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Systematic commissioning of the Plasma Control System for ITER Start of Research Operation

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ABSTRACT

The design of any system is incomplete without a clear strategy for deployment. Accordingly, as part of the systematic development of the ITER Plasma Control System (PCS), a comprehensive commissioning plan has been created to rigorously verify its functionality. Commissioning is a complex and high-stakes task that must be executed with precision to minimize potential risks. Any issues at this stage could lead to significant loss of operational time or, in the worst case, a disruption of the plasma discharge with the potential to damage the device. The challenge of developing this plan is compounded by the wide range of PCS functions requiring validation, which increases the risk of overlooking critical tests. A substantial portion of commissioning will have to take place during actual ITER plasma operation, adding further complexity. These factors make it imperative to establish a complete, systematic, and efficient plan. This paper details the development of that plan and demonstrates how it ensures thorough validation while aligning closely with ITER's broader strategy for its initial operational phase, the Start of Research Operation (SRO).

1. Introduction

The ITER Plasma Control System (PCS) is the central control system responsible for operating the tokamak and controlling the plasma within it [1–4]. A systematic approach is being applied to design and deploy this system at ITER [5]. This system engineering approach enables proper management of the integrated complexities of the system and its many components [6,7]. Importantly, it tracks the relationships between the design justifications, design requirements determined at the start of the design process, and the implementation choices, design verification, validation, and eventual commissioning which may take place years later. Thus, commissioning is not a set of ad-hoc tests that come to mind when the system is first switched on; rather, the commissioning plan can be systematically derived from the design justification, requirements, and models determined during its design [5]. The design of any system is not complete without a viable and comprehensive plan for its commissioning, ensuring it can be deployed with minimized risk. For the PCS of any tokamak, commissioning is complex as it is integrated with the deployment of the tokamak and many of its auxiliary systems. Many of the PCS functions can only be commissioned with plasma, while plasma operation itself requires a functioning PCS. Hence, it is evident that a careful PCS commissioning strategy needs to be developed to minimize any risks related to control errors.

The ITER PCS is designed and deployed following the staged approach of the ITER development [5]. The new ITER baseline and ITER Research Plan (IRP) will initiate first tokamak operation during the so-called Start of Research Operation (SRO) campaign [8–10]. During SRO, after a period of Integrated Commissioning (IC), first ITER Plasma Operation (PO) will be achieved after which the operation is expanded to L-mode plasmas with a plasma current up to 15MA, and higher-performance H-mode discharges with plasma currents up to

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7.5MA, all solely heated by means of high-power Radiofrequency heating. This paper will describe how the ITER PCS can be commissioned for SRO, starting with a brief introduction of the fundamentals of commissioning in relationship to a system design Section 2. This also includes a few definitions that are specific to ITER operation. Section 3 will then detail the systematic method applied to derive the necessary commissioning tests that collectively form the PCS commissioning plan. It will show that the PCS design description and its commissioning plan are integrally linked, and any good design also requires a viable commissioning strategy. The details of the PCS commissioning plan for the SRO campaign are outlined in Section 4. The strength of the method is that one obtains a systematic and analytical plan on which various checks and analysis can be applied, for which results will be shown in Section 5. The paper concludes with a summary of the main findings in Section 6.

2. Definition of commissioning

Commissioning is the process that ensures a system, and all its components are installed, tested, operated, and maintained in accordance with stakeholder requirements. Within the systems engineering framework applied to the design of the ITER PCS [5], the commissioning plan is directly linked to the design description, which includes stakeholder requirements, component specifications, and the extensive simulation tests and calculations used to assess design viability. Commissioning serves two complementary purposes: verification and validation. Verification evaluates whether each component of the system has been implemented correctly and whether all specified design artefacts—such as sub-functions, support functions, and exceptions—are present and properly executed. In this way, verification demonstrates that the system is complete and that the design contains all required elements, confirming that the system has been designed correctly [11]. Verification necessarily precedes validation. Validation, by contrast, determines whether the system performs as intended in practice, confirming that the system not only meets specifications but also fulfils its intended purpose [11].

