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Progress in the ITER Plasma Control System design ☆

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ABSTRACT

The ITER Plasma Control System (PCS) controls all aspects of the ITER plant necessary to achieve the pulse scenario. This includes control over the magnets, fueling and auxiliary heating systems, but also many functions that monitor plasma operation limits and instabilities. This paper will describe how the ITER PCS is designed and report on the design status, highlighting some of the critical functions and design issues. The main functions such as magnetic, fueling and heating control and initial disruption avoidance are well underway, being detailed in the system engineering database (PCSDB) and being implemented in the PCS simulation platform (PCSSP) in Matlab/Simulink which jointly provide the PCS design description. The PCSSP is also key in permitting design assessment by simulating and testing the multitude of functions which comprise the PCS. We illustrate the overall PCS architecture with an example use-case: the complex, multi-task control scenario required to manage plasma operation with the Electron Cyclotron Heating (ECH) system. This has taken on even greater importance given the recent ITER organization re-baseline proposal which requests a very significant increase in the installed ECH power, doubling from 20 MW to 40 MW for the first operation phase, Start of Research Operations, and increasing further up to 67 MW for the deuterium–tritium campaigns. The PCS design in this case requires a clear breakdown into manageable sub-functions which focus on parameter monitoring, actual control, and the complex interface between the ITER PCS and the ECH system itself. Control functions include not just the control of the ECH power, but also related tasks, such as the control of [Neoclassical] Tearing Modes. The implementation requires the design of actuator management functions which efficiently manage the potentially conflicting actuation requests from PCS functions to the ECH system, as well as the exception handling functions that provide appropriate reactions to deal with off-normal events during plasma pulses.

1. Introduction

The ITER device is designed to demonstrate the technological feasibility of nuclear fusion as a precursor to developing future fusion power plants. A collaborative effort involving 35 nations, it is currently under construction in southern France. This project presents significant scientific and technological challenges, encompassing advanced superconducting technology, large-scale engineering, long-pulse operation, active cooling, high power and plasma current, and the management of very high stored energies. The primary goal of ITER is to achieve a fusion power gain factor of $Q \geq 10$, generating 500 MW of fusion power for more than 300 s. It is essential to recognize that ITER is not an experimental device for trial-and-error approaches; instead, it is constrained by a limited number of plasma discharges, all strategically aimed at fulfilling its core objectives.

In addition to the aforementioned formidable challenges, the control of ITER plasma will be extremely demanding. During ITER pulse operation, the Plasma Control System (PCS) ([1,2] and references therein)

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will be responsible for coordinating and supervising, continuously and autonomously, the available actuators, while managing all relevant aspects of plasma control. The goal of this uninterrupted and self-directed operation is to optimize fusion power output in accordance with the desired operational objectives.

Unlike previous and existing research tokamaks, where the PCS development could evolve gradually alongside the machine's operation ([3] and references therein), the ITER PCS must be fully designed, implemented, tested, and commissioned prior to the first plasma operation. This presents a unique challenge and underscores the critical importance of the PCS in ensuring the success of ITER's principal objectives. Given the need to manage over 30 actuator systems and more than 50 diagnostic systems [4], the ITER PCS introduces a new level of complexity. These include the fueling (gas and pellet injection), magnet systems (central solenoid, poloidal field, vertical stability, edge localized mode coils, and correction coils), as well as heating and current drive systems (electron cyclotron, ion cyclotron, neutral beam injection).

On the other hand, the system is required to manage a broad set of control tasks characterized by highly non-linear and complex interactions, such as magnetic control, kinetic control, operational limits, instability control, and exception handling. While individual control functions have been studied extensively [3], the ITER PCS must coordinate these tasks concurrently within a single discharge — an unprecedented control challenge in fusion research.

The PCS development has been the outcome of extensive collaboration between ITER and several research institutions. This paper first provides a summary of the key features of the ITER PCS, outlines the system engineering approach used in its design and implementation, and presents the current status of the design in Section 2. In Section 3, a use case involving the Electron Cyclotron Heating (ECH) actuator is presented to demonstrate the PCS's ability to manage multiple control tasks, showcasing the system's development methodology.

2. ITER PCS and staged development approach, status update

2.1. Main features of the ITER PCS

In addition to its primary role of ensuring high performance and reliable plasma control under nominal conditions, the PCS also serves as the first line of defense within ITER's "defense-in-depth" strategy against potentially damaging events, such as system faults, plasma instabilities, or disruptions. Although dedicated protection systems, including the Advanced Protection System and the Central Interlock System [5], are in place to safeguard the machine, the PCS is integral to preventing harmful events from escalating.

The PCS is designed as an integrated control system [6], encompassing a range of control functions that handle both continuous operations, such as fueling and heating control, and asynchronous functions, like exception handling. A critical aspect of the PCS design is its model-based approach [7,8], which employs simulations to predict the behavior of the physical system. This allows for thorough testing and commissioning before actual operation, ensuring the system is prepared to respond effectively.

The ITER PCS, while generally concentrating on standard control functions such as magnetic field regulation, fueling, and heating – common to other tokamaks – stands out due to two unique distinguishing requirements.

