CONFERENCE PRE-PRINT

PERFORMANCE OPTIMISATION OF TOKAMAK OPERATION IN ASDEX UPGRADE THROUGH NOVEL FEEDBACK CONTROL CAPABILITIES

W. Treutterer, M. Biasizzo, P. David, E. Fable, M. Gehring, L. Giannone, I. Gomez, A. Gräter, J. Illerhaus, R. Kermenov, O. Kudlacek, G. Raupp, M. Reisner, B. Sieglin, M. Weiland, T. Zehetbauer, The ASDEX Upgrade Team (see author list of H. Zohm et al, 2024 Nuclear Fusion https://doi.org/10.1088/1741-4326/ad249d)
Max-Planck Institute for Plasma Physics
Garching, Germany
Email: Wolfgang.Treutterer@ipp.mpg.de

D. Kropackova
Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University,
Brehova 7, 115 19, Prague 1, Czech Republic

Abstract

Optimising the performance of tokamak operation is not only a matter of tuning individual control circuits, but needs a holistic approach with a focus on the effective interplay of all control system components. The ASDEX Upgrade Discharge Control System (DCS) has enabled outstanding results of physics effects studies and operation scenario development. This is facilitated by efficient and highly robust algorithms for measurements data processing and plasma state estimation, a versatile feedback control suite, a powerful actuator management approach that optimises the utilisation of the limited number of actuators, and a pulse supervision control reacting to events and plasma state conditions to achieve a maximum exploitation of the pulse and to protect device and investment. Moreover, Fenix, a fast "flight simulator" with a full model of the control system and a control-oriented plasma and plant model, assists in scenario design, validation and control method development, thus accelerating the turnaround time from the design of emerging capabilities to their exploitation in plasma pulses. Larger and more complex fusion devices such as ITER and DEMO will in particular benefit from such a control structure and active contributions are being made to the architectural design of their control systems.

1 INTRODUCTION

One of the most prominent goals of the ASDEX Upgrade device is the advancement of thermo-nuclear fusion science in general and the support of future fusion reactors' design and operation. ASDEX Upgrade therefore has a focus on developing operation scenarios and control strategies that can be transferred or scaled to larger devices like ITER, DEMO and a future fusion reactor [1], [2]. Performant tokamak operation is the result of the interplay of many aspects including efficient state observers, well-concerted control circuits, failure and event resilient control concept, high system availability and proper planning. Optimising the performance thus requires a holistic view on the operation of a tokamak control system.

The design of plasma controllers involves minimisation of overshoot, settling time and cross-coupling. But this is only possible, if accurate and comprehensive plasma state measurements are available in real-time - fast enough for a control reaction. The introduction of Machine Learning technology in the plasma control domain enables estimations, where the classical evaluation using physics codes such as transport models would be computationally too expensive [3]. As reference [2] presents examples for feedback control of density, heating, detachment and disruption margin, the design of optimised control will not be further detailed in this paper. Precise state information is also essential for taking alternative routes in case of failure or unexpected events. Failed measurements can be replaced using redundant information from other sources, actuator management can substitute tripped actuators, or pulse supervision can switch to an evasive control strategy, while continuing to pursue the experimental goal. Thus, the resilience of the system and its availability can be improved.

Proper preparation of plasma pulses reduces the risk of failures and thus saves precious experimental time. Fenix, a control-oriented flight simulator, is a tool based on the ITER Plasma Control Simulation Platform (PCSSP), that models the tokamak and plant system dynamics, as well as the connected control system activities [4], [5]. Fenix combines the ASTRA transport code, the FEQUIS equilibrium code [6] and a Simulink based PCS simulator. A similar approach taken by CEA [7] employs Metis and LIUQUE/NICE for the physics modelling. The Fenix simulator serves several purposes, all of which contribute to better prepared pulses and thus to optimised operation. Unlike a pulse design tool or simulator [8], Fenix provides a fast but realistic forecast of the closed loop behaviour and can also describe the impact of perturbing events. Finally, Fenix serves also as a test bed for rapid prototyping of novel control schemes, such that only the final proof and fine-tuning require dedicated experimental pulses.

