ITER Plasma Control System Final Design and Preparation for First Plasma

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Abstract

The ITER Plasma Control System (PCS) has successfully completed its final design for the First Plasma (FP) and Engineering Operations phase and plant system commissioning has begun as ITER prepares for this first operation phase. Commissioning of the essential plant systems will continue as each plant system is completed and made ready for operation. Once the tokamak is assembled, the cryostat top lid is closed and pump down begins, this will start approximately one year of integrated commissioning to prepare all of the relevant plant systems for FP operation. After a scheduled one month of plasma operation with the goal of achieving a plasma current > 100 kA for at least 100 ms, there will be about six months of engineering operation to complete commissioning of the superconducting magnet systems to full current without plasma to complete this initial ITER operation phase. The PCS Final Design for FP will be described as well as the integrated commissioning sequence of the main plant systems required for this operations phase. The plans for the FP operation campaign will be described, including specific challenges present on ITER due to large vacuum vessel eddy currents, issues associated with ECH assist, neutral pressure and impurities. This will be followed by the Engineering Operation phase to commission full current operation in the Central Solenoid, Poloidal Field and Toroidal Field (TF) magnets, possibly including plasma operation at full TF of 5.3 T to have improved conditions both for Ohmic plasma initiation and Electron Cyclotron Heating absorption.

1. INTRODUCTION

As described in the ITER Research Plan (IRP) [1], the First Plasma (FP) campaign will be preceded by nearly one year of Integrated Commissioning (IC), the progressive integration of ITER plant systems to jointly commission their operation in preparation of tokamak plasma operation, which will include the first operation of the ITER magnet system. Once IC is complete and systems are ready for plasma operation, there will be about one month
to attempt to achieve FP at half the maximum toroidal field of 2.65 T with a goal of achieving a plasma current $I_p > 100$ kA for at least 100 ms duration and possibly up to 1 MA for up to a few seconds duration. Although limited in its objectives, ITER FP will test and use all the main tokamak operation functions. Following these attempts at FP, there will be about six months of Engineering Operation (EO) to commission the Central Solenoid (CS), Poloidal Field (PF), and Toroidal Field (TF) superconducting magnet systems and power supplies to full current operation up to the nominal maximum TF of 5.3 T, without plasma. If there is difficulty achieving FP Ohmically, there will be up to 5.8 MW of Electron Cyclotron Heating (ECH) power available to launch from one upper launcher to assist in ionization and burnthrough. Further plasma attempts may be made after the magnets are commissioned up to 5.3 T, where plasma initiation will be easier due to longer connection length and improved ECH absorption at the fundamental frequency of 170 GHz. This phase (IC, FP, and EO) is expected to require at least 470 operational days of two or three shift operation.

The Plasma Control System (PCS) is key to the integrated operation of the ITER plant. Its final design for FP operation was performed by members of the ITER Organization and a team of external plasma control experts from fusion laboratories within the EU, Russian Federation and the US, building upon the Conceptual [2] and Preliminary [3] designs. This PCS for FP final design includes basic magnetic control (PF/CS) and kinetic control (H gas injection and ECH startup assist), initial exception handling, PCS requirements for the pulse schedule (PS), commissioning and operations as well as provisions in the architecture to accommodate the advanced controls needed for high performance operation, which will be designed in subsequent phases for Pre-Fusion Power Operation (PFPO-1 and PFPO-2) and Fusion Power Operation (FPO). Important to the input of the PCS for FP design, are the various operation scenarios that are to be expected. Not only plasma operation itself, but also integrated commissioning scenarios, such as the first commissioning of the ITER magnets, integrated commissioning of gas injection and ECH or the further tests to be done during EO that all require the use of PCS.

The final design of the PCS functions for FP will be described as well as the steps of the IRP through IC, FP, and EO, including the challenges at the ITER scale for this limited first operation phase.

![ITER PCS schematic showing interactions between the input and output support functions, kinetic and magnetic controllers, and the Pulse Supervision Controller within the PCS and the links to measurements and actuators.](FIG. 1. ITER PCS schematic showing interactions between the input and output support functions, kinetic and magnetic controllers, and the Pulse Supervision Controller within the PCS and the links to measurements and actuators.)