- Exception Handling (EH): is essential in ITER due to the significant operational costs associated with potential damage caused by disruptions or other malfunctions. To minimize downtime and avoid costly repairs, the PCS must be thoroughly prepared for operation through careful design and commissioning. This involves covering the vast variety of potential events to reduce the likelihood of unforeseen issues during operation. Handling such a wide spectrum of scenarios is a major challenge task. And it demands an architecture that is not only robust and manageable but also flexible and extendable to accommodate an increasing number of events over time. The effectiveness of this EH depends on the accuracy of actuator and diagnostic models, the precision of plasma state reconstruction and estimation, and the implementation of a comprehensive event handling strategy. Ultimately, all of these tasks must be executed within a real-time framework (RTF), with a strict computational time limit. As such, the development of effective functions for EH, along with reliable plant and plasma models for testing, is critical.
- Collaborative development: with hundreds of control functions assembled through broad international collaboration, the PCS requires a systematic and standardized method for development. This ensures consistency and efficiency across the extensive range of control systems involved, enabling the PCS to manage the highly complex ITER environment effectively.

These features underscore the unprecedented complexity of the ITER PCS design and its critical role in both normal and exceptional plasma control operations, ensuring the system's readiness for the fusion challenges, by anticipating the implementation of necessary control functions in response to ITER pulse demands.

2.2. PCS staged approach and functional breakdown

The PCS design process follows a staged development approach [1] which is aligned with the ITER Research Plan (IRP) [9]. The latter has been updated from the previous 2016 Baseline through 2023 and 2024 in response to a re-baselining of the ITER Project imposed by the Covid Pandemic and technical challenges faced during machine assembly [10]. This approach allows for the gradual increase in both the complexity and capability of hardware and software, step by step expanding the system's operational range. It also ensures proper validation of plant and plasma models before transitioning to full-performance operations. Consequently, the PCS design strategy has been made configurable, extendable, and flexible, allowing for tuning and optimization.

- The ITER PCS is being designed through a system engineering, staged development process, with the same development steps repeated at each stage.
- The design for the next operational stage is conducted in parallel with the implementation, verification and validation (V&V), commissioning, and operation of the previous stage.

Currently the PCS development is approximately halfway through the first stage, Fig. 1, which corresponds to the Start of Research Operations (SRO) phase under the new baseline [10]. In addition, some functions have been implemented within the RTF for initial testing [8].

In view of SRO, the PCS design team has made significant progress on the control functions [1] listed below, following the system engineering approach briefly described in the next section.

1. Magnetic control (coil currents, plasma shape and position control, vertical stability [11], error field control [12–14], etc.)
2. Kinetic control (plasma fueling [15], auxiliary heating and profile control)
3. Instability control (control of [Neoclassical] Tearing Modes ([N]TM))
4. First Wall Heat Load and Edge-Localized-Mode control [16,17]
5. Wall conditioning
6. Exception Handling and Actuator Management [18]
7. Disruption prevention and avoidance

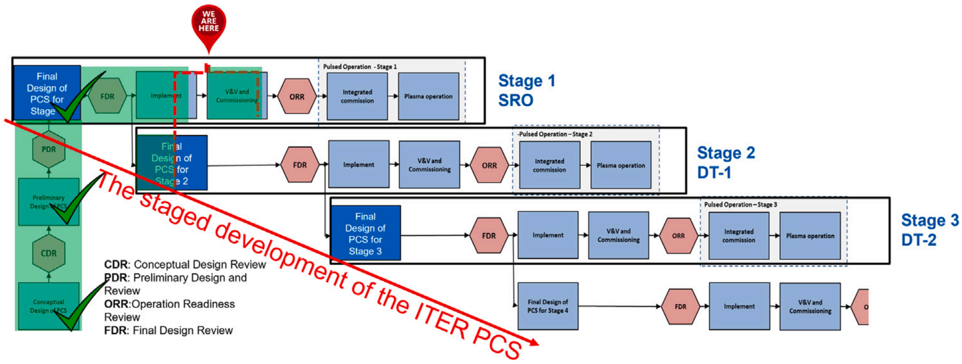

Fig. 1. PCS staged development approach [1]: current status.

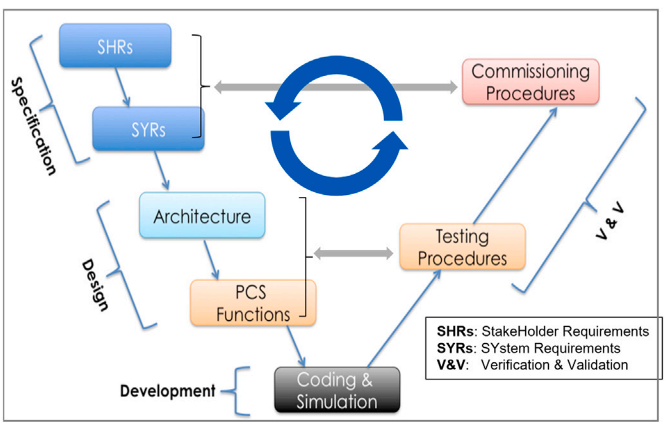

Fig. 2. V diagram of the system engineering approach.

2.3. Summary of system engineering approach for PCS design

In this section, we briefly revisit the system engineering approach adopted for the systematic design of the complex ITER PCS. For further details, readers are referred to [1].

To ensure a structured development process for the hundreds of control functions within the PCS, a systematic methodology is applied, typically involving three key features:

- Clear definition of system boundaries and scopes.
- Specification of detailed functional and interface requirements, including handling of exceptions.
- Capability to model and simulate all system behaviors, including exceptions, to verify and validate that they meet the defined requirements through testing.

We have employed the V-diagram of the system engineering approach [1] ensuring that our design process follows these steps in a rigorous and sequential manner. This procedure follows a V-shaped model, Fig. 2, as each step on the testing and validation branch (right branch) directly corresponds to and verifies the related stages of the specification and design process (left branch). This approach allows us to identify any potential errors in the design and, through iterative refinement, continuously improve the system's design integrity.

