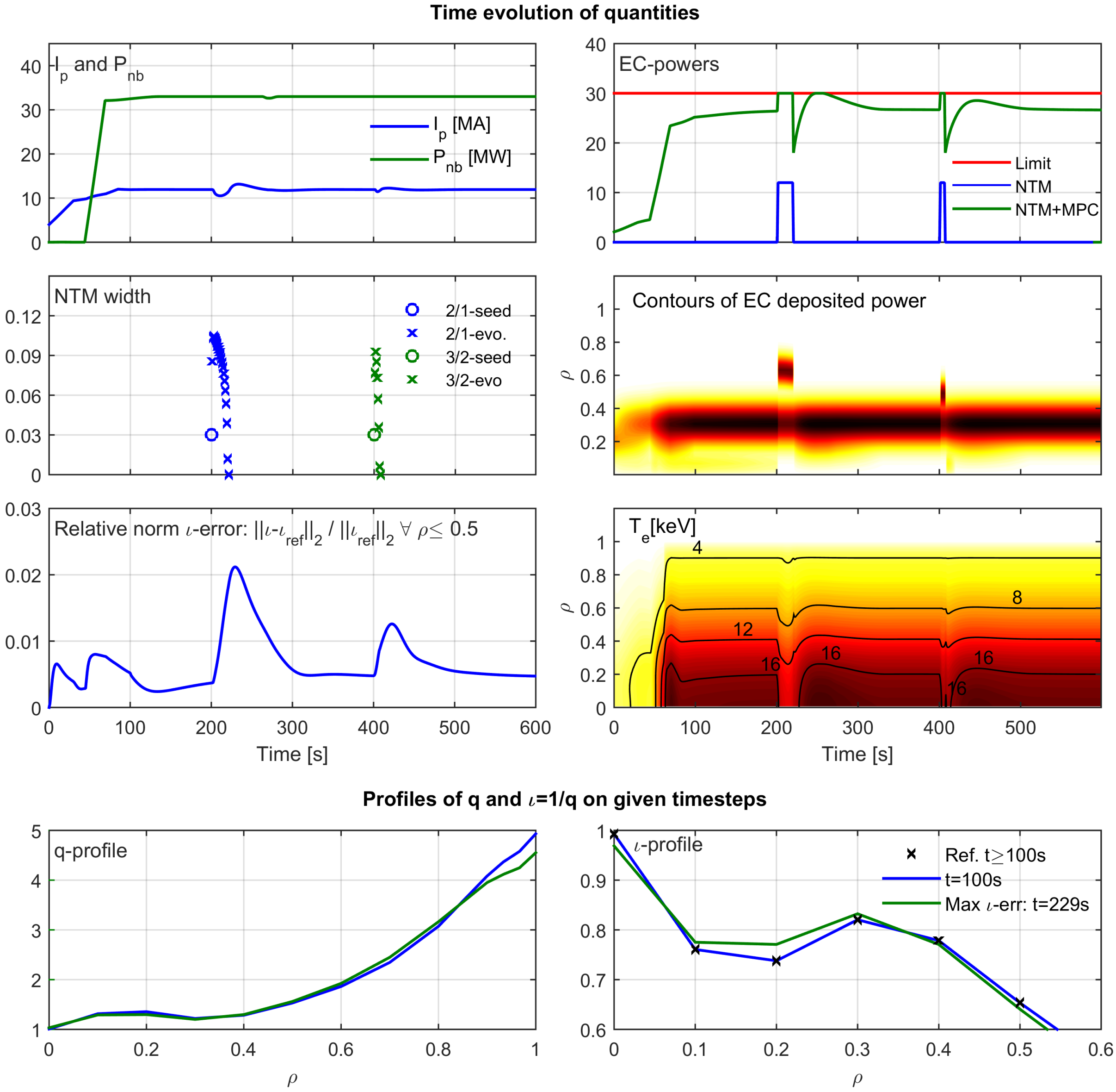

Fig. 2: Simulation results of effective simultaneous control of NTMs and profiles. Seed islands created for 2/1 NTM (200s) and 3/2 NTM (400s), resulting first in a significant drop in T_e. NTMs are fully suppressed while MPC profile controller uses plasma current I_p and remaining EC-power to reduce q-profile tracking error and keep $q \geq 1$.

in [7, 10]. The MPC-controller can request EC-power deposition at three fixed ρ-locations: $\rho_{\text{tor}} = [0.05, 0.2, 0.3]$, where ρ is the normalized toroidal magnetic flux coordinate. The NTM controller can request EC-power deposition at the location of the NTMs if present, assuming perfect alignment and no power modulation. In practice, a low level control system will ensure that gyrotrons and steering mirrors deliver the requested EC-power deposition. The total available EC-power is 30MW, which exceeds the power presently planned for ITER, but note that no IC-power is used in these simulations. Priorities are set such that in case of an NTM, the NTM controller will request 12MW per NTM (2/1 or 3/2). With the remaining available power, the MPC-control objective is to track the nominal q-profile in the region $\rho \leq 0.5$ while ensuring

$q \geq 1$, where it can use the power to the three EC-beams, NBI power, and plasma current I_p.

The simulation results are presented in Figure 2. Seed islands of 3 cm are created after 200 s for the 2/1 NTM and after 400 s for the 3/2 NTM, respectively. The 2/1 NTM is suppressed in 16 s and the 3/2 NTM in 6 s. At the times of maximum island widths, a peak can be noticed clearly in the deposited EC-power $V'P_{ec}$, whereas a drop in T_e is visible. By modifying the inputs, the MPC controller can limit the growth of the relative error in the q-profile during the presence of the NTMs, while keeping $q \geq 1$. An important side effect of the limited changes in the q-profile is that the ρ-positions of the NTMs do not change significantly.

Conclusion and outlook

We have shown simulations of the simultaneous operation of a profile controller and an NTM controller within a PCS architecture where these controllers are aware of their resources, allocated by a high level actuator management layer. Closed-loop simulations for the ITER tokamak show that the proposed design can effectively respond to the occurrence of an NTM by suppressing it, while at the same time the MPC profile controller maintains the safety factor profile close to its reference and within the operational limits.

This preliminary work can be continued in multiple ways. The simultaneous control of profiles and NTMs can be tested on the newly developed Plasma Control System Simulation Platform (PCSSP) [11]. Other control tasks sharing the same actuators could be added. The provided expected profile predictions and constraint violations can be used by the central decision layer to improve decision making. Extending the MPC controller to track also β_{pol} may enable temporarily lowering β_{pol} for faster suppression of NTMs. Also more advanced NTM-controllers could be implented, and the low level actuator management can be extended, e.g. based on [5].

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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.