STATUS OF THE ITER PLASMA CONTROL SYSTEM CONCEPTUAL DESIGN

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Introduction

The physics requirements for plasma control in ITER have been described in some detail in the ITER Physics Basis [1] and its update [2, 3]. A general description of plasma control in ITER was also published a few years ago [4] and more recently in [5]. Now that ITER construction is underway, the formal system requirements for the Plasma Control System (PCS) have been specified in a high level document that describes the key features of the PCS and the interfaces between the PCS and the diagnostic measurements, actuators, and other plant systems. The PCS is a fundamental part of the Control, Data Access and Communication (CODAC) system on ITER. It will be controlling the evolution of all plasma parameters that are necessary to operate ITER throughout all phases of the discharge. This paper will summarize briefly the physics and operational requirements for the PCS and describe the integration and interfaces between the PCS, CODAC and the Central Interlock System (CIS).

Physics and Operation Requirements for the PCS

ITER is scheduled to have first plasma before the end of 2018 (minimal plasma with $I_p \approx 0.1$ MA) and the PCS should have the basic control systems operational by that date. After a brief operational phase of 6 months for magnet commissioning, Phase 2 Machine Assembly will follow where the main in-vessel components and much of the heating systems will be installed. The second operational phase is scheduled to begin in 2021 when physics experiments will begin to bring the tokamak to full technical performance of $I_p = 15$ MA and $B_T = 5.3$ T. For this second operational phase, the PCS must have the main plasma control algorithms operational. More advanced plasma control algorithms needed for high performance plasmas (e.g. fusion burn control) will be implemented as required throughout the ITER program. The PCS should be available in its first-plasma configuration for integrated tests of CODAC and machine components by around 2016. Work on the conceptual and engineering design is starting now, so that the envisioned control algorithms and concepts may also be tested on existing machines.

The ITER PCS consists of the following subsystems: 1) wall conditioning and tritium removal, 2) plasma axisymmetric magnetic control, 3) plasma kinetic control, 4) non-axisymmetric stability control, 5) exception handling.

Since the ITER superconducting toroidal field coils will be on for extended periods of time, wall conditioning schemes other than steady glow-discharge (e.g. ion cyclotron discharge cleaning) must be developed to prepare the wall surfaces for plasma operation. Tritium removal techniques are also critical due to the in-vessel tritium inventory safety limit of 700 g imposed by the nuclear regulators. The fundamental control tasks (shape and position control, vertical stabilization etc.) will be performed by the axisymmetric magnetic control subsystem. Plasma kinetic control (power and particle flux, fueling, heating and current drive, fusion burn, q-profile) will play an increasingly large role for ITER and will also require some R&D effort, as some features are not routinely operational on present day machines (q-profile, density profile) or have not yet been developed (fusion burn control). The non-axisymmetric stability subsystem will control all kinds of MHD instabilities (edge localized modes, neoclassical tearing modes, sawteeth etc.). Exception handling will play an important role in achieving the desired physics performance of the machine and is described in further detail below.

Integration into CODAC

The PCS is an integral part of the ITER CODAC system. It has interfaces to the scheduling system, the interlock system and the general CODAC infrastructure such as networks. Details can be found in Figure 1. The main CODAC network relevant for PCS is the so-called ”synchronous data bus network” (SDN). This is a real-time network which will transmit all necessary diagnostic data, status and availability of plant systems and handle the communication to the actuators for control. The decision on a network standard is currently being pursued. The main features will be around 5000 data channels with a total data rate of a few ten MB/s at a cycle time on the order of 1 ms. In order to keep the data rates within reason, data intensive systems needed for control (IRTV for heat load control, electron cyclotron emission etc.) will need to be locally processed such that the necessary information for the PCS is extracted without transmitting the full raw data. The plant operation network will handle the non latency-critical data transfer to the mass data storage and other plant systems.