2. **PCS FINAL DESIGN FOR FIRST PLASMA**

The PCS final design for FP has been approved and is being prepared for implementation within the CODAC conventional control system [4]. Figure 1 shows a schematic of the ITER PCS with input and output support functions, kinetic and magnetic controllers, and a Pulse Supervision Controller that monitors the plasma and plant systems and control functions to execute global actuator management and exception handling functions.
2.1. Magnetic control

In the FP phase, the magnetic control system [5] will generate commands to the CS/PF coil power supply system
(CPSS) to provide the required electromagnetic plasma breakdown conditions in the breakdown region, to sustain
the plasma after breakdown during the burn-through phase and control the plasma current, radial plasma position,
and plasma shape for a nearly circular plasma limited on either the inboard or outboard temporary stainless steel
poloidal limiters (Fig. 2). Disruption force limits on the attachments of these temporary limiters to the vacuum
vessel (VV) require control algorithms to ensure that the $I_p < 1$ MA at half the nominal toroidal field, 2.65
T at $R = 6.2$ m. In the FP phase, the CPSS of the superconducting coils CS1U and L, CS2U and L,
CS3U and L and the PF1 and PF6 will have only one converter installed out of two and the vertical stability
circuit VS1 using PF2 – PF5 will only operate at 1/3 voltage with two converters out of six installed. The
magnetic control system, including Switching
Network Units (SNUs), which produce the main
contribution to the plasma loop voltage, can achieve
a wide “magnetic null” at the gas breakdown with
toroidal electric field up to 0.3 V/m, which is limited
by the insulation of the superconducting coils. The
in-vessel VS, ELM, and Correction C oils (CC) will
also be installed, but will not be used during this
phase. Nearly the full set of both in-vessel and ex-
vessel magnetic diagnostics will be operational
(except for divertor coils) [7]. Large currents will be
induced in the highly conductive VV of order 1.5 MA
during plasma initiation [8]. Simulations indicate that
$I_p$ can be measured down to a level of 10 – 50 kA [9],
though methods to take into account the impact of the
vessel current contribution are still being developed.
The coil voltage commands for a given plasma
scenario will be input mainly through feed-forward
control to the magnetic controller. Up to 15% of the
coil voltages may be allocated to an additional
feedback control to correct for uncertainties in the
axisymmetric models of stray fields due to ferromagnetic materials (e.g. steel rebar of the concrete near the
tokamak) and non-axisymmetric eddy currents.

2.2. Kinetic control

FP kinetic control will include only H$_2$ gas injection and ECH for plasma breakdown assist with up to 5.8 MW of
170 GHz power from seven beams. The Gas Injection System (GIS) [10] consists of 10 Gas Valve Boxes (GVBs)
with 4 in the upper ports and 6 in the divertor. Only the 4 upper port GVBs will be required in the FP campaign,
though all GVBs will be installed by FP. H$_2$ or He will be used for Glow Discharge Cleaning (GDC) prior to FP
to prepare the walls for plasma operation, but this will not be controlled by the PCS. A combination of feedforward
and feedback control of the GIS will allow triggering the SNUs at a chosen pre-fill neutral pressure equilibrated
in the vessel to achieve reproducible breakdown conditions, which are challenging in ITER due to the large VV
volume (~1700 m$^3$), low toroidal electric field and inherent delays due to the length of the gas lines (18 – 26 m)
of order 0.5 s for H [11]. The mass flow controlled (MFC) valves will be installed with two different throughputs
with one in the range of 0.1 – 5 Pa m$^3$/s and another in the range of 5 – 100 Pa m$^3$/s. Plasma breakdown is expected
only over a narrow range in neutral pressure in nearly pure H$_2$ of 0.5 – 1 x 10$^4$ Pa [8], which will require using
the low throughput MFC valves for H$_2$ fueling or pulse width modulation of the larger throughput MFC valves.
The low startup electric field ~0.3 V/m, the large gas volume and neutral fueling source limit the allowed prefill
range and increase the required power for breakdown. Due to the limited plasma duration (< 3 s) and the gas line
delays, density control in the FP phase can only be achieved with feedforward control (Fig. 3). The peak FP
electron density is expected to reach up to 2.5 x 10$^{18}$ m$^{-3}$, which is above the minimum line average density that
can be measured by the Density Interferometer Polarimeter (DIP) of 7.5 x 10$^{17}$ m$^{-3}$ [12].
The first 8 gyrotrons and one upper launcher of the ECH system will be installed for FP. Each gyrotron can inject 0.83 MW of power into the tokamak. Since the beryllium blanket and tungsten divertor will not yet be installed in the FP phase, the diagnostics and other in-vessel components are unprotected from the ECH power. To avoid damage due to unabsorbed power, the ECH beams will be reflected off mirrors mounted on the VV inner wall into an ECH absorbing beam dump in the opposite equatorial port with 4 beams crossing the breakdown region about 40 cm below the midplane and 3 beams crossing about 40 cm above the midplane (Fig. 4). The footprint of the ECH beams on the inner wall mirrors allows space for only 7 of the 8 beams to be reflected into the ECH beam dump to avoid the mirrors sticking into the plasma region, so that the maximum injected ECH power will be 5.8 MW with one spare gyrotron. The ECH beam dump design includes an absorbing ceramic coating that is expected to allow at most 300 ms at 5.8 MW of ECH power before possible delamination of the coating, but prototype tests will be performed to validate this design limit. The absorbed power at plasma initiation of a single pass ECH beam is only expected to be of order a few percent of the injected power at half field (i.e., 2nd harmonic X-mode ECH) [13]. Feedback of the prefill pressure is coordinated with the timing of the SNU triggering, the formation of the PF null, and the triggering of the ECH pulse for robust plasma initiation control.
2.3. Exception handling