Two key tools support this design framework: the PCS Database (PCSDB) and the PCS Simulation Platform (PCSSP), which play essential roles in managing data and simulating system behavior. Further details on these tools are provided in the following sections.

2.3.1. PCSDB

The PCS system engineering DataBase [19] grants efficient traceability and justification of design choices and requirements while facilitating collaboration across large teams and supporting long-term maintenance. The PCSDB autonomously records a vast array of artifacts from each design step in the V-diagram, Fig. 2, ensuring both the performance of individual PCS functions and the overall system.

As illustrated in Fig. 3, the architecture [20] captures all PCS functional blocks recorded in the PCSDB. Each functional block is linked to multiple elements corresponding to various stages of the V-diagram, such as system requirements, performance metrics, test cases, and assessment results. Each functional block also has a one-to-one relationship with its counterpart in the PCSSP (at the "Coding & Simulation" step). The simulation assessments are autonomously recorded and cross-referenced with performance requirements in the PCSDB, reinforcing traceability and validation throughout the design process. Notice that at this stage, only the functional performance of the blocks within the test cases is evaluated through simulation. This assessment does not involve any hardware-related evaluation.

It is important to note that models, representing diagnostics, actuators plant and plasma, while they are themselves not PCS functional blocks, play a key role in assessing PCS functions. The models are thus designed in accordance with each step of the V-diagram and are recorded in the PCSDB in a systematic manner.

2.3.2. PCSSP

The ITER PCS simulation platform [7,8] allows us to assess the performance of the designed PCS in a simulation environment, ensuring all functions meet their specified requirements. The Matlab/Simulink environment has been chosen to develop PCSSP due to several benefits, among which there are the following:

- It enables standardization across all components within the control system.
- It provides the capabilities to plug-in/out the PCSSP to other modules, simplifying integration with other simulators.
- It particularly facilitates automatic code generation, allowing direct embedding into the ITER RTF [21].

Starting from 2024, a new version of the PCSSP based on object-oriented programming has been released, offering a systematic and autonomous methods for initiation, setup, simulation, and testing for each object. Fig. 4 depicts a general PCSSP object, defined by the PCSSP module class, which applies uniformly to all functional blocks. Each module in this class (green block) is attached to its own workspace, known as simulink data dictionary (sldd), allowing for stand-alone operation and testing. The top-level model acts as a wrapper to integrate multiple modules. The general methods of the class are autonomously applied to both individual modules and to the top model, ensuring seamless, self-driven execution across the system.

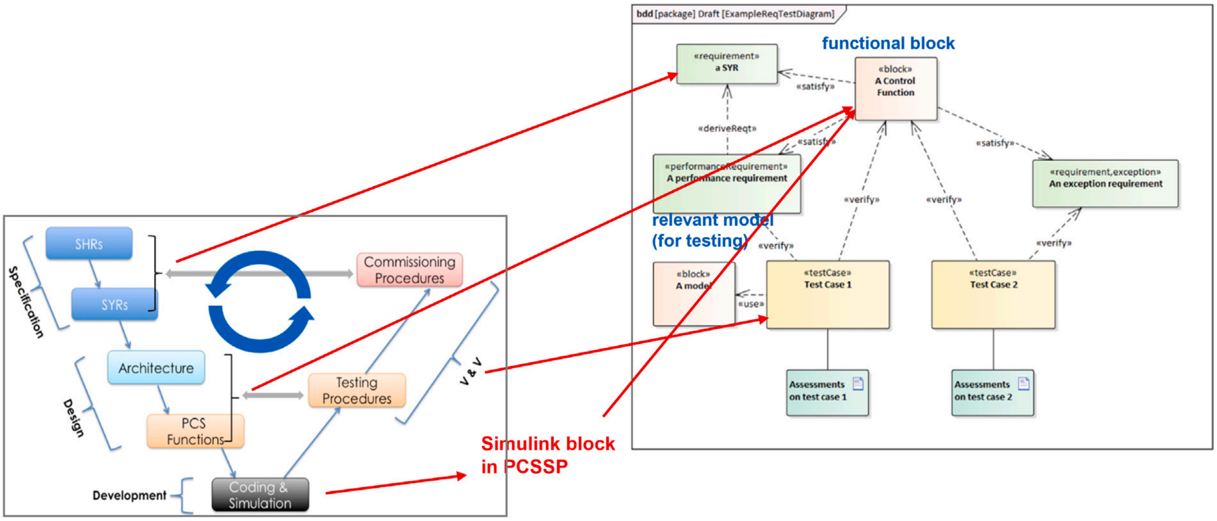

Fig. 3. Example of a functional block in the PCSDB.