Interface to the scheduling system The ITER scheduling system will be used for the off-line preparation of pulse segments, backup segments and some event-driven segments (e.g. NTM control segment or the initial soft-stop segment) at remote experimental sites and the validation of prepared schedules. Once a pulse schedule has been composed, validated and transfered to the ITER site and after the completion of all validation processes is ready to be executed, the necessary plant system configuration in-

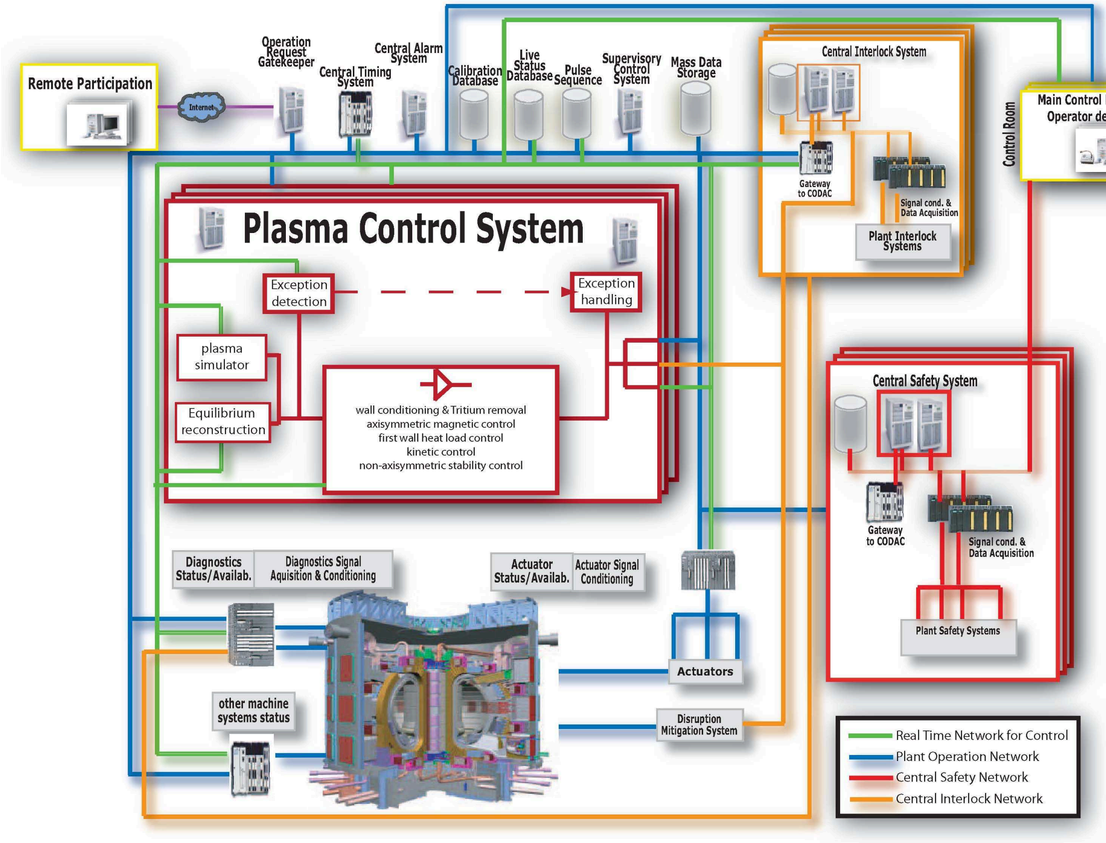

Figure 1: Schematic of the relationship between the PCS and other CODAC Systems.

formation, the reference waveforms and the initial set of algorithms and parameters will be transmitted to the supervisory control system (SCS). This will in turn pass on these parameters to the plant systems and the PCS. After the pulse execution begins (at a to be specified time or event), the PCS will have full control over all necessary plant systems and orchestrate the discharge. Any necessary reconfiguration of plant systems during a discharge will be triggered by the PCS.

Interface to the Central Interlock System

Overall control of ITER plasmas will be supervised by a three-tier hierarchical system: 1) Plasma Control System (PCS), which will be responsible for the dynamic feedback control and maintenance of the plasma parameters within specified ranges; 2) Central Interlock System (CIS), which will be responsible for rapid shutdown of operational systems and plasma in case of inadequate response of the PCS, or an overriding need to protect the plant; 3) Central Safety System (CSS), which is a safety important component that is designed to ensure the protection of the people and the environment.

The PCS is being designed to control plasma operation within the range of expected operational limits across the ITER operational scenarios. As the first tier in machine protection, the PCS will ensure that the plasma remains within a specified range of operational limits. The protection functionality of the PCS will be implemented in the event & exception handling system. It will monitor the current plasma parameters, status and fault information from various plant systems and according to a specified logic react to events ranging from plant system faults to plasma-driven events. It will also ensure the best possible utilization of the long ITER discharges by providing the possibility to switch to prepared backup segments in case the requested plasma parameters cannot be provided. It should be noted however, that the central interlock and central safety system are ultimately responsible for machine protection and safety. The PCS operational space is a subset of the CIS operational space, so that if PCS were to fail to control the plasma or shut it down before a trigger condition for the CIS is met, CIS would be triggered to rapidly terminate the plasma. Likewise if both PCS and CIS were to fail, the CSS would be triggered if people or the environment were in danger.