This phase also includes initial exception handling algorithms that change control schemes in real-time in the event of possible plant system and diagnostic faults, coil current and field limits, excess ECH power, plasma initiation failures, start-up runaway electrons, and plasma current limits [14]. Exception handling must first detect the event, determine whether the event requires a change of control under the current context, prioritize in the case of concurrent events, and determine the most appropriate (set of) action(s) to take. In the FP phase, little feedback control is possible because of the short plasma durations, so these initial exception handling policies are generally to shut down plant systems when faults occur or operation limits are exceeded. The PCS can, for example, turn off coil voltages and ramp down coil currents, change the gas flow or switch off the ECH. Some policy differences occur depending on the state of the SNUs, the level of plasma current, as well as for requests from the Central Interlock System (CIS). Figure 5 shows an example of an exception exceeding an $I_p$ limit of 500 kA and the subsequent actions to switch out the SNUs, set the CS/PF coil voltages to zero, ramp down the coil currents, and shut off the gas injection. For FP, at least 90 global exceptions were identified, which may not be exhaustive, but the exception handling system is configurable so that additional exceptions can be added in the future as needed.

2.4. Architecture and pulse schedule

Already in the FP design, the PCS architecture [15] has been designed to ensure that it is capable of handling all control functions that will be needed not only for FP, but for all subsequent design phases, which allows implementing control algorithms for high performance fusion operation in the future without changing the PCS architecture. The PCS will evolve throughout ITER operation and it must be flexible and extendable, while containing complexity through the reuse of modular components. The coupling between the various control functions of the PCS due to shared actuators or impact on plasma parameters requires an integrated control architecture. The main integrating function of the PCS is through the Pulse Supervision Controller (Fig. 1) that manages the execution of the Pulse Schedule (PS), generates and coordinates the reference waveforms to all controllers, monitors the plasma evolution and plant systems and performs global exception handling. The architecture also includes input and output support functions that monitor and process diagnostic inputs, manage...
actuators and support local exception handling of plasma and plant system faults. Decoupling of functions is achieved by separating control actuator commands from the actuator command management, which is carried out by separate support functions. To ensure components of the architecture easily combine, a standardized Compact Controller has been developed to provide modularity and reusability of components, dynamic control goal switching, local monitoring and separation of concerns. The design also includes a standardized scheme to manage exceptions.

Information from the Synchronous Data Network (SDN) and from within the PCS itself is available dynamically when and where it is needed through a publish/subscribe scheme that also provides configurable functionality through the PS as well as exception handling. The architecture includes provisions for actuator management to be able to replace tripped actuators and manage them dynamically through a hierarchy of goals. Advanced decision logic is foreseen through configurable and extendable behavior trees to navigate complex paths for integrated control.