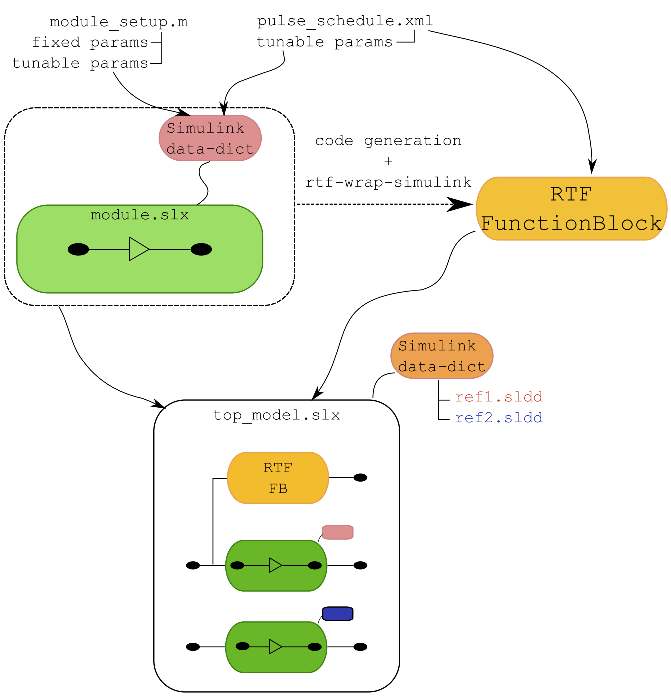

Fig. 4. PCSSP oriented program.
Each functional block in the PCS is implemented as a simulink model object *module.slx* which is associated with its own local workspace called *Simulink data − dict* (e.g. ref1.sldd, ref2.sldd). The *top_model.slx* can include multiple child modules. Similarly the *Simulink data − dict* of the *top_model* includes .sldd of the module children. Code-generation from both individual modules and the *top_model* is automatic from Simulink model, and readily integrable into the ITER RTF.

3. Demonstration: ECH control for multiple control tasks

3.1. Upgraded ECH

As an illustration, this section will focus on the Electron Cyclotron Heating system, one of the primary heating and current drive systems available during ITER's first plasma operation phase (SRO). In the new ITER baseline [10], the ECH system has gained even greater significance, with an upgrade doubling its power capacity from 20 MW

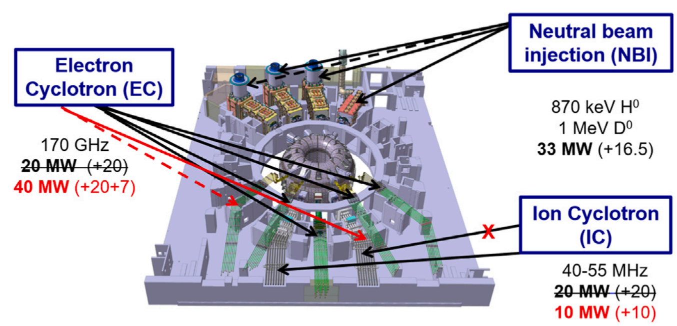

Fig. 5. Upgraded ITER heating and current drive systems. The capacities of the ECH and the Ion Cyclotron systems are highlighted in red.

to 40 MW in SRO, further up to 67 MW for the DT campaigns, see Fig. 5. The increase of ECH power is in place to mitigate the risks to the IRP from changing the first wall material from beryllium to tungsten, and to enable the achievement of $Q \geq 10$ with 500 MW fusion power within a reduced neutron fluence (see [10,22]).

The ECH system will serve as the primary auxiliary heating source during the SRO phase. It will perform several critical functions, including:

- Assisting plasma breakdown through EC pre-ionization
- Supporting burn-through
- Heating L-mode scenarios
- Heating H-mode discharges
- Tearing mode control
- Enabling EC wall conditioning

Due to the system's wide range of applications, an Actuator Manager (AM) is required to optimally allocate the ECH resource across these various control tasks. In recent years, extensive research on AM has been conducted, with several studies being applied to ITER-like scenarios ([18,23] and references therein).

As depicted in Fig. 6 (left), the ITER ECH system for SRO consists of one Equatorial Launcher (EL) with three steering mirrors and three Upper Launchers (UL) with two mirrors each. The EL primarily deposits power near the plasma center, making it ideal for core heating. In contrast, the UL can direct power off-axis which is more appropriate for instability control. Fig. 6 (right) illustrates the ITER cross-section along with a typical baseline plasma magnetic equilibrium, indicating

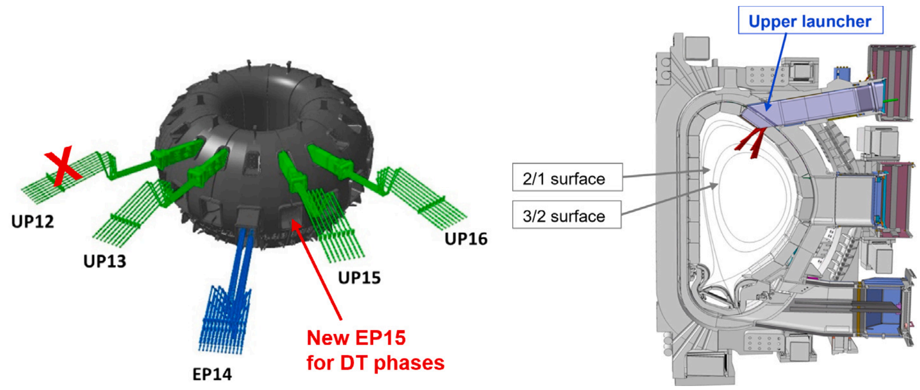

Fig. 6. ECH 3D configuration with equatorial port (EP) and upper ports (UP), and 2D cross-section with tearing mode surfaces.

the locations of[N]TM surfaces. The [N]TM [24] is one of the principal instabilities which degrades plasma performance and potentially triggers disruptions that could damage the machine. To mitigate this risk, we must control the UL to target power onto these [N]TM surfaces, stabilizing or suppressing the modes and preventing disruptions.