There are three main possibilities to quickly shut down the ITER plasma. If there is sufficient time to gradually ramp down the plasma current, the PCS will execute a soft-stop. This is a segment that provides the fastest way to ramp down the current with minimum stress on components. This segment will be dynamically updated during the discharge depending on the current plasma parameters. A similar segment will exist which provides the fastest controlled way of ramping down where ramp down speed had priority over component stress levels. The fastest plasma termination strategy is the mitigated disruption, which is a massive noble gas injection into the plasma. It will virtually immediately cause a disruption which is however less severe on the machine than an unmitigated one [6]. The disruption mitigation system is exclusively triggered by the CIS, but a trigger can be requested by the PCS. Likewise, CIS will give -as far as possible- advance warning to PCS if a shutdown is imminent such that PCS can start to ramp down the current or even terminate the plasma completely before CIS will fire the disruption mitigation system.

Exception Handling System

The exception handling system of the ITER PCS will be an integral part of the three tier safety and machine protection architecture of ITER. A successful ITER experimental campaign will strongly depend on the quality and capability of this system. Exception detection and handling are implemented at some level in other tokamaks [7, 8] and large-scale accelerator facilities [9], but not on a scale as foreseen for ITER.

The PCS exception handling system will provide the means to deal with any event or exception not clearly predefined by a timestamp.

Examples include failures of plant systems, plasma related events (L-H and H-L transitions, MHD instabilities). When an exception is detected that requires a change in plasma control to maintain plasma performance or to avoid damage to the machine, the PCS will decide whether to a) continue the pulse with a change in control algorithm or scenario, b) perform a plasma soft-stop, or c) trigger a mitigated disruption via the CIS.

Exceptions can be divided into 6 categories: 1) plant system failure, 2) plasma performance degradation, 3) partial loss of functionality, 4) specified operational limit exceeded, 5) plasma-driven events, 6) predicted exceptions.

The impact of exceptions can be divided in classes with different severity: 1) unrecoverable exceptions (e.g. magnet quench), 2) plasma confinement control (e.g. shape, position, vertical stabilization, instabilities), 3) control necessary for physics performance (e.g. q-profile), but not essential for plasma operation.

The exception handling goals can be of different nature: 1) re-establish plasma performance by adaptive control or change of algorithm, 2) Maintain the plasma at reduced performance with different physics program, 3) Maximize component lifetime and minimize component damage.

Exception detection is a complex problem for ITER. An adequate response of the exception handling system is crucially dependent on not only plasma parameters which are directly accessible in the PCS, but it also relies on detailed identified fault conditions communicated by the various plant systems. Furthermore, the timescales of exceptions for ITER can range from milliseconds to several seconds or even minutes depending on the nature and type of exception. An example would be the failure of parts of a plant system (e.g. parts of the H&CD system dropping out). In this case, an appropriate response would be to try to bring the plasma back to a stable state to avoid any instabilities or disruptions developing due to lack of heating or loss of current drive and then if possible activate backup heating (a loss of neutral beam heating power could be compensated by additional ECH if available) to continue operation. One of the more advanced features of exception handling is event prediction. For ITER, this can include disruption prediction or using the plasma simulator to predict when parameter limits are likely to be exceeded. This feature of course crucially depends on the quality of results delivered by the simulator and disruption predictor. A further feature is the dynamic update of soft-stop segments. Depending on the current plasma conditions, the best and fastest way to execute a soft stop can vary. So it is advantageous to continuously update the soft-stop strategy in order to have the best possible way for a fast ramp-down available at any given time.

Outlook and Conclusion

The ITER PCS will be a crucial system to guarantee successful ITER operation. Efforts for a conceptual design of the ITER Plasma Control System are underway and a detailed design can be expected during the next two years. PCS will feature many control schemes that are not routinely implemented in present machines and some will have to be developed during ITER operation. The event and exception handling capabilities will be an important factor to achieve the maximum physics output of the long ITER discharges.

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