Developments on actuator management, plasma state reconstruction, and control on ASDEX Upgrade

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Abstract

In present day tokamaks, the role of the control research is to support the physics experiments and to prepare technologies for future devices such as ITER and DEMO. This paper presents the developments done under the MST1 program collaboration on ASDEX Upgrade in the area of the actuator management, plasma density reconstruction, and feedback control of the electron temperature. In the area of actuator management, the actuator interface was unified for the neutral beams and for the gyrotrons, which enables to freely group these actuators to bigger objects, so called virtual actuators. In the area of plasma state reconstruction, a significant progress was made in the real time estimation of the plasma density in discharges with ion cyclotron heating. This enabled execution of experiments requiring electron temperature control in discharges with ion cyclotron heating, which are reported as well. Other control applications such as fusion power emulation using heating actuators are not described in detail, but a list of relevant references is given.

Keywords: tokamak, plasma control, actuator management

1. Introduction

As in most modern tokamaks, the control research is playing an increasingly important role in the ASDEX Upgrade (AUG) program. The control features and tools serve both as support of the physics research program and as technological tests for future fusion devices such as ITER or DEMO. This paper presents these developments performed under Medium Sized Tokamaks (MST) project on the ASDEX Upgrade. Some of them are described in detail, other ones are listed and relevant references are provided. The paper is organised as follows:

Section 2 presents the recent developments on the structure of the AUG Discharge Control System (DCS) [1], in the area of the actuator management. These improvements will enable the combination of multiple actuators used for a single control task and thus will provide a broader range for controller actions as well as more flexible replacements of tripped actuators.

Section 3 describes further developments of the density observer RAPDENS [2], [3] with the focus on improvement of the real time density measurement in the discharges with ICRH heating, where the interferometers are corrupted by multiple fringe jumps.

Section 4 shows the experiment on the electron temperature (T_e) control using ECRH in discharges with significant ICRH heating. Execution of these experiments have been enabled by the developments presented in sections 2 and 3.

On top of that, further control development activities, not described within this paper in detail, have been performed at AUG. For example, we have continued the development of the density limit disruption avoidance controller [4], [5]. Also the RABBIT code for NBI has been implemented in real time [6], [7], [8]. Together with the actuator management developments, it will enable to control of quantities such as NBI ion or electron heating, NBI current drive, or NBI momentum input.

The final section 5 of this paper presents some of the medium term plans for developments of the ASDEX Upgrade kinetic control and actuator management.

2. Actuator management

Actuator management is a novel resource allocation concept, employed by modern tokamak control systems to enable effective and intelligent use of the available actuators.

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2.1. *Existing actuator management parts: Virtual actuator*

On ASDEX Upgrade, an algorithm for replacement of tripped neutral beams has been historically used as a predecessor of actuator management. The first development of actuator management for ECRH has been made and reported in [11]. In this work, feedback modes were assigned to individual ECRH systems (gyrotron and mirrors) based on minimisation of a cost function. However, this solution suffers from the fact that each of the gyrotrons is controlled by a different controller, that is not aware of actions of other controllers. This means, that for a given control task, such as central heating or NTM control, gyrotrons are not interchangeable. Given the limited number of installed gyrotrons this can be an impediment, if a dedicated gyrotron should not be available, e.g. for operative reasons.

To remove this limitation, ASDEX Upgrade has introduced 2 virtual actuators (Central heating and Edge heating ECRH group) for all 8 ECRH gyrotrons. The virtual actuators are objects that combine heating sources with similar functionality sorted by priority. The priority order is chosen by the experimental leader and takes into account actuator properties such as reliability, diagnostics compatibility, or physics properties (for example current drive efficiency). Instead of individual gyrotrons as previously, controllers now attach virtual actuators, which pools all actuators with the desired properties. The number of controller outputs is equal to the number of virtual actuators the controller is attached to. Virtual actuators may request the accumulated power of all actuators, but can transparently benefit from an automatic replacement of tripped actuators, when only part of the resources is actually required. Typically, the reliability of gyrotrons and neutral beams changes from one day to another depending on actual status of the heating system, and it is generally preferred to use the most reliable actuators first (with the highest priority). With more power required or with some of the more reliable actuators being lost, the less reliable actuators with comparable properties but lower priority are used. For example, if an experiment requires on-axis ECRH heating and off-axis ECRH current drive, both tasks are accomplished using separate virtual actuators. In that case, the ECRH systems that centrally heat the plasma should be assigned to one virtual actuator, and the systems that drive the off-axis current should be mapped to the second one. In case that any gyrotron is lost, it is replaced by one with similar properties, thus the overall impact of the trip on experiment is reduced. The details about the concept of virtual actuators can be found in [12] and some examples of applications in the area of the electron temperature control or β control are described in [13]. In the future, it is intended to develop higher and more intelligent layers of actuator management that would assign real actuators to virtual actuators based on the goals of the experiments and state of the plant. Such a work has already been done for TCV [14].