3.2. Control perspective on ECH

The control of the ECH system is considerably more complex than simply toggling the power on or off. The ECH system comprises numerous components, each with distinct control requirements, including the high-voltage power supply (HVPS), gyrotrons, launchers, mirrors, and transmission lines. While some components can be controlled independently, others must be coupled due to specific constraints, such as gyrotrons sharing the same HVPS, or multiple beams directed onto the same mirrors (details in Section 3.3).

The upgrade of the ECH system for SRO affects not only the total power – from 20 MW to 40 MW by increasing from 24 to 48 gyrotrons – but also the system configuration. In the 2016 Baseline, a gyrotron beam, during a single pulse, could be switched in real-time between two different launchers – either to EL or to one of four ULs – and several beams could also be switched between two mirrors within an UL. However, in the re-baseline, with increased power capacity, there is no longer a need to reallocate power between launchers or between mirrors on the same UL. Now, each gyrotron beam is routed to a single mirror on a single launcher. Therefore, the system configuration has been changed:

- Remove capacity (and need) to switch gyrotrons from equatorial to upper launcher and vice-versa.
- Remove capacity (and need) to switch gyrotrons between mirrors on the Upper Steering Mirror (USM) and Lower Steering Mirror (LSM).

This simplification is highly beneficial from a control perspective, since it reduces operational complexity. Specifically, the 3 s delay previously required to switch power between mirrors has been eliminated, streamlining control operations and enhancing system responsiveness.

3.3. PCS-ECH interface

Briefly speaking, the ECH system consists of multiple gyrotrons that direct beams to a mirror either on a EL or on an UL. Each launcher is equipped with several movable mirrors, allowing real-time steering of the beams to different plasma regions. This facilitates heating, current drive, and the control of instabilities such as [N]TMs and sawtooth oscillations.

In the SRO phase, there is one EL with three mirrors and three ULs, each with two mirrors, for a total of nine mirrors. As outlined in Section 3.2, the complexity of controlling the ECH system necessitates effective actuator management strategies to optimize its use for multiple simultaneous control tasks. These strategies must be applied both to the PCS and the ECH system, managed locally by the Electron Cyclotron Plant Controller (ECPC) [25]. Since they perform distinct functions, a well-defined interface between the ITER PCS and the ECH system is essential to prevent ambiguity.

The PCS-ECH interface, established before the new baseline, is designed to be simple and flexible, allowing easy adaptation to future system configuration changes on both the PCS and ECH sides. The initial interface between the PCS and ECH, as described in [26], is further refined here with the concepts of Launch Point and EC Actuator Unit.

3.3.1. Launch point approach

The proposed PCS-ECH system interface positions the boundary at the beam's Launch Point (LP), defined as the point on the final mirror of a launcher where the beam is injected into the plasma (the end point of each transmission line). In other words, a LP is identified by the combination of a gyrotron and an associated final mirror. Under the re-baseline, each gyrotron is connected to one mirror, thus defined by only one LP. It is also important to note that each mirror hosts multiple LPs, collectively determining the direction of those beams. Each LP is characterized by distinct beam properties, such as:

- Power
- Beam direction (determined by the mirror angle and beam path)
- Power modulation (frequency, phase, duty-cycle)
- Polarization vector (complex electric field vector, influenced by the beam's incident angle relative to the plasma last closed surface or separatrix)
- Beam properties at the LP (e.g. width, size, ellipticity)

Additionally, each LP has derived properties representing the effect on the plasma, including power deposition profiles, absorbed power, and current drive. These parameters depend on plasma conditions, such as the estimated power deposition radius in ρ coordinate (normalized radial coordinate), polarization, absorbed and reflected power, etc.

Since multiple beams are launched from a single mirror but follow distinct trajectories, each beam associated with the same mirror exhibits a slightly different beam direction, particularly for the beams on UL. The beam tracing code, e.g. TORBEAM [27], must be performed for each LP to evaluate the beam's effect. Since beam tracing depends on plasma states, it is logical to implement this function within the PCS.

The PCS receives LP-beam properties from the ECPC (current states and capacities) and, in return, sends commands to control the LPs (e.g., power, modulation, polarization) and mirror angles. While these individual beam directions are important for accurate computation in