A well-structured software foundation can be easily maintained, extended and adapted to the varying operational needs and goals. For example, mastering the enormous amount and variety of experimental proposals in the European WPTE program, together with the highly specialised investigations in the AUG local campaigns at high availability and reliability, has only been possible by the ASDEX Upgrade Discharge Control System (DCS) being a modular, configuration-driven control system framework [9]. It is a well-known finding in software development, that architecture requirements are a subclass of performance requirements, i.e. that the architecture of a system has a formative impact on its achievable performance. DCS developed on ASDEX Upgrade and MARTe originating from JET, as well as the ITER Real-Time System (RTS), which emerged from both, all adhere to the SOLID principles [10]. These properties support operation by easier maintenance and extensibility, as well as by a significant reduction of errors.

A closer look reveals that performance optimisation for tokamak operation consists of three major aspects: structural, functional and organisational optimisation. In the following, section 2 describes the ASDEX Upgrade approach to structural optimisation, which allows for efficient and collision-free interoperation of the various components with well-defined roles and scopes. The recent functional optimisations, with focus on the optimisation of individual control tasks by increasing accuracy and reaction speed, while reducing errors, cross-coupling and uncertainties, are the topic of section 3. Measures for organisational optimisation of the preparation and execution workflow with new analysis and planning tools are presented in section 4.

2 STRUCTURAL PERFORMANCE OPTIMISATION

The SOLID principles, in particular the Single Responsibility, the Open-Closed and the Interface Segregation principle, foster the modular and re-usable design of a code and its data model. Applied to control system frameworks, these principles lead to a separation of concerns between software modules for measurement, observation, monitoring, control, command output and overall supervision. A typical DCS operation setup thus consists of 10 non-realtime services for workflow organisation and configuration management, 36 real-time diagnostics, 16 processes for measurement and observer codes, 13 monitoring applications, 21 compact controllers, 5 processes for actuator management and interfacing and three components for control cycle generation, segment scheduling and reference generation, which together build the pulse supervision control. In addition, the DCS runs a variety of administrative background services for data transfer, health monitoring, logging and archiving. Within each control cycle, the real-time processes exchange more than 2300 signal samples. Due to frequent modernisation of the underlying hardware and real-time operating systems the duration of the control cycle could recently be shortened to one millisecond.

A further consequence resulting from the application of SOLID principles is that the functionality is defined in terms of combinations of generalised functions with application-specific customisations. The generalised functions have well-defined scopes of responsibility and can be maintained with low effort. In addition, the limited scope facilitates extensions and makes it simpler to isolate and fix potential errors. On the highest level, adding or modifying functionality does not even require code changes but is accomplished just by adapting configuration data. For example the Compact Controllers in section 2.3 are implemented that way.

2.1 Measurement and Observers

Extracting a comprehensive and accurate set of process variables from raw measurements is a key functionality of tokamak control systems. In contrast to data-acquisition, control, monitoring and actuator management codes, which can be generalised to large extents, evaluation codes typically are rather specialised and often depend on an underlying physics model. Often their output can serve multiple purposes. The electron density, for example, is not only used for density control but also for neutral beam shine-through protection, for density limit disruption avoidance or for reconstruction of the plasma shape by reflectometry. According to the DCSs' paradigms of modularity and re-usability, process quantities are computed in separate and independent units and made publicly available to all control functions. While control functions actually have full access to the full system state information, the software framework nevertheless organises the distribution in a way that avoids unnecessary data transfer, thereby minimising the transport cost.

2.2 Integrated Machine Learning Support

For computation-intensive calculations, the DCS has recently been extended with a standardised real-time GPU-inference support for machine learning (ML) applications. The inference engine executes deep neural network models generated from a re-usable data conditioning and training pipeline. A density-profile estimator trained with an Integrated Data Analysis (IDA) reference has already been implemented and facilitates more accurate and reliable density and pressure control [3]. Further applications such as a neural-network equilibrium reconstructor are in preparation. First experiments show promising results.