The introduction of virtual actuators have broadened the control possibilities on ASDEX Upgrade, however, there are still some limitations arising from the fact that traditionally all types of heating actuators on ASDEX Upgrade (NBI, ECRH, ICRH) have been treated as segregated entities in the control system. Due to this, it has not been possible to combine different types of actuators in a single virtual actuator and use them for a common control task. Removing this restriction was the goal of the work described in the next part.

2.2. *Unified Actuator Object*

In order to allow combination of different actuator types in one virtual actuator and to ease further development, a unified actuator object has been introduced and applied on all 8 ECRH gyrotrons and all 8 neutral beams on AUG and in future also both ICRH antenna pairs. All unified actuator objects are represented by the same set of features (operation readiness, minimum and maximum command, and availability) to the virtual actuator, which means that the virtual actuator can combine all types of the heating actuators at AUG. The possibility for grouping is currently only available for heating actuators, however, in long term it is intended to extend this scheme to fueling actuators (valves, pellet injectors) as well.

The flow of the information exchange between the unified actuator, virtual actuator, and a controller is shown in Figure 1. At the beginning of each real time cycle, the unified actuators receive information about the plasma and plant status in the form of a DCS signal. Based on this, each of them evaluate their availability as well as maximum and minimum command it can provide. The virtual actuator sums up available resources, computes the limits (maximum controller command, minimum controller command) and the feed forward request (such as 3 neutral beams) and transforms this request to Watts. The result of this computation is sent to the controller. The controller computes the control command which is sent back to the virtual actuator. The virtual actuator distributes this command over the available actuators. The command for each unified actuator is communicated as a normalised value between 0 (off) and 1 (full power) and the unified actuator is afterwards responsible for executing the command and sending it to the plant system in the form of the DCS signal. In case only a fraction of a power source is required, the actuator command can be issued either by pulse width modulation (for NBI and ECRH), or by analog power modulation (for ICRH and rarely for ECRH).

As mentioned above, each actuator is described by a limited set of properties to the upper layers of actuator management (so far only virtual actuator). The first of the features loaded from the heating system settings is the **operation readiness**. This is checked for each actuator before the discharge execution and actuators that are not ready for operation are not considered later.

The second set of features is the **minimum and maximum command**. For heating actuators, this value is in

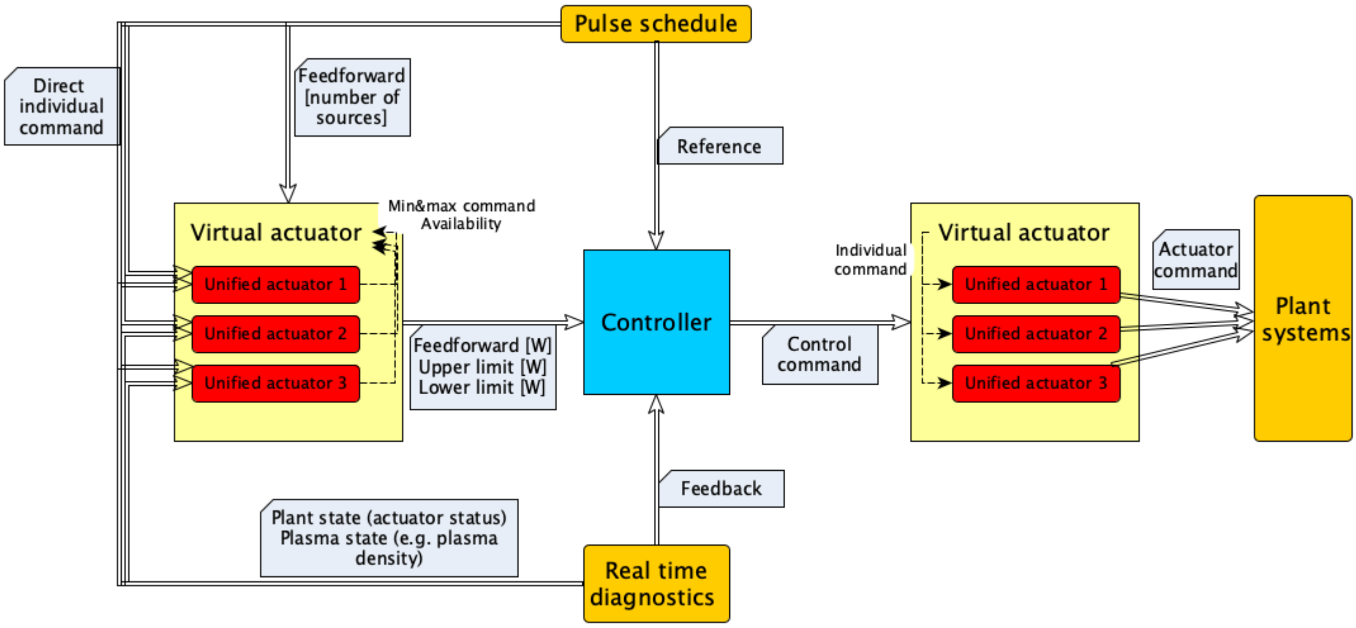

Figure 1: The information flow between unified actuator, virtual actuator, and the controller as implemented in DCS. The double line indicates that the exchange is done a by a real time DCS signal, the dashed lines are used to show connection between objects located in the same software structure that exchange the information directly. The flow in this figure shows the situation for a controller with single output. In case the controller would have N outputs, it would be connected to N virtual actuators.