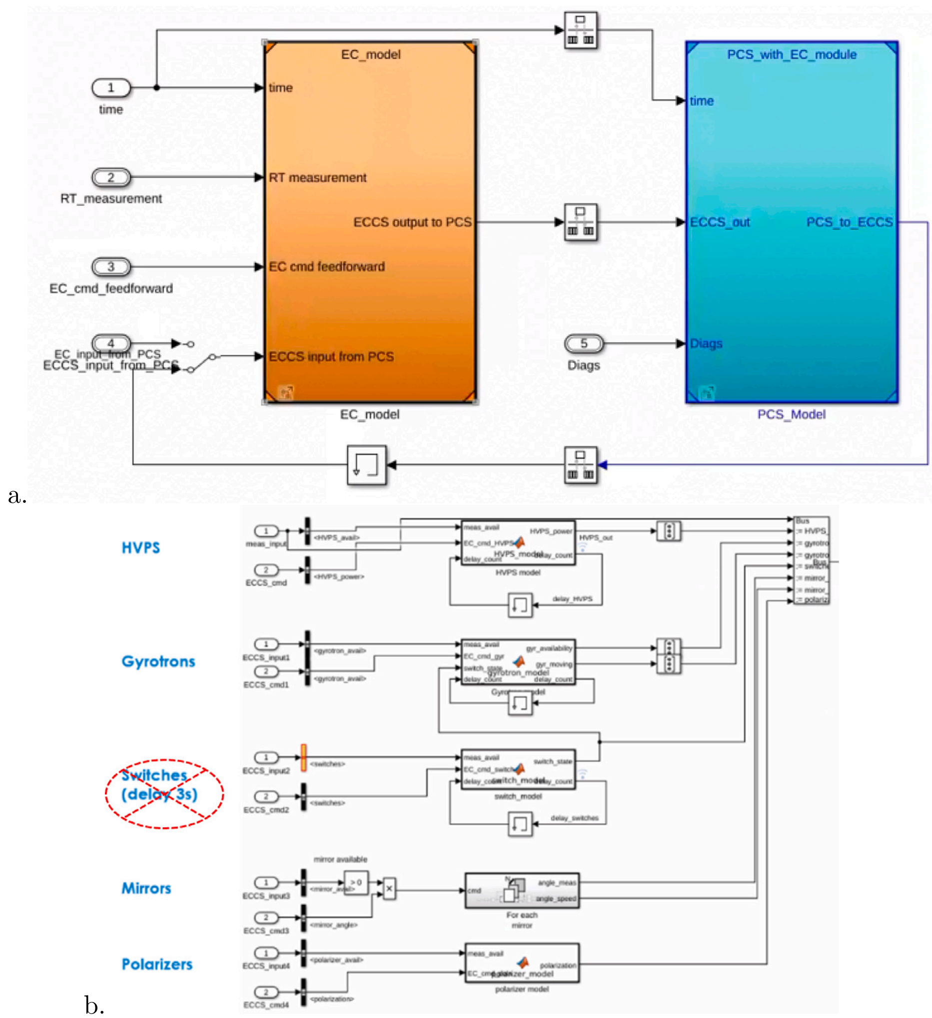

Fig. 7. ECH actuator/plant model in PCSSP: a. closed-loop, b. EC model components under the orange block.

e.g. TORBEAM code, the PCS cannot to control each beam independently. Instead, it regulates the average direction of all beams on a given mirror by adjusting the mirror angle.

There are two key technical constraints that should be taken into account for LP and mirror control:

- Power control constraint: LPs connected to gyrotron pairs (i.e., gyrotrons sharing the same HVPS) deliver the same power when both are active. Thus, to avoid different power commands confusing the local control system, the PCS must provide the same power command to these coupled LPs.
- Mirror angle control constraint: LPs on the same mirror have dependent beam direction derived from the same mirror angle. Therefore, the PCS can only command one mirror angle, not individual beam directions for each LP.

3.3.2. *Electron cyclotron actuator unit*

Given the constraints introduced in Section 3.3.1, it is preferable to assign LPs on the same mirror to the same control task, aiming to deposit the beams in the same or nearby plasma regions, thus avoiding control conflicts. This grouping of LPs forms an EC Heating Actuator Unit (EAU). In the upgraded ECH system, there are nine EAUs — three groups of 8 LPs for the three EL mirrors and six groups of 4 LPs on six UL mirrors.

This decision, however, is made by the PCS, at the AM level. As a consequence, the AM treats each EAU as a single actuator, with combined power and capacity from its LPs. The configuration of LPs within each EAU is tunable and can be readily adapted to future upgrades of the ECH system beyond SRO. Commands for power and mirror angle are then distributed to the corresponding LPs and mirrors, and subsequently relayed to the ECPC.

3.4. *EC actuator plant model design*

Since the EC plant is not a PCS subsystem, but is a plant system that plays the role of a (rather complex) actuator for the PCS, an EC plant simulation model is needed to assess the closed loop performance of the PCS control functions. The design procedure of this surrogate model for the EC plant consistently follows the V-diagram methodology. Here, we present the development, implementation and testing of the EC model within the PCSSP.

As shown in Fig. 7, a detailed representation of the EC plant system architecture, simplified models – including separate functional blocks for HVPS, gyrotrons, mirrors, and polarizers – has been designed and implemented in the PCSSP. Once detailed models are available for each block represented in Fig. 7, one can easily substitute to obtain more accurate results. The switch system can now be easily removed from the simulation with the new ECH configuration. However, switches between the gyrotrons and dummy loads remain. Therefore, the switch element will prove valuable for simulating the commissioning and re-commissioning processes of the gyrotrons with the dummy load.