2.3 Compact Controllers

During each of the scenarios a tokamak plasma encounters during a pulse, the control system has to follow a multitude of control objectives. This is a non-trivial task as many control variables are coupled through plasma physics in an often-non-linear way. Magnetic and kinetic profiles, for instance, interact as can be seen in the pressure term of the Grad-Shafranov equation, and thus the heating of the plasma also influences its shape. Conversely, shape parameters like triangularity affect the energy confinement. The DCS tracks up to twenty control parameters concurrently - from plasma current to X-point radiator position - using feedback control, where the choice of controlled variables depends on the scenario and its objectives. Furthermore, the number of actuators is limited, and they often affect several plasma parameters. An example are the ECH beams, which can heat the plasma globally but at the same time change profiles or drive currents locally. Moreover, the deposition location of ECH beams can be moved dynamically and with it the beam effect on the plasma, hence altering the control properties.

Given this complexity, system development can easily wind up with highly specialised but not re-usable controllers, or with controllers that share actuators but possibly conflict in their objectives. To prevent this, all ASDEX Upgrade controllers are built on the Compact Controller scheme. Control modes, which are sets of controlled parameters, a policy and its gain factors, can be dynamically switched according to a schedule or to commands from a supervisory level [11]. This design paves the road for goal-driven pulse execution, which is essential for an efficient utilisation of experimental time and resources. DCS Compact Controllers ensure structural integrity through a fixed controller-actuator mapping, while offering dynamic switching of control objectives via control modes. This way, Compact Controllers can respond quickly and transparently to changed operational conditions, for instance by falling back from fast optimised control settings to slower robust ones in case of measurement degradation. Likewise, they can cope with necessary changes in the control structure, such as switching between isoflux and gap control in the ramp-up and ramp-down phases of a plasma pulse.

2.4 Actuator Management

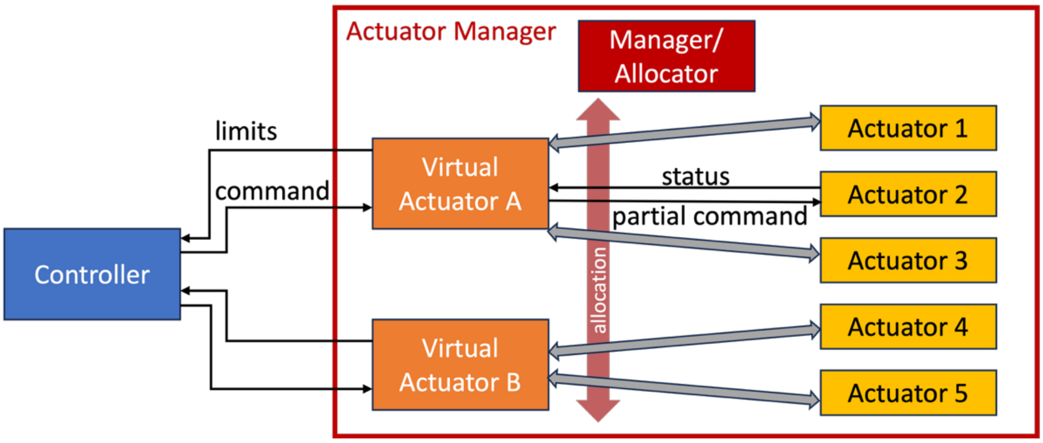

Figure 1: Actuator Management scheme with virtual actuators mapped to a collection of real actuators for a MIMO controller different output channels, e.g. central heating and current drive.

The static mapping is too rigid for heating and gas fuelling systems where failed actuators can be substituted by redundant ones, or when moveable actuators like ECH gyrotrons change their effectiveness. Therefore, an actuator management layer has been developed offering virtual actuators for control, which represent a set of idempotent real actuators for a purpose [12], substituting failed elements but also aggregating several elements into a more powerful one - even a mix of different actuation principles like NBI and ICRH heating is possible. DCS controllers negotiate their requests with the actuator management which flexibly distributes the requests over the available and suitable actuators according to configurable policies, such as greedy or balanced distribution. In return, the controllers are informed about the currently available actuation range, allowing them to apply anti-windup strategies as illustrated in Figure 1. The latest addition to actuator management allows dynamically re-allocating actuators to virtual actuators based on actuator availability and plasma state and thus further maximise the resource exploitation, when e.g., more power is needed for NTM stabilisation while a gyrotron should be unused at that time. The allocation of an actuator to a compact controller is thus adapted but remains unique. Actuator management therefore is not the same as actuator sharing.