Watts. This is typically set before the discharge both for NBI and ECRH by the heating systems, but in principle it can be also computed in real time as required for ICRH that will be implemented in future, since the maximum power the ICRH can deliver to the plasma depends on the efficiency of power coupling, which depends on plasma state and changes during the discharge. Also, in case that an actuator becomes unavailable during the discharge, the maximum command is updated to 0. Note that the minimum command does not necessarily need to be 0, since some actuators, for example neutral beams needed for diagnostic purposes, can temporarily be explicitly requested in pulse schedule.

The last of the features currently in use is the **availability** of actuator, which is updated in real time based on the interlock status. There are several interlocks: some of them are general for all heating actuators, some are actuator type specific.

The first common check for both NBI and ECRH is the availability of the actuator from the heating system point of view. This type of interlock is activated for example in case of too much stray radiation for ECRH or in case of power supply trip. This information comes in a single real time signal for each heating source from the heating system.

The second common check is the so called energy limit: for each AUG discharge, there is a limit on maximum energy that can be injected to the plasma by the heating sources. If this limit is exceeded, all heating sources are disabled by DCS.

The third common check is the so called cycle interlock. To avoid fatigue of the heating system, the number of duty cycles per discharge is limited for each actuator that uses pulse width modulation to deliver a fraction of the nominal power (typically, ASDEX Upgrade allows 100 duty cycles for ECRH gyrotrons and 200 for neutral beams). If the number of permitted cycles is exceeded, the duty cycle interlock is activated and the actuator is tagged as unavailable. It is also possible to change the modulation strategy to reduce the number of on/off switches for actuators that are already close to the duty cycle limit and avoid activation of this interlock. In this case, the actuator is turned on only if more than 50 % of the maximum power is required and turned off in case less than 50 % is required.

On the top of that, ECRH operation is not allowed in the ramp-down phase of the discharge or after emergency stop of the discharge for microwave diagnostics protection. It is also temporarily disabled for 4.5 ms (3 DCS real-time cycles) after a pellet is launched to allow the transient degrading effects of pellet ablation to disappear from the diagnostic measurement.

Also NBI is subject to a number of interlocks. NBI is not allowed, for instance, if the real time density measurement signal is corrupted. Moreover, for each beam, there is a hotspot sensor that monitors overheating of the first wall due to beam shine through. If this hotspot alarm is activated, the corresponding beam is disabled and the activation flag is set to off. In case of the hotspot sensor failure, there is a backup computation, so called "energy interlock", which estimates the amount of beam energy penetrated through the plasma to the wall in the following way:

$$E_{st} = \int_0^t P_{beam}(t) \cdot f(n_e(t)), \quad (1)$$

where E_{st} is the shined through beam energy, P_{beam} is the beam power time evolution, and f is the fraction of shine-through power, which depends on the line averaged plasma density n_e.

In 2021, we are going to add unified actuator descriptions for ICRH antennae and thus make them available for virtual actuators. Also, additional properties such as power deposition location, current drive efficiency or momentum input is planned to be made available to virtual actuator for future. This could be used for example for more intelligent replacement of tripped actuators.

2.3. New capability: Combination of different heating actuators

Thanks to the unified actuator object, one of the restrictions of the DCS has fallen: it is possible to use multiple types of heating sources, for instance a mixture of NBI sources and gyrotrons, for a common control goal like β control. The development of tools that will enable using these features from the pulse schedule editor has not been completed by the end of the last campaign, thus this feature could not be demonstrated in real discharge.

This will open the door to several more features that have not been available before. First of all, it will be possible to improve β control, which is of importance for the discharges on the improved energy confinement mode (I-mode) development. Due to its narrow existence window in terms of auxiliary power input, β feedback control has led to significant advancements in the research of the I-mode. It has been shown that I-mode can be kept stationary using NBI heating [9], which was previously not possible on AUG. However, using exclusive NBI heating for β feedback necessarily leads to torque input, which might not be desired. Therefore, a mixed NBI/ECRH β controller is of high interest. Moreover, experiments indicate an increased L-I transition threshold if nitrogen is introduced into the divertor [10]. As of now, it is unclear if this is related to insufficient edge ion heat fluxes. β control using a combination of NBI and ECRH will change the electron/ion heating ratio and will enable a detailed investigation and unraveling of this issue. After implementing ICRH into the unified actuator scheme, it will be possible to combine all three types of heating actuators for a β controller.