Commissioning is the process of evaluating whether a system fulfils its high-level stakeholder requirements. This evaluation relies on the systematic testing of lower-level system requirements derived from those top-level objectives. For the ITER PCS, this means demonstrating that each function operates within its specified performance parameters and is capable of correctly controlling the planned ITER operation scenarios for a given operational stage. While commissioning is often treated simply as proof that a system "works as intended", this alone is insufficient. Testing limited to specific operation scenarios cannot guarantee reliable performance across the full range of conditions envisioned in the design. Effective commissioning must therefore go beyond confirmation of functionality: it should seek to explain system behaviour, validate the underlying design models, and ensure robustness across diverse operational contexts. Essentially its behaviour extrapolation must be plausibly correct. The model-based systems engineering approach adopted for the ITER PCS places design models at the core of the commissioning process, ensuring that both system behaviour and design intent are rigorously validated [5,12,13].

Commissioning is a risk mitigation strategy designed to detect and correct faults by systematically evaluating a system, preventing early that minor issues escalate into serious problems when the operational space is expanded. While device-damaging risks are often the most immediate concern, in the context of plasma control, failures can have critical operational consequences. For example, loss of vertical stability control may trigger a Vertical Displacement Event (VDE), or incorrect regulation of magnet currents could impose excessive forces on the tokamak structure. These examples illustrate high-level risks, and the commissioning plan must address them through a stepwise approach to critical operational limits. Limit prevention and avoidance mechanisms implemented by the PCS should ideally be tested well within safe margins, far from the actual operational thresholds.

Beyond the risk of plant damage, commissioning also addresses the potential for significant operational downtime. An efficient commissioning plan minimizes redundant testing by establishing a clear logical sequence and ensuring that test results are interpretable and generalizable to other operational scenarios. A critical aspect of this process is the validation of the models assumed during PCS design. This includes models of plasma and tokamak behaviour, as well as actuator and sensor (diagnostic) systems. Key questions include: Do diagnostics (i.e. sensors) and actuators communicate correctly with the PCS? Does the plasma respond as predicted to the PCS commands? The PCS must accommodate a range of expected behaviours, allowing its control to be tuned and optimized efficiently. Effective testing, combined with targeted simulations, accelerates this optimization process, particularly for complex integrated control schemes such as those required for ITER magnetic control [14]. Additional risks can emerge from untested combinations of integrated system behaviours. To mitigate this, the PCS should be integrated with plant systems step by step, and its functionalities should be gradually brought online, reducing the likelihood of unexpected interactions escalating into operational problems.

The ITER PCS is designed to be highly configurable, allowing the system to be tuned and optimized as operation progresses. But it is still possible that a major non-conformity arises when test results reveal that plant behaviour falls outside the range anticipated during PCS design, and the controller cannot be appropriately adjusted. Resolving such discrepancies would require redesigning the control functions and, crucially, reimplementing the real-time code. During ITER operation, ad-hoc code changes are highly undesirable, as they carry the risk of introducing new faults and would necessitate careful recommissioning, causing significant operational delays. This highlights the critical importance of thorough verification and validation of the PCS implementation to ensure that no software bugs compromise deployment or system performance.

Based on the considerations outlined above, all commissioning tests can be systematically categorized, as shown in Table 1. This structured categorization supports the development of a comprehensive PCS commissioning plan. The systems engineering and model-based design approach allows each commissioning test to be directly linked to features identified during PCS design. These features include specific PCS function blocks and their input/output ports, associated exceptions, simulation-based design assessments, relevant performance requirements, and the assumed models of plasma and auxiliary system behaviour. At the highest level, they are also tied to the overarching PCS requirements, defined by the proposed ITER operation scenarios. This encompasses the expected ITER pulses, including plasma current ramp-up, plasma shape, entry into H-mode, and applied heating levels.

The current focus lies on the first deployment of PCS functionality for SRO. At later stages, the restart of ITER operation will require retesting or recommissioning of the PCS. The recommissioning tests for the restart of ITER operation will likely be a smaller subset of those listed in the first deployment plan.

3. Method to develop the PCS commissioning plan

Building on the principles described in the previous section, a structured workflow has been established to systematically develop the

Table 1
Categories that can be assigned to each commissioning task.

A	Verifying whether a system component or function is available
B	Validating the component's function works without basic errors
C	Verifying and Validating the interface of the component with other systems
D	Validating that the system or function performs according to the requirements
E	Validating models of plant behaviour, as assumed during the design
F	Stepwise system integration and expansion of the system operation range

PCS commissioning plan. This plan defines the tasks to be performed and their execution sequence. The overall PCS commissioning plan comprises numerous tasks, each representing a specific test. These tasks, referred to as commissioning use-cases, can be associated with one or more categories. Ideally, commissioning use-cases should be identified during the design phase, while knowledge of the intended use and design assumptions is current, rather than by operators after design completion. The commissioning categories listed in Table 1 provide guidance on the expected types of use-cases, ensuring comprehensive coverage across all aspects of the system. Additionally, the commissioning use-case template, shown in Table 2, standardizes documentation and ensures that each use-case contains all relevant information.