The design of actuator management initially emerged from ASDEX Upgrade for NBI, ECH and ICH. It was boosted by the extensions developed for ITER operation with a massive up-scaling to higher actuator numbers and a widened scope towards fuelling [13], including additional use cases such as ELM pacing and NTM control. A next step would be a tighter integration with pulse supervision control introducing strategic goal-driven allocation policies [14].

2.5 Pulse Supervision and Exception Handling

The DCS uses a segmented pulse schedule that contains time intervals both for nominal (planned) and extraordinary (event handling) execution paths with rule-based transitions. The Pulse Supervision Control (PSC) in DCS executes these rules monitoring event indicators and plant state and consequently scheduling segments with their respective control objectives and set-points [9]. The PSC is the top-most component in the DCS control hierarchy, and coordinates the overall activity of the control system, such that operation risk is minimised and the pulse exploitation can be maximised.

Tokamak operation can often be overwhelmingly complex for a single central decision unit. DCS is therefore equipped with a hierarchy of defence policies, where each evaluation and control function is prepared to fix smaller issues locally, like the substitution of unavailable inputs or fallback algorithms which attempt to provide the function output in an alternative way and thus confine the propagation of abnormal events through the system. This local exception handling is accompanied by a data quality mechanism that signals its credibility to any consumer. Consequently, the PSC needs to deal only with issues that cannot be fixed locally, but require a concerted reaction of various control functions.

2.6 Control Architecture

From its roots the DCS has been composed as a distributed, machine-agnostic architecture which can be embedded in any dedicated fusion device context by adaptors, plugins and function specialisations [9]. With its distributed and configuration-centric concept DCS is intrinsically adaptable for use in other devices such as WEST [16], extensible to novel applications requiring higher computation resources like estimators based on artificial intelligence, but also scalable to contexts with higher complexity [17]. In fact, the DCS architecture, together with the MARTe framework had a strong influence on the design of the ITER control system, in terms of both functional organisation and software patterns [18], [19].

3 FUNCTIONAL PERFORMANCE OPTIMISATION

3.1 Observers

The standard set of reconstruction codes in a plasma control system compute lumped parameters like plasma position and shape, neutral and electron density, or confinement parameters like β_{pol}, β_N and W_{mhd}. Advanced control schemes, however, aim at a more fine-grained control of localised quantities like plasma current, temperature and density distribution and correspondingly require spatially resolved plasma state information. Therefore, a number of physics codes that originally had been developed for post-pulse analysis, such as the Janet++ Grad-Shafranov equilibrium solver [20], TORBEAM for ECRH beam tracing [21] and RABBIT for neutral beam heating profile estimation [22], have been upgraded to real-time control applications of the DCS in the past years. Janet++ computes the poloidal flux matrix and from it a number of equilibrium parameters which provide mandatory geometric information to other codes such as RAPTOR, RAPDENS, RABBIT and Torbeam. When reversely coupled to real-time codes like RAPTOR, Torbeam or RABBIT, its solver can take the current and the pressure profile as additional constraints into account increasing the accuracy of the result. Efforts are being taken to include the calculation of the current diffusion term directly into Janet++. The real-time evaluation is initialised with the result of the previous time step and iterates the result until convergence, with a maximum of four loops. This means, that execution time always remains below 4 ms. While this would be too long for vertical stabilisation, it is fast enough for profile shaping as the current diffusion time at AUG is in the range of seconds and the confinement time between 15 and 100 ms.

RABBIT and Torbeam are codes reconstructing the impact of NBI and ECRH beams, respectively. ECRH is a versatile actuator for localised heating and current drive. Torbeam is used to trace the ECRH ray from the launching mirror through the plasma to determine the power deposition location as well as the sensitivity to mirror movements. This information is primarily used for MHD control. On its way, the ray is subject to diffraction depending on the local density. The density profile is obtained from the inversion of several line averaged plasma density measurements in combination with the poloidal flux distribution supplied by the equilibrium solver Janet++ [23].