Another possibility will be to feedback control the electron and ion heating as well as their ratio using NBI and ECRH. Both ion and electron heating from NBI are computed in real time by RABBIT code [6], [7] and ECRH heats only electrons. Thanks to the new actuator management, it will be possible to prepare a Multiple Input Multiple Output (MIMO) state space controller that will for example modify the ion heating fraction for given total heating power. This controller will be connected to two virtual actuators, one dedicated to NBI and the other one dedicated to ECRH. This scheme will be in future extendable to control any quantity computed by RABBIT such as NBI current drive or the momentum input.

3. Plasma density state observer RAPDENS development

The real time density measurement on AUG is performed using 5 interferometers and 2 bremsstrahlung channels. The interferometers are the first choice real time density measurement, but are not reliable in pellet discharges and in discharges with ICRH heating due to multiple fringe jumps that can not be corrected. The bremsstrahlung measurement b is related to electron density by

$$b = C \cdot Z_{eff} \cdot n_e^2 \cdot T_e^{1/2}, \quad (2)$$

where Z_{eff} is the effective charge, n_e is the electron density, T_e is the electron temperature, and C is a constant. Since Z_{eff} is not known in real time and and real-time T_e measurement is not reliable for some discharge types (such as high density shots), it is not straightforward to compute plasma density from bremsstrahlung with sufficient precision. Another problem arises from the low signal-to-noise ratio of the bremsstrahlung measurement. This means that due to unreliability of interferometers, there is no reliable direct real time n_e measurement for the pellet and ICRH discharges on AUG. To improve the situation, the Kalman filter based state space observer RAPDENS was developed for the real time density estimation on AUG [2], [3].

RAPDENS was successfully used for density control by pellet injection [15], where the density was reconstructed exclusively based on a control oriented model and the bremsstrahlung measurement. However, the real time n_e measurement was still failing for the ICRH discharges, where some, but typically not all interferometry channels get corrupted by multiple fringe jumps, and the performance of RAPDENS with control oriented model and the bremsstrahlung measurement only is not sufficient.

To handle these issues, the improvements have been made on the control oriented model and detection of the corrupted interferometry channels. Details of this work can be found in [16]. The control oriented RAPDENS model was improved by replacing the ad-hoc density transport model by more sophisticated Bohm-gyroBohm transport model [17], and by introducing more sophisticated source and sink terms. The Bohm-gyroBohm transport model is not routinely used in real time operation, since it depends on the T_e profile and current profile that are not always reliable. However, it can be activated by a configuration parameter if required.

Thanks to the better predictions made by the control oriented model, it is possible to detect interferometry channels corrupted by fringe jumps. This is done by comparison of the model prediction for each interferometer channel and the actual measurement. If the difference is above the size of a fringe jump ($5.72 \cdot 10^{18}$ m^{-3}), it is considered that the interferometry channel suffered a fringe jump. If multiple fringe jumps appear on a single channel, the channel is considered corrupted and is not used in the diagnostics update any longer.

RAPDENS with the improvements described above was implemented in the DCS and delivered reliable real time density estimates for all studied ICRH discharges. An example of this is shown in Figure 2 for AUG discharge 37768. In this case, the traditional real time density measurement is corrupted by the fringe jumps, while the RAPDENS correctly excludes the corrupted interferometry channels. This enabled execution of the experiments described in section 4.

4. Electron Temperature Control in ICRH discharges

In the last years, an electron temperature T_e controller using ECRH as actuator was developed. This controller uses the T_e profile at toroidal ρ grid from RAPTOR updated by real time ECE [18] as measurement. The controller ignores the temperature inside toroidal $\rho = 0.15$ and outside of toroidal $\rho = 0.8$. The central value is ignored because there are no real time ECE measurements in core of the plasma which makes the RAPTOR estimate of core T_e unreliable. The edge T_e is not considered because edge plasma is optically thin and the ECE diagnostics does not work properly all the time. The reference T_e profile is the profile at the time the controller is started which means that the goal of the controller is to keep the T_e profile constant. A model based controller design was employed to develop the controller. The details of that work can be found in [19].

The controller was used in several physics experiments such as studies of neoclassical toroidal viscous torque or NBI fast particle confinement studies. In these experiments, fixing T_e makes the experiments easier to interpret. Depending on the control mode, either central ECRH or central ECRH and off-axis ECRH can be used as an actuators. In the experiments reported in this paper, we have used central ECRH only.