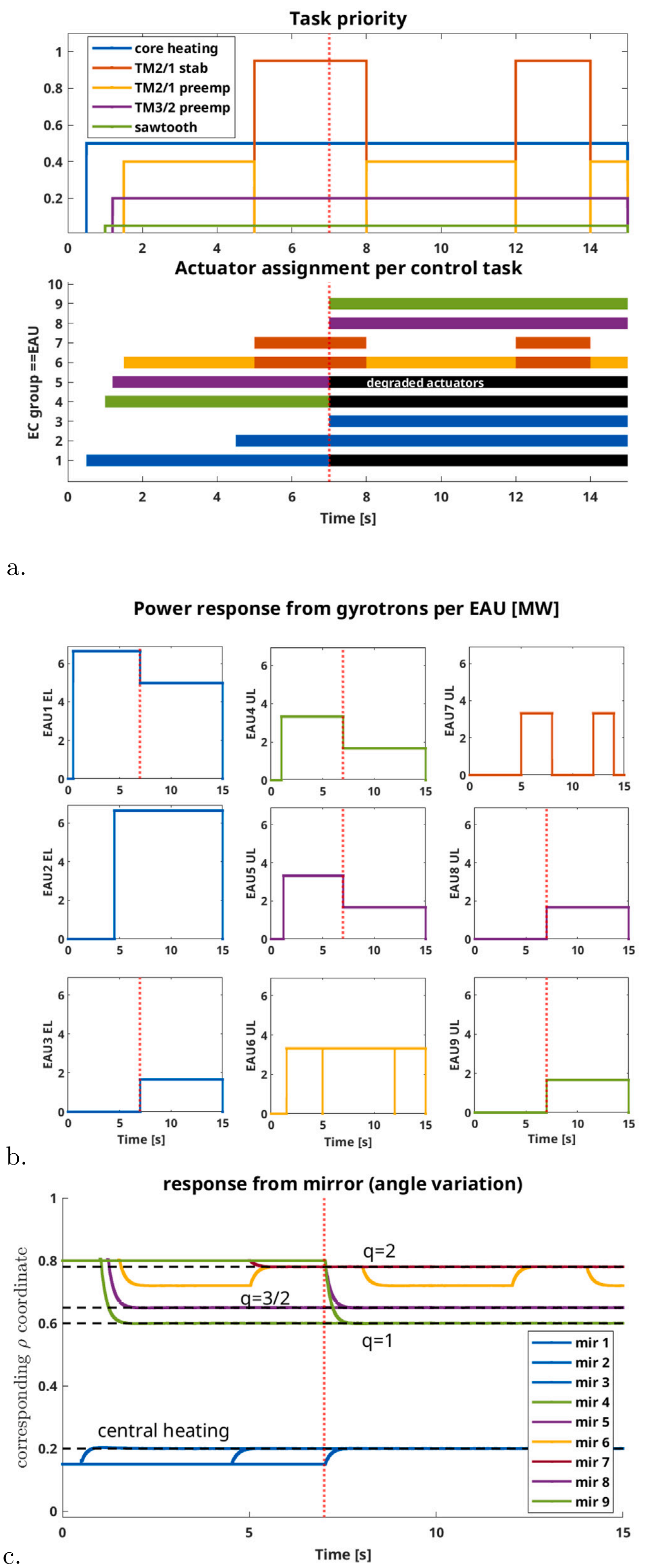

Fig. 8. ECH control for multitasks with actuator sharing and actuator failure event handling.

The model has been designed to be both generic and adaptable, facilitating seamless adjustments to changes in system configuration, such as the upgrades within the re-baseline.

3.5. Simulation results of ECH closed-loop control

For demonstration, corresponding to the testing step in the V-diagram in Fig. 2, this section presents one of hundreds of use-cases we have developed so far. A simulation is deployed to demonstrate a complex ECH control scenario, where multiple control objectives – such as core heating, sawtooth control, and [N]TM control – must be achieved simultaneously within the same plasma discharge.

Consider the scenario with nine groups of EC LPs, referred to as EAUs in Section 3.3, corresponding to beams directed at nine mirrors — three on the EL and six on the UL. These EAU actuators are responsible for fulfilling several control tasks, including central heating, sawtooth control, the preemption and stabilization of [N]TMs. All of them demand EC power, however each requires that power be deposited at different locations inside the plasma. The tasks are assigned with time-varying priorities, reflecting their importance, and these priorities can change dynamically based on the plasma situation, see Fig. 8.a. For example, [N]TM stabilization becomes the highest priority task only when a [N]TM is detected.

In the absence of a specific [N]TM model, dummy feedforward signals are generated to represent the power requests for these tasks. In addition, surrogate models are used for Pulse Supervisory Control (PSC) and the AM to coordinate the EAUs and control tasks. Based on the task priorities, the AM allocates the available EAUs accordingly (color-coded for clarity). For instance, EAUs 1, 2, and 3 on the EL are allocated for core heating, EAU 4 on the UL for sawtooth control, and the remaining EAUs on the UL for [N]TM preemption and stabilization.

Fig. 8.b illustrates the power response from the EC plant model across the nine EC groups. It shows the total power delivered by each EAU (with colors corresponding to their assigned tasks). At 7 s, a simulated failure of several gyrotrons results in degraded power capacity for some EAUs, meaning the current allocated EAU actuators can no longer fully satisfy the power demands of several tasks. The AM compensates for the loss by reallocating redundant sources — such as activating EAU 3 to support core heating, and engaging EAUs 8 and 9 for sawtooth and [N]TM preemption tasks in response to the event.

Fig. 8.c demonstrates the response of the ECH system through mirror movements, simulated with a simplified control-oriented model [28] which mimics the mirror dynamics, featuring a nominal rotation speed of approximately 5 degrees per second [28,29]. The three mirrors on the EL (blue lines) gradually reposition the beams toward the plasma center for core heating. The mirrors on the ULs rotate accordingly, steering the beams to the required locations to fulfill their assigned tasks, such as sawtooth control (at q=1) and [N]TM control (q=2 and q=3/2). At the moment of gyrotron failure, $t = 7$ s (vertical red-dot line), mirrors 3, 8, 9, corresponding to EAU 3, 8, 9 respectively, are activated and moved to the positions required by their tasks.

It is worth noting that, re-assigning gyrotrons to a different control task might require adjusting the polarization and the mirror position, that may require a significant amount of time (e.g. several seconds). These information will have to be taken into account by the AM to optimize the allocation.

Thanks to the system upgrade in the re-baseline, there is now sufficient power available on both the EL and UL, eliminating the previous 3 s delay required to switch power between mirrors. This enables a much faster control response to events, significantly improving control performance, a level of efficiency that was not achievable in the past.