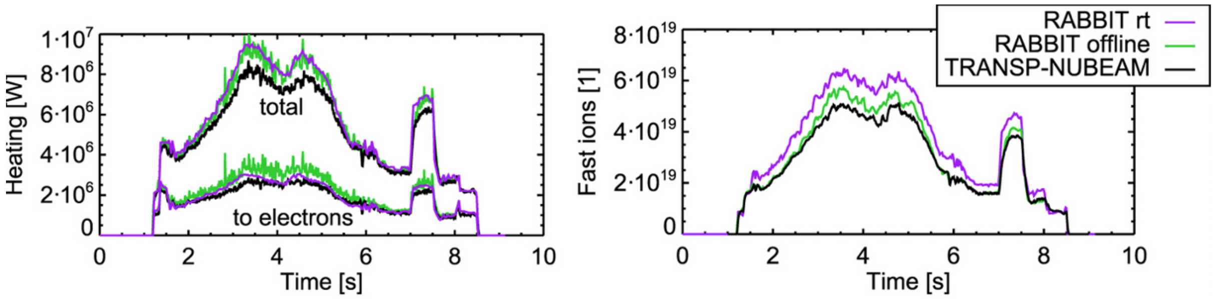

Figure 2: RABBIT results in comparison to TRANSP-NUBEAM (M. Weiland, Nucl. Fusion 63 066013 [22])

RABBIT, on the other hand, has a physics-based model of neutral beam injection and estimates beam deposition properties, such as power density profile for electrons and ions, fast ion distribution and current drive. Compared to the offline version, real-time RABBIT has only access to n_e and T_e profiles but still exhibits reasonable agreement with non-realtime TRANSP-NUBEAM results [22] as shown in Figure 2. Future plasma rotation measurements from real-time charge exchange promise a more precise consideration of NBI power loss and significantly improved results.

Other real-time capable codes such as the RAPTOR transport solver [23] and the RAPDENS density profile observer [24] have been adapted to the ASDEX Upgrade experiment. They do not only rely on diagnostic inputs, like reconstructors, but are model-based estimators, also using actuation inputs and feeding a Kalman filter with the comparison of model results and measurements. This type of observer yields reasonable results even with noisy or unreliable data input, can deal with unobservable quantities and can also be operated as a forecaster. Recently, a study showed that RAPTOR profiles are already reasonably good, but would benefit from enhancing the transport model and adding diagnostic inputs from MSE or polarimetry [25]. RAPDENS is currently the only method to reliably reconstruct plasma density in pellet discharges at ASDEX Upgrade. An upgrade of its density model and boundary conditions yielded improved profiles [26]. A real-time bolometry tomography code is under development, which will provide a 2D radiation distribution from which control-relevant quantities like power over separatrix P_{sep} can be derived [27], [28].

3.2 Control Objectives

Currently, the DCS runs six independent Compact Controllers, each with a number of control modes. Each of these controllers can operate all or part of its mapped actuators also in feed-forward mode, which is a convenient option for physics exploration. Table 1 shows an excerpt of the control features. For recent results achieved with these controllers refer to [2].

Controller	Actuators	Control objectives
Plasma current	Central solenoid current	Plasma current
Plasma position	2 Control coil currents	Plasma centre or outer radius
Plasma shape	8 PF coil currents	Strike points, triangularity, elongation
Gas and pellet fuelling	3 gas channels, 1 pellet centrifuge	$n_{e\ core}$, $n_{e\ edge}$, n_0
Radiation	2 impurity gas channels	P_{rad}, $T_{divertor}$, Xpoint-radiation, MARFE
Heating, current drive and MHD	8 NBI sources, 8 ECRH gyrotrons, 4 ECRH mirrors,	β_{pol}, P_{heat}, P_{ion}, local heating and current drive, MHD, alpha heating simulation

	2 ICRH antennae	
Error field (preliminarily attached to fuelling control)	*16 RPM coil currents*	*ELM suppression, density pump-out*

Table 1: DCS controllers

4 ORGANISATIONAL PERFORMANCE OPTIMISATION

One of the most precious resources is experiment time. The typical duration of an ASDEX Upgrade pulse is about 8 to 10 seconds, but preparation and post-shot activities amount to 20 minutes. Maximising the exploitation of the device implies making best use of the plasma pulse, as well as efficient schedule preparation in between plasma pulses.