This controller was however not working reliably for the discharges with the ICRH heating due to the problems with the real time density measurement described above and the experiments presented here have been possible only after RAPDENS upgrades described in Section 3. The reason for this is that the density measurement is one of the RAPTOR inputs. If it gets corrupted, RAPTOR T_e estimated become unreliable as well. At the same time, the possibility of controlling T_e in discharges with ICRH is of high interest for transport studies. For example, in developing scenarios with medium/high ICRF heating it is interesting to investigate and thus control the turbulence type and level by changing the ratio of T_e and

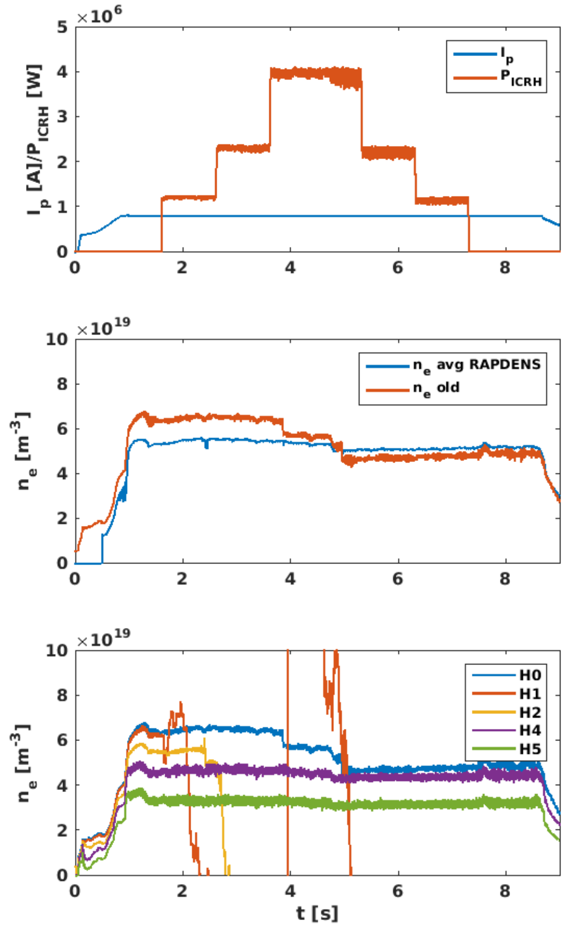

Figure 2: The time evolution of the plasma current (I_p), ICRH heating power (P_{ICRH}), volume average density reconstructed by RAPDENS, the traditional method of the real time density measurement as well as all 5 interferometry channels at AUG. Note that RAPDENS density reconstruction is active only after the current exceeds some level (typically 300 kA).

ion temperature T_i. Fixing T_e makes these studies easier to execute and interpret. To enable this using the existing T_e controller, the improvements of RAPDENS described in section 3 have been made.

An example of functionality of such a controller is shown in Figure 3 for AUG discharge 37768 (same as the discharge in Figure 2). The T_e profile in a discharge with and without control is shown in Figure 5. In our scenario, the ICRH power was ramped up and down in steps at constant density and plasma current and the NBI heating was modified. To keep the T_e profile unchanged, the controller adapts the central ECRH heating. As seen in figure 37768, the electron temperature remains practically unchanged till the NBI is switched off. The only exception is the central T_e ($\rho_t = 0$ blue line in Figure 3), which is however ignored by the controller. The reason for this is that there is no reliable real time T_e measurement in the core, which makes RAPTOR estimates of that quantity unreliable.

Figure 4 shows the time evolution of the mean square error between the reference and measured T_e with and without feedback control computed both using real time T_e profiles from RAPTOR and the profiles computed by IDA [24] offline.

Figure 5 compares the T_e profiles with (discharge 37768) and without active control (discharge 37764) at 3 s, 4 s, and 5.3 s to the profile at 2 s, which corresponds to the reference T_e profile in the discharge with active T_e control. The times for comparison were selected to be sufficiently after the change of the external heating power so that the controller has time to compensate the change in external heating.

One can see that while the T_e changes dramatically in the discharge without control, it remains almost constant when the control is active. This is apparent both in the real time RAPTOR profiles and the profiles from offline IDA analysis.

5. Conclusions and Future Work

This paper presents some of the kinetic control, state reconstruction, and actuator management developments done on AUG within the Medium Sized Tokamak collaboration. Together with the past activities it shows growing possibilities of control at AUG. Together with the developments on the side of the DCS system stability and maintainability [21], it significantly increases the AUG control possibilities and the support that can be offered to the physics experiments. In near future, it is planned to develop further the plasma state reconstruction and the actuator management.

5.1. Plasma State Reconstruction and Kinetic Control Plans

In near future, major focus will be put into the development of the plasma current profile controller to support studies on advanced tokamak regimes [22]. First of all, we intend to improve the quality of the equilibrium reconstruction by including the current diffusion information from RAPTOR in the AUG equilibrium reconstruction code JANET++ [23]. This clearly improves the information about the plasma current distribution both offline [24] and in real time [25]. After this step is completed, it is intended to add the real time NBI current drive information from RABBIT and EC current drive information from TORBEAM [26] as additional RAPTOR inputs to further enhance the current profile estimation quality. Afterward, it is planned to include the real time polarimetry measurement that could provide diagnostics correction of the computed current profiles. This will not only enable the current profile control, but also improve the performance of the controllers mentioned in this paper.