The PCS will be configured before each pulse through the PS, which will include all of the PCS and plant system settings, chosen controller configurations, prescribed waveforms, pulse scenario and segments, and exception handling policies. Figure 6 shows a schematic of an Operational Pulse Schedule for pulse execution. A Pulse Design Simulator (PDS) is being developed to design, simulate, and pre-validate a pulse design and to prepare PSs well ahead of operation through the Pulse Schedule Preparation System (PSPS). An approved PS will then need to be finally validated with the available plant system status on the day the pulse is to be run using the Configuration, Verification, and Validation Framework (CVVF).

2.5. Systems engineering approach and design assessment

The PCS has been developed with a systems engineering approach using a PCS database (PCSDB) [16] to keep track of all aspects of the PCS design, which has been assessed within the PCS Simulation Platform (PCSSP) [17], to ensure that the design satisfies the system and performance requirements. The PCSDB aims to achieve full traceability from architectural components and control functions up to high level requirements and down to code testing and commissioning procedures. It also provides a means to manage changes to the PCS as it evolves, generate reports, and find gaps in the design. The design assessment has used simplified models of the plasma, tokamak, actuators, and diagnostics to simulate control functions, in closed loop with the PCS implementation in PCSSP. The assessment evaluates metrics that quantify the PCS performance and then verifies that the metric values are within the required performance bounds. The assessments were carried out for a series of test cases designed to test both nominal control and exception handling for FP scenarios. Fig. 5 shows an example of an assessment of exception handling. Within the limitations of these simplified models, the assessment results confirm that the PCS design meets requirements and is ready to be implemented for FP and engineering operation.
2.6. PCS system commissioning

The plans for commissioning and initial operation of the PCS for FP have also been developed as part of the PCS Final Design for FP. After implementation of the PCS, individual system commissioning tests will be carried out to confirm that the PCS performs as designed. These tests will include initial tests with actuator (ECH, GIS, CPSS) and diagnostic (magnetics, $H_{te}$, hard x ray, neutral pressure) plant systems, for example, to check data exchange and tests on dummy loads. PCS system commissioning needs to confirm that basic communications and functionality of the PCS and its interfacing plant systems have been established and that the PCS and the main tokamak systems are ready to begin integrated plant operation.

3. INTEGRATED COMMISSIONING (IC)

ITER operation formally begins with the IC phase following closure, pumpdown and leak testing of the VV and cryostat. Individual plant system commissioning with conventional control, interlock, and safety system tests should be completed before IC with connections to the tokamak begins. Of particular importance is the qualification of the VV as nuclear pressure equipment by the hydrostatic pressure test of the VV interspaces up to a water pressure of $37.4 - 38.7$ barg. The operations phase begins with VV baking to $200^\circ C$ and GIS commissioning into the VV, leading to GDC to clean up the VV and reduce impurity partial pressures measured with the Residual Gas Analyzers sufficiently to prepare for plasma operations. Note that GDC can only be performed with the TF off. Initial ECH commissioning with power into the VV can occur in parallel.

Following initial low current magnet commissioning tests with the magnets still warm, the thermal shield will be cooled to $80^\circ K$ and the magnets to $4.5^\circ K$ so that integrated commissioning of the magnets and coil power supplies with the PCS can begin in parallel with magnetic diagnostic commissioning. Specific measurements of the structure of the inboard (high field side) TF will also be performed in this phase to determine how best to align the blanket modules (shield blocks and first wall panels) in Assembly Phase 2 that precedes FFPO-1 [18]. Magnet commissioning will continue up to a TF of $2.65 \ T$ and CS/PF currents up to half their maximum values when all systems should then be ready for the FP campaign. The IC phase will be completed by a fully integrated test of PCS control of the CS/PF coils and SNUs as if for FP operation, but with gas control to avoid plasma initiation.