Commissioning tests should be authored by the experts that design of the respective PCS functions. With a large design team that may change over the years, it is important to record who authored the information. Identifying the author facilitates follow-up for questions, which is often necessary. The description and scope define the purpose of the test and its broader context, such as part of IC of magnet control, interface testing, integrated control for plasma initiation, or high-performance plasma operation. Scope can often be further specified by referencing particular ITER operation scenarios. The method statement is a critical and often challenging section to complete. It details how the test will have to be conducted, typically in a series of steps, and shall consider the feasibility of the test, particularly for complex plasma operation scenarios. Preconditions indicate the prerequisites required before testing, such as pulse initiation, successful plasma initiation, availability of diagnostics and actuators, other functions being successfully commissioned, or the ability to control plasma shape. The minimal and success guarantees define the implications of test outcomes. Failure of a test may prevent progression—for example, failing a vertical stability control test could preclude operations with elongated plasmas. Conversely, successful validation of a model instils confidence that the control function will perform correctly across other, future operational scenarios. This information can also be used to determine the risk taken when the tests proposed by the commissioning use-case are not carried out. While at best all tests proposed by this plan are to be executed, practical considerations of efficiency and time often require prioritizing and omitting certain tests. There are also several generic commissioning use-cases, that apply to most functions. These are not specific to one function, but tests that need to be done generally, such as verification of the input and output ports of FB or validating performance requirements. Generic commissioning use-cases also provide a further systematism to the plan.

It should be clear that a collection of use-cases authored independently by multiple contributors does not automatically form a consistent or coherent commissioning plan. As described in ref. [5], the development of the PCS commissioning plan—an integral part of the PCS design—is an integrating task. This means that, during design-integration meetings, all newly provided commissioning information is reviewed to ensure consistency, identify gaps, and resolve issues related to tests that involve or affect multiple functions. These reviews are essential for improving the efficiency of the overall plan. The integration task also manages the consolidation of use-cases into coherent procedures, grouping related tests logically and ensuring that the resulting procedures reflect a viable and coordinated execution sequence. Furthermore, it checks alignment with the IRP and verifies the feasibility of the operation scenarios required for specific tests. Through this iterative process of feedback, verification, and refinement, the commissioning plan is continuously optimized as the PCS design evolves.

Table 2
Information blocks that make up a commissioning use-case.

Name/Title	Clear identifiable name for the test
Author	Person who wrote the commissioning use-case
Description	Describes what the test is about
Scope	Provide the scope under which the test is done
Scenario	If possible, identify the ITER operation scenario for the test
Preconditions	Lists the preconditions to be met before doing the test
Method statement	Describes how the test is done
Minimal & success guarantees	What implies a successful test and the risk if unsuccessful.
Functional blocks (FB)	One or more PCS functions to which the test applies
Design models	If any list relevant models assumed during the design

The first coordination to develop a coherent plan starts with grouping the use-cases into procedures. The overall commissioning plan is broken down phases (SC, IC, PO), and these are broken up into procedures that logically group use-cases of a certain kind or those linked to a certain phase. Procedures help structure the many tests required, though the choice of grouping is inherently flexible. Tests can be organized by interfacing system (e.g., PCS interface with magnet power supplies or fuelling system), by PCS functional area (e.g., magnetic control, kinetic control, or disruption avoidance), or by the design team responsible for the functions. Note that each of these high-level functional areas can be broken up into several specific control functions or Functional Blocks (FB). Linking functionality to the teams with the appropriate expertise is generally more effective than strictly functional grouping. For example, vertical stability control is best grouped with the magnetic control team rather than with instability control under the broader PCS function category. It is important to recognize, however, that a perfect breakdown is rarely possible; overlaps between design tasks are inevitable. This can result in some tests being duplicated by different teams, but a lack of clarity regarding responsibility is more problematic, as it can lead to missed tests. The current approach allows for flexible reorganization of commissioning use-cases as needed, facilitating the creation of detailed, dedicated test plans in the future. It also enables comprehensive review and analysis of the plan from multiple perspectives, as will be demonstrated in Section 5.