5.2. Actuator Management Plans

After introducing the unified actuator object for the NBI and ECRH, the next step in the actuator management development will be the extension of this concept to the ICRH. Another development plan is to introduce more intelligent replacement of a tripped actuators. So far the tripped actuator was replaced by the next unused actuator in the priority list regardless of its properties. We would like to introduce the possibility of replacing the tripped actuator by the most similar one. The decision criteria can be either the preference of the physicist responsible for the experiment (such as "if beam N trips, replace it by beam M if possible"), or it can be based on actuator properties available in real time (for example replacing a tripped beam by another one with the most similar ion-to-electron heating fraction).

Currently, the assignment of the unified actuators to the virtual actuators is defined at the time the pulse schedule is loaded. In future, it is planned to allow dynamic allocation of the unified actuators to virtual actuators. The actuator allocation time trace can be either predefined (for example virtual actuator V will have actuators A and B between 1 and 3 s, and actuators C and D between 3 and 5 s) or decided by higher layers of the actuator manager. The latter opens the space for development of advanced real time decision making.

Acknowledgements

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References

[1] W. Treutterer et al, ASDEX Upgrade Discharge Control System—A real-time plasma control framework, Fusion Engineering and Design vol. 89, pp. 146-154, 2014

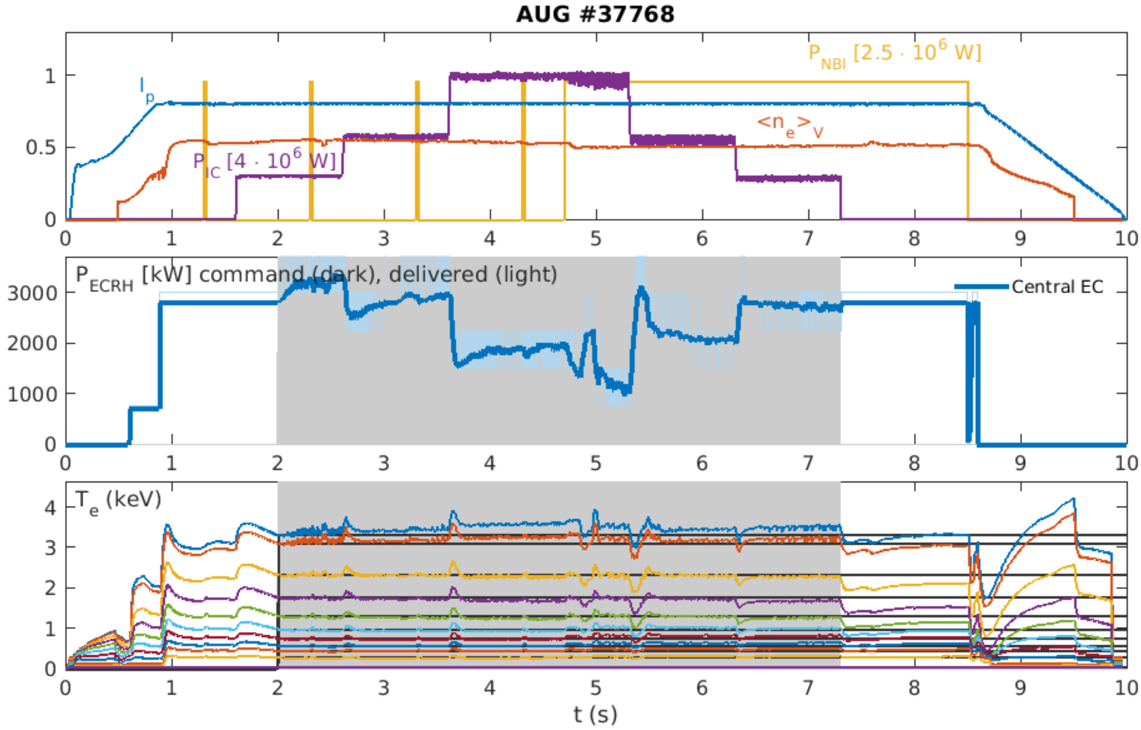

Figure 3: First plot: the time evolution of the plasma current (I_p in MA), electron density (n_e in 10^{20}), neutral beam heating power (P_{NBI}), and the ion cyclotron heating power (P_{IC}). Second plot: the central ECRH power (P_{ECRH}). Third plot: the electron temperature and 11 toroidal ρ points between the plasma centre and the separatrix estimated by RAPTOR and the constant reference for each of them. The grey area shows the time interval where the controller was active.