4.1 Automated Schedules

One method to achieving this goal is the automation of runtime procedures like parameter scans or optimum searches. While conventionally every iteration is executed in an individual pulse, the rule-based segment scheduling in the DCS can fold all iterations into a single or only a few experiments. The H-mode density limit (HDL) disruption avoidance scheme, for instance, allows exploiting the operational space up to a given margin to the disruptive boundary of an HDL, which depends on the machine condition. This boundary, defined as a function of the H-factor and the critical edge density fraction, is cast into a segment branching rule, causing the scheduling of an HDL repair segment, which reduces the gas puff and increases the heating power for a certain period of time [30],[31] [31]. When used for scanning, the next iteration with modified parameters can be started within the same pulse. Shot #43359 for example, comprises five such iteration loops as illustrated in

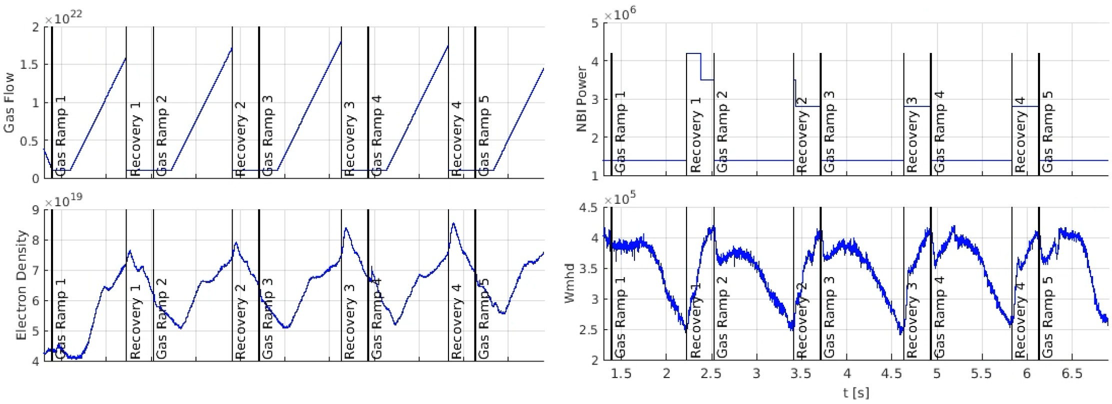

Figure 3: H-mode density limit scans in shot 43359 using conditional segment branching

Figure 3.

4.2 Pulse Preparation

Careful planning of pulse schedules involves meticulous error checking, avoids adverse scenario paths or system misconfigurations and leads more quickly to exploitable results. Besides component-centric validators such as static limit checks, value-plausibility conditions or complex ECRH gyrotron polarisation verification, experiment “flight simulators” are gaining importance for integration testing. Their mission also includes the development of operational scenarios, the design of controllers and the prototyping of novel properties of control system, diagnostic and actuators. A lot of design decisions, including the robustness against failures, perturbations and plasma events can already be evaluated and assessed in simulations.

For this purpose, Fenix, the ASDEX Upgrade flight simulator, has been developed at ASDEX Upgrade on the base of the ITER Plasma Control System Simulation Platform (PCSSP) [32], [4], [33]. It combines the 1.5D transport and equilibrium solver ASTRA with a Simulink® based full plasma control system model and can simulate full plasma discharges including technical, ramp-up and ramp-down phases [34]. With a control-oriented, reduced ASTRA configuration, a simulation run takes less than 15 minutes and is thus suitable for iterative prototyping. An outstanding feature is its capability to study the effects of all sorts of events and possible combinations including the reaction of the control system. Fenix can execute dry runs of planned pulses and thus assert that a pulse schedule is free of accidental inputs. The forecast allows validation of the attainability of a given experimental goal. The margin to operational constraints and regime boundaries can be explored and scenarios optimised such that they avoid critical regions where the nonlinearities in plasma behaviour and machine responses can cause unexpected instabilities. For this reason, several facilities have meanwhile expressed their interest in the Fenix core engine customised with their own Fenix model. It has already been adopted for EU-DEMO design studies [32], by TCV [35] and recently also by ITER for their PCS design assessment [36].