4. FIRST PLASMA CAMPAIGN (FP)

The FP campaign will continue these tests for about 1 month adding gas injection to culminate in achieving plasmas with at least $I_p > 100 \ kA$ for at least $100 \ ms$ at $2.65 \ T$. Since feedback control of the plasma current will not be possible for these limited durations, the plasma current may exceed $100 \ kA$, but the design of the FPPC allows disruption loads up to at most $I_p < 1 \ MA$ at $2.65 \ T$ with expected plasma heat loads for up to $3 \ s$ duration. Feedforward controls will be implemented in the PCS to ensure that $I_p < 1 \ MA$. To achieve FP, the vacuum conditions and gas injection must be optimized to provide sufficiently uniform and pure H neutral pressure within the required range of $0.5 - 1 \ mPa$ and the PF system operation must be optimized to provide, during the CS discharge with the SNUs, a PF null ($< 2 \ mT$) over a large region ($\sim 1.6 \ m$) for gas breakdown and subsequent increase of the current in a nearly circular plasma leaning on the inboard temporary limiters [9]. FP will be attempted first Ohmically and then, if necessary, ECH power will be added for short pulses ($100 - 300 \ ms$), slowly increasing the power, if needed, up to the $5.8 \ MW$ maximum injected power. FP optimization must include avoidance of slide-away/runaway electrons during plasma initiation through careful control of the GIS, ECH, and CS/PF waveforms, ensuring that sufficient density is achieved for a given plasma current. Following demonstration of FP, or if FP is not possible at $2.65 \ T$, further plasma attempts will be made at $5.3 \ T$ during the EO phase.

5. ENGINEERING OPERATION (EO)

The EO phase will commission the TF, CS, PF and CC coils to full current operation without plasma over a period of about 6 months to demonstrate that the coils and power supplies are capable of achieving nominal plasma current $15 \ MA$ and toroidal magnetic field $5.3 \ T$ in later operation phases. The CS/PF coil power supply voltage limits of the FP phase, as described in Section 2.1, allow full coil current operation, but do not allow a complete demonstration of a $15 \ MA$ scenario. The activities during the EO phase include verifying the performance of the magnets with increasing current levels and acquiring “as-built” magnet data, including measurements of coolant flow, steady-state heat loads, AC losses, mechanical response to temperature gradients and eddy currents. Further commissioning of the conventional control, interlock, and central safety systems as well as the magnetic diagnostics and tokamak systems monitoring structural stresses will also be performed in this phase.
If FP was achieved only with ECH assist at 2.65 T, an important question for the IRP, under what conditions can Ohmic plasma initiation be achieved will have to be tested during EO. If FP was not achieved at all at 2.65 T, further attempts will be made at 5.3 T during the EO phase, since the increased connection length and ECH absorption at the fundamental 170 GHz frequency at 5.3 T will improve conditions for ECH pre-ionization and plasma initiation. Since the FPPC are designed to withstand disruption loads only up to plasma currents of 0.5 MA at 5.3 T, the PCS will implement feedforward controls to ensure $I_p < 0.5$ MA.

Once integrated magnet commissioning is complete up to the nominal currents for the CS/PF and TF and FP is achieved, additional Ohmic plasma start-up studies may be performed at low TF values (1.8 T). This decision will depend on the outcome of the FP campaign. It is important to investigate Ohmic plasma startup during this campaign so that a decision can be made as to whether or not dual frequency gyrotrons will need to be procured for plasma initiation at 1.8 T in PFPO-1.

If operational time is available in the EO campaign after having achieved all objectives above, further short pulse limiter operation with the FPPC (limited to a maximum plasma current of 1 MA at 2.65 T) may be performed if this is considered an effective way to advance the commissioning of the PCS and diagnostics with plasma ahead of the PFPO-1 phase.

6. CONCLUSION

ITER tokamak assembly and plant system commissioning has already begun for the first components (one VV sector, one pair of TF coils and thermal shield) and plant systems (steady-state electrical network and component cooling water) and will continue as further components are built and systems come online. The Final Design of the ITER PCS for FP and Engineering Operation has been assessed and approved and is ready for implementation within the CODAC conventional control system. Once the first assembly phase is complete, the cryostat top lid is installed and pumpdown begins, the first operations phase will begin with a period of about 11 months of integrated commissioning. This will be followed by a brief one month plasma operation phase to demonstrate FP with $I_p > 100$ kA for at least 100 ms at a TF of 2.65 T. A longer 6 month engineering operation phase will then commission the CS, PF, and TF magnets up to their nominal current levels, meeting the requirements to support tokamak operation up to the nominal 15 MA / 5.3 T.

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