[2] T. Blanken et al, Control-oriented modeling of the plasma particle density in tokamaks and application to real-time density profile reconstruction, Fusion Eng. Des., Volume 126, January 2018, Pages 87-103

[3] T.C. Blanken et al., Model-based real-time plasma electron density profile estimation and control on ASDEX Upgrade and TCV, Fusion Eng. Des., 147 (2019), 111211

[4] M Maraschek et al 2018 Plasma Phys. Control. Fusion 60 014047

[5] B. Sieglin et al, Rapid prototyping of advanced control schemes in ASDEX Upgrade, Fusion Eng. Des., Volume 161, December 2020, 111958

[6] M. Weiland et al, RABBIT: Real-time simulation of the NBI fast-ion distribution, Nuclear Fusion, July 2018, Volume 58, Number 8

[7] M. Weiland et al, Simulation of neutron emission in neutral beam injection heated plasmas with the real-time code RABBIT, Nuclear Fusion, June 2019, Volume 59, Number 8

[8] M. Weiland et al, RABBIT: A high-fidelity code to simulate the NBI fast-ion distribution in real-time, Theory of Fusion Plasmas: Varenna–Lausanne International Workshop, 2020

[9] T. Happel et al, Stationarity of I-mode operation and I-mode divertor heat fluxes on the ASDEX Upgrade tokamak, Nuclear Materials and Energy, Vol. 18, January 2019, Pages 159-165

[10] T. Happel et al, Approaching detachment in I-mode - response of core confinement and the edge pedestal in the ASDEX upgrade tokamak, accepted to Nuclear Fusion, available at https://iopscience.iop.org/article/10.1088/1741-4326/abd7b7

[11] C.J. Rapson et al., Actuator management for ECRH at ASDEX Upgrade, Fusion Eng. Des., 96 (2015), pp. 694-697

[12] O. Kudlacek et al, Actuator management development on ASDEX Upgrade, Fusion Eng. Des., 2019.02.026, in press

[13] O. Kudlacek et al, Use of virtual actuators in ASDEX Upgrade control, Fusion Eng. Des., Volume 159, October 2020, 111735

[14] N.M.T. Vu et al, Tokamak-agnostic actuator management for multi-task integrated control with application to TCV and ITER, Fusion Eng. Des., Volume 147, October 2019, 111260

[15] P. Lang et al, Feedback controlled, reactor relevant, high-density, high-confinement scenarios at ASDEX Upgrade, Nuclear Fusion 58 (2018), 036001

[16] T. Bosman et al,Kalman Filter density reconstruction in ICRH discharges on ASDEX Upgrade, poster 703 SOFT 2020, submitted to Fusion Eng. Des.

[17] Erba M., et al, Validation of a new mixed Bohm/gyroBohm model for electron and ion heat transport against the ITER, Tore Supra and start database discharges, Nuclear Fusion, 1998, Volume 38, 1013–28

[18] F. Felici et al, Real-time physics-model-based simulation of the current density profile in tokamak plasmas, Nuclear Fusion 51 (2011), 083052

[19] F. Felici et al, Model-based design, simulation and testing of an electron temperature profile controller on ASDEX-Upgrade, EPS 2017 Belfast

[20] R. Fischer et al., Integrated Data Analysis of Profile Diagnostics at ASDEX Upgrade, Fusion Sci. Technol., 58, 675 (2010)

[21] B. Sieglin et al, Exploitation of DevOps concepts for the ASDEX Upgrade DCS, submitted to FED 2020

[22] A. Bock et al, Non-inductive improved H-mode operation at ASDEX Upgrade, Nuclear Fusion 57 (2017), 126041

[23] L. Giannone et al, A data acquisition system for real-time magnetic equilibrium reconstruction on ASDEX Upgrade and its application to NTM stabilization experiments, Fusion Eng. Des, Volume 88, December 2013, Pages 3299-3311

[24] R. Fischer et al, Coupling of the flux diffusion equation with the equilibrium reconstruction at ASDEX Upgrade, Fusion Science and Technology 69 (2016), 526-536

[25] F. Carpanese et al, First demonstration of real-time kinetic equilibrium reconstruction on TCV by coupling LIUQE and RAPTOR, Nuclear Fusion 60 (2020), 066020