5 OUTLOOK

Performant tokamak operation is a moving target with structural, functional and organisational aspects. Efficient structuring of the control system and workflows is the most persistent investment. The DCS framework, constituting a complex system has matured over many years of operation. Actuator Management has recently introduced a significant gain in operational flexibility and reliability. Also, an upgrade of the pulse supervision logic is in preparation, aiming at further rule-based shot sequence automation based on the Behaviour Tree technology. Advanced tokamak control increasingly requires spatially resolved plasma information in real-time. Therefore, a suite of reconstruction codes and model-based observers has been added to DCS computing plasma current, density and temperature profiles for monitoring and control. Machine learning is expected to resolve bottlenecks in equilibrium and transport solvers or in pattern recognition, where the complexity and required granularity of models and algorithms currently prevents a timely computation for control purposes. Soon Thomson scattering and charge exchange measurements will become available in real-time and will supply redundant information on local electron density and temperature, that that is reliable even if ECE, the other basic electron temperature diagnostic, becomes unavailable for certain plasma parameters, but also additional quantities like ion temperature and Z_{eff}, replacing current assumptions in the codes and improving their accuracy.

Prospective organisation is also a powerful performance driver. Building on the enhanced quality of plasma models and sophisticated simulation platforms so called flight simulators will play an increasingly important role for proper pulse preparation. They have the potential to boost the effectivity of tokamak operation by significantly reducing the error rate in control, scenario design, and in shot execution. The Fenix flight simulator is currently used for scenario and control system development. A fast descendant of it running a real DCS instance instead of an emulated model is under development for use as a control-room validation tool for routine sanity checking of planned pulses immediately prior to their execution. The ASDEX Upgrade control system DCS demonstrates that these optimization methods can successfully be applied to a fusion experiment with outstanding operational flexibility and that they can further be expanded towards even more complex novel fusion devices like ITER.

REFERENCES

[1] H. Zohm et al, Overview of ASDEX Upgrade Results in Preparation of ITER and DEMO, 2024 *Nucl. Fusion* **64** 112001

[2] O. Kudlacek et al, Overview of advances in ASDEX Upgrade plasma control to support critical physics research for ITER and beyond, 2024 *Nucl. Fusion* **64** 056012

[3] J. Illerhaus et al, A real-time GPU-accelerated deep learning inference integration pipeline and its electron density profile reconstructor pilot project for control at ASDEX Upgrade, 2025 *FusEngDes* **220** 115274

[4] P. David et. al, Update of the integrated flight simulator for ASDEX Upgrade, 2025 *Open Plasma Science*, doi: 10.46298/ops.14788

[5] E. Fable et al, The modeling of a tokamak plasma discharge, from first principles to a flight simulator, 2022 *Plasma Phys. Control. Fusion* **64** 044002

[6] E. Fable et al, FEQIS: A free-boundary equilibrium solver for integrated modeling of tokamak plasmas, 2025 *Open Plasma Science*, doi: 10.46298/ops.14641

[7] R. Nouailletas et al, Development of a flight simulator for the WEST plasma and control system, 2025 *FusEngDes* **219** 115299

[8] M. Bellouard, Transport simulations for the development of ITER Pulse Design Simulator, 2024 KTH Royal Institute of Technology, https://kth.diva-portal.org/smash/get/diva2:1848656/FULLTEXT01.pdf

[9] W. Treutterer et al, ASDEX Upgrade Discharge Control System—A real-time plasma control framework, 2014 *FusEngDes* **89**, pp 146–154

[10] R.C. Martin, Clean Architecture, Prentice Hall, 2018, ISBN 978-0-13-449416-6

[11] W. Treutterer et al, ASDEX Upgrade's new plasma control scheme, 2006 *FusEngDes* **81**, pp. 1927-1931