3.6. Simulation results of event monitors

While the AM and controllers are responsible for coordinating and executing various control tasks, the PSC plays a critical role in EH [30], one of the key features of the PCS, see Section 2.1. Each control task – such as those outlined in Section 2.2 – must define relevant events that may be considered exceptions. Some of these events can be managed locally within the control functions, while others must be escalated to

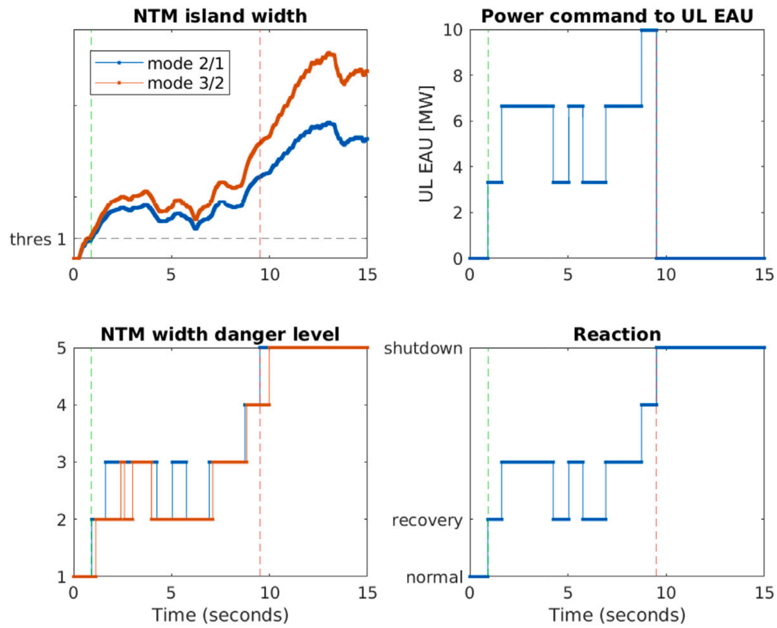

Fig. 9. [N]TM event monitor, serving as input of event handling in PSC.
Different thresholds are predefined per mode, however, for simplicity, only "thres 1" is illustrated in the top-left panel. The vertical red dashed line marks the onset of the shutdown phase, which occurs when the Mode 2/1 danger level reaches its maximum.

the PSC for general handling. In the context of ECH and [N]TM control, we illustrate the [N]TM Event Monitor, which serves as a precursor for PSC intervention.

In this example, we consider two different [N]TMs: 2/1, and 3/2. Again, since at the moment there is no [N]TM model available in the PCSSP, artificially generated signals are used to represent the input for the island width of each mode, Fig. 9 top-left. Based on these inputs, the event monitor can classify different levels of danger for each mode by setting different predefined thresholds per mode, Fig. 9 bottom-left. Then the proposed reactions based on the detected danger level is shown in Fig. 9 bottom-right. For example, at danger level 2, corresponding to the first threshold of mode 2/1, around $t = 0.9s$, the PSC would activate the [N]TM control task, which asks to steer the EC UL beams to the locations where the [N]TMs are detected, in an attempt to stabilize them, Fig. 9 top-right. However, since there is no feedback loop in this scenario, the EC beams have no effect on the [N]TMs, and the modes continue to grow (it is important to note that this illustration emphasizes the functionality of the event monitor, rather than the control effectiveness). As the threat escalates, the power requests for the beams increase accordingly. Ultimately, when the danger of mode 2/1 reaches its maximum threshold (level 5) at around $t = 9.5s$ (vertical red dashed line), the final reaction is to shut down the discharge to prevent damage to the machine. This illustrates the interaction between EH, AM, and controllers in a complex control environment, ensuring that escalating risks are met with timely and appropriate responses.

4. Conclusion

The design of the ITER Plasma Control System for the early operation phase has made significant progress, demonstrating the robustness and efficiency of the system engineering approach employed. The systematic design methodology, based on the V-diagram, integrates two critical tools – the PCS Simulation Platform and the PCS Database – which enable the structured development, validation, and maintenance of the multiple control functions required for ITER.

The simulation of a complex use case for Electron Cyclotron Heating control, involving multiple tasks such as core heating and tearing mode control, demonstrates the effectiveness of this approach. By efficiently managing ECH actuators and handling exception events, this use case illustrates how the PCS coordinates critical functions while maintaining adaptability and reliability. Future work will focus on integrating beam tracing code and control-oriented models for [N]TM control. This systematic engineering process ensures that the ITER PCS will meet the demanding requirements of the early plasma operation phase, setting the stage for future expansions and upgrades.

CRediT authorship contribution statement

A.T. Vu: Writing – original draft. **P.C. de Vries:** Writing – review & editing. **G. Carannante:** Validation. **I.S. Carvalho:** Writing – review & editing. **M. Cinque:** Validation. **I. Gomez:** Validation. **O. Kudlacek:** Validation. **M. Mattei:** Writing – review & editing. **Ph. Moreau:** Validation. **R. Nouailletas:** Validation. **L. Pangione:** Writing – review & editing. **F. Pesamosca:** Writing – review & editing. **L. Piron:** Writing – review & editing. **A. Pironti:** Validation. **R.A. Pitts:** Validation. **G. Raupp:** Validation. **T. Ravensbergen:** Writing – review & editing. **M. Reich:** Validation. **S. Rosiello:** Validation. **G. De Tommasi:** Writing – review & editing. **W. Treutterer:** Validation. **D. Weldon:** Validation. **D. Valcarcel:** Validation. **L. Zabeo:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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