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

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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 [1]. This is facilitated by particularly efficient and highly robust algorithms for measurement 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 an unparalleled 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.

Accurate control is not only the product of a sophisticated control design that minimises overshoot, settling time and cross-coupling, but crucially also depends on the fast and precise estimation of the feedback-controlled quantities from diagnostic measurements and reference models. For this reason, a number of physics codes that originally had been developed for post-pulse analysis such as the JANET equilibrium solver, the RAPTOR transport solver, the RAPDENS density profile observer, TORBEAM for ECH beam tracing and RABBIT for neutral beam heating profile estimation have been upgraded to real-time control applications in the DCS in the past years. Recently, the DCS has 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 [2]. Further applications such as a neural-network equilibrium reconstructor are in preparation.

The efficacy of a controller is also determined by the available actuation resources allocated to it. Spatial and cost constraints limit the overall number of resources, which on the other hand often can serve different purposes, such as ECRH gyrotrons with steerable mirrors, that can be used for central heating, as well as for current drive and MHD mode destabilisation. DCS controllers negotiate their requests with the actuator management which flexibly distributes them over available actuators and in future will even dynamically assign and allocate resources as needed. In return, they are informed about the currently available actuation range, allowing them to apply anti-windup strategies [3].

All ASDEX Upgrade controllers follow the compact controller scheme, in which control modes in the form of 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. This design paves the road for goal-driven pulse execution, which is essential for a performant utilisation of the experimental time and resources.

Which control objectives are adequate for a given plasma scenario and in the context of the present plasma state and the currently available resources, is a strategic decision that must be taken at a higher level of the DCS. The Pulse Supervision Control in the DCS analyses event indicators and plant state in order to schedule control objectives and adapt set-points, such that operation risk is minimised and the pulse exploitation can be maximised. This feature was utilised in the H-mode density limit (HDL) disruption avoidance scheme utilizes the conditional DCS segment branching logic not only to tune a scenario keeping margin to a critical area [4], but also impressively demonstrates the capability of real-time optimisation searches scanning the actual operational boundaries of regimes such as HDL and NTM during pulses [5].

Mastering the enormous amount and variety of experimental proposals in the European MST and WPTE programs, together with the highly specialised investigations in the AUG local campaigns with high availability and reliability, has only been possible due to the conception of the DCS as a modular, configuration-driven

framework paired with accompanying measures such as the development of Fenix, a control-oriented flight simulator.
Flight simulators serve two main purposes, the development and validation of pulse scenarios and the design and initial tuning of controllers. Fenix, the ASDEX Upgrade flight simulator teams up the 1.5D transport and equilibrium solver ASTRA and a Simulink® based full plasma control system model [6]. It simulates full plasma discharges including technical, ramp-up and ramp-down phases [7]. 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. For this reason, numerous facilities meanwhile have expressed their interest in the Fenix core engine. It has already been adopted for EU-DEMO design studies and recently also by ITER for their PCS design assessment.
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 [8][9]. With its distributed and configuration centric concept it is intrinsically scalable for use in other devices [10], to novel applications requiring higher computation resources like estimators based on artificial intelligence, but also to contexts with higher complexity [11]. 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. Actuator Management with dynamic actuator-controller allocation [12] and supervisory decision logic based on the Behaviour Tree technology [13] are the latest novel developments of the ITER PCS, that originate from DCS ideas. Also the Fenix flight simulator benefits from this heritage as it is based on the ITER Plasma Control System Simulation Platform (PCSSP) and exploits the concepts in common between DCS and the ITER PCS.
The contribution will illustrate these assets by presenting a selection of the above mentioned examples.

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