[12] O. Kudlacek et al, Developments on actuator management, plasma state reconstruction, and control on ASDEX Upgrade, 2021 *FusEngDes* **171** 112563

[13] O. Kudlacek et al, Actuator Management for the First ITER Plasma Operation, 2024 *FusEngDes* **216** 115071
[14] O. Kudlacek et al, System Architecture for Actuator Management in ITER PCS, this conference
[15] W. Treutterer et al, Transforming the ASDEX Upgrade discharge control system to a general-purpose plasma control platform, 2015 *FusEngDes* **96–97**, pp. 712-715
[16] J. Colnel et al, Adapting DCS real time framework for WEST plasma control, 2018 *FusEngDes* **129**, pp. 24-28
[17] B. Sieglin et al, DCS Satellite: Enhanced Plant System Integration on ASDEX Upgrade, 2019 *FusEngDes* **146**, pp. 1737-1740
[18] W. Treutterer et al, Architectural concept for the ITER Plasma Control System, 2014 *FusEngDes* **89**, pp 512-517
[19] J. A. Snipes et al, ITER Plasma Control System Final Design and Preparation for First Plasma, 2021 *Nucl. Fusion* **61** 106036
[20] L. Giannone et al, Magnetics only real-time equilibrium reconstruction on ASDEX Upgrade, 2024 *Plasma Phys. Control. Fusion* **66** 045017
[21] M. Reich et al, Real-time beam tracing for control of the deposition location of electron cyclotron waves, 2015 *FusEngDes* **100**, pp. 73-80
[22] M. Weiland, Real-time implementation of the high-fidelity NBI code RABBIT into the discharge control system of ASDEX Upgrade, 2023 Nucl. Fusion **63** 066013
[23] F. Felici et al, Integrated plasma state reconstruction, off-normal event handling and control, with application to TCV and ASDEX-Upgrade, preprints of the FEC 2020
[24] T.C. Blanken et al, Model-based real-time plasma electron density profile estimation and control on ASDEX upgrade and TCV, 2019 *FusEngDes* **147** 111211
[25] M. Reisner et al, The RAPTOR based control scheme at AUG and benchmarking its results with real time inputs against post-processed data, 2025, submitted to *FusEngDes*.
[26] D. Kropackova et al, Real-time density profile simulations on ASDEX Upgrade and the impact of the edge boundary condition, 2025 *FusEngDes* **219** 115196
[27] P. David et al, Optimization of the computation of total and local radiated power at ASDEX Upgrade, 2021 *Nucl. Fusion* **61** 066025
[28] K. Moser et al, Gaussian Process Tomography at ASDEX Upgrade with Magnetic Equilibrium Information and Nonstationary Kernels, 2022 *Fusion Science and Technology* **78**, pp. 607-616
[29] C.J. Rapson et al, Improved localisation of Neoclassical Tearing Modes by combining multiple diagnostic estimates, 2017 *Nucl. Fusion* **57** 076023
[30] B. Sieglin et al, Dynamic pulse scheduling in ASDEX Upgrade: Disruption avoidance and investigation of the H-Mode density limit, 2023 *FusEngDes* **191** 113546
[31] B. Sieglin et al, H-Mode density limit disruption avoidance in ASDEX Upgrade TCV and JET, 2025 *FusEngDes* **215** 114961
[32] W. Treutterer et. al, Concepts of the new ASDEX Upgrade flight simulator, 2019 *FusEngDes* **146**, pp. 1073-1076
[33] C. Wu et al, Architecture design and internal implementation of a universal coupling between controllers and physics in a tokamak flight-simulator, 2024 *Fusion Science and Technology* **80** Isssue 6, pp. 766-771
[34] E. Fable et al, A full-discharge tokamak flight simulator, 2020, preprints of the 28th Fusion Energy Conference
[35] R. Coosemans et al, Full-discharge simulations of TCV using the Fenix flight simulator, EPS 2025
[36] L. di Grazia et al, Development of magnetic control for the EU-DEMO flight simulator and application to transient phenomena, Fusion Engineering and Design Volume 191, June 2023, 113579