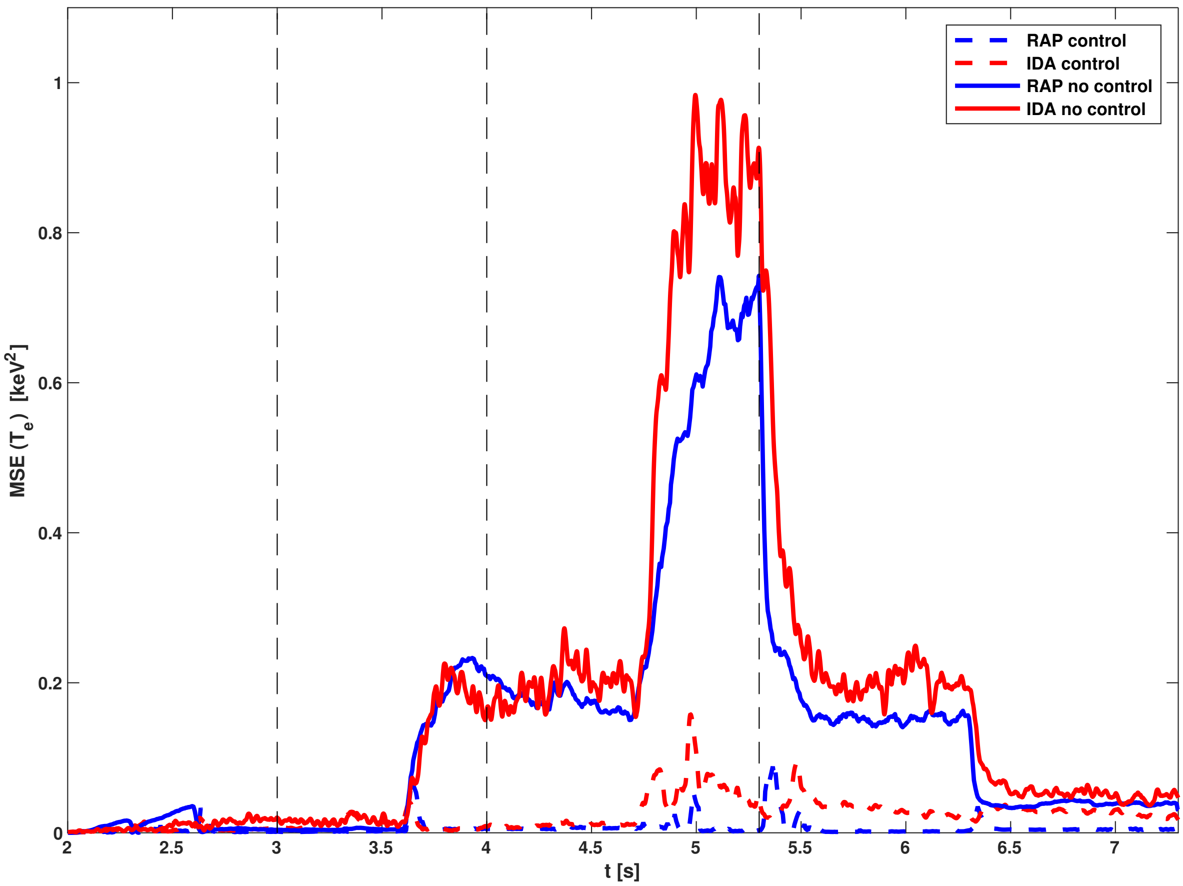

Figure 4: The time evolution of the mean square error of T_e profile for discharge with (37768) and without (37764) feedback control in RAPTOR and IDA. The black vertical lines indicates the times when the temperature profiles in 5 are shown.

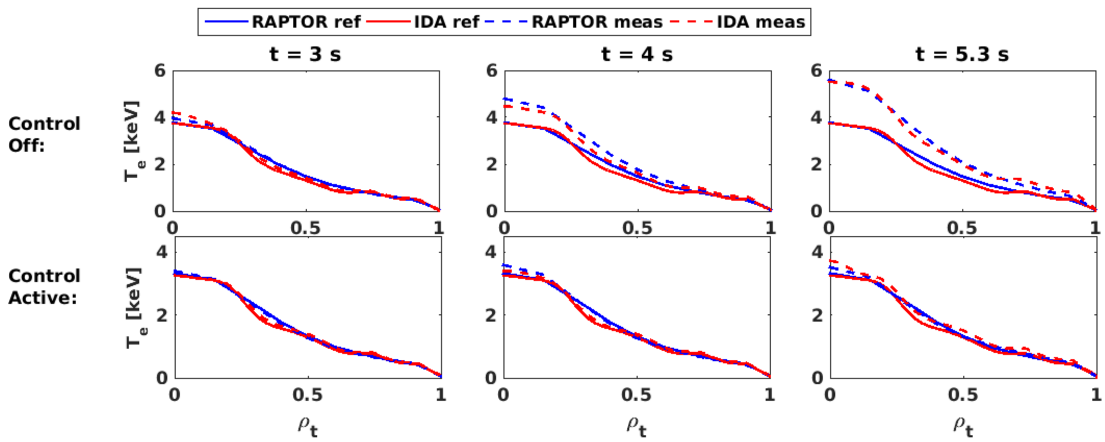

Figure 5: The temperature profile from real time RAPTOR observer and post-shot IDA algorithm at different times of discharge 37764 (no active T_e control) and 37768 (active T_e control). The time traces of the plasma current and heating were the same in both discharges and are depicted in Figure 3. The reference profile is taken at 2 s, the time the controller starts in the discharge with active control of the T_e.

[26] E. Poli et al. , Comput. Phys. Commun. 225, 36 (2018)