The procedures are divided into steps that define the sequence in which the use-cases are executed. The prerequisite information included in each use-case often already implies a certain order—for example, some tests must necessarily precede others. In other cases, the sequencing is dictated by the operation scenario required for the test, such as starting with plasmas at lower current and moving to higher currents later. The choice of steps remains flexible and may reflect different organizing principles: increasing plasma current, grouping by test type (e.g., first support-function tests, then feedforward tests, followed by feedback tests), or other practical considerations. For example, the procedures to test Error Field Control have steps that grouped work on the different types of controllers the design team have proposed, while the procedure to commission ECH control groups the work into basic control of the ECH plant, basic ECH power control, and more advanced control functions related to tearing mode control by ECH. But most follow a temporal sequence of steps. Most procedures have a few steps, but more than 10 of them was found to become unpractical. The final ordering is typically refined iteratively during discussions with the design team. In addition. procedure templates can be established to provide generic steps for how tests should be conducted. These templates guide the development of commissioning use-cases. Generic commissioning procedures are detailed in [5] and will not be repeated here. Some iteration is typically required between drafting the use-cases, grouping them into procedures, and aligning them with the procedure templates. Common steps in PCS commissioning procedures include verifying the configurability of a function, checking its input and output ports, validating the design models, and assessing control performance. Adhering to these guidelines ensures that all essential tests are conducted systematically across all PCS functions.

The PCS commissioning plan must align with the overall commissioning and deployment of the ITER plant. For example, commissioning the interfaces between the PCS and its actuators requires that the actuators be ready for testing. Similarly, most PCS control function tests must be integrated with the commissioning of the corresponding actuators. Any PCS tests involving plasma discharges must use scenarios executable during the SRO campaign. In some cases, specific plasma operation scenarios are selected for specific PCS commissioning use-cases. However, demonstrating that a PCS function operates without errors under a given scenario is not always sufficient. True performance is verified when functions are pushed to their operational limits or subjected to response tests, such as gas puffs to assess fuelling response or vertical stability (VS) control interruptions to evaluate VS behaviour. Consequently, some PCS commissioning use-cases may require dedicated variants of standard operation scenarios.

Scenario variants involve significant modifications to standard operation sequences and require careful validation, often through dedicated simulations, to assess both the associated risks and its feasibility. This creates an iterative feedback loop between the development of PCS use-cases and the detailing of ITER operation scenarios for the SRO campaign. For example, compass scans are used to identify tokamak error fields by ramping down plasma density below a critical threshold to trigger error-field locked modes. The commissioning use-case for ITER error-field control requires validation of model assumptions, such as the error field, across multiple plasma currents [15]. Similarly, testing plasma vertical stability may require increasing plasma elongation. The PCS commissioning plan methodology therefore generates a list of required operation scenarios and, where necessary, defines specific scenario variants to accommodate the tests.

The PCS commissioning plan not only aligns with the overall ITER deployment but also informs specific details of the IRP [9]. It is developed using both a bottom-up perspective, focusing on individual PCS functions that require testing, and a top-down perspective, considering overall ITER deployment. The top-down approach ensures validation of stakeholder requirements against the PCS design, confirming the system's ability to control plasma operation scenarios during SRO [5].

Execution of the plan begins with validating the lowest-level requirements, progressing from testing individual functions to integrated system operation during ITER plasma campaigns. While seemingly obvious, this stepwise approach is critical for risk mitigation (Category F in Table 1). It ensures that the focus should be to execute tests as early as possible with the lowest possible risk (e.g. doing them preferably prior to PO, during IC, or at the lowest possible plasma or coil currents). This means Basic features of the functions, like debugging and feasibility of output and input ports should be tested well before the start of operations. Other interesting examples of this are testing the detection of instabilities (e.g. Neo-classical Tearing Modes (NTMs) well before such modes can be triggered naturally during an ITER discharge, or testing the avoidance of operational limits, before such limits have actually been reached. Fig. 1 summarizes the guidelines, templates, and frameworks that collectively support the systematic development of the ITER PCS commissioning plan. The process is iterative, ensuring that all expected tests for each function are captured, aligned with generic test procedures, and coordinated with the deployment of the ITER plant. Table 3 provides an overview of the main rules applied in developing the PCS commissioning plan.

The ITER PCS design follows a systems engineering approach, with all aspects of the design recorded in a dedicated database, the PCS DataBase (PCSDB) [5–7]. The PCSDB enables tracing the relationships between stakeholder requirements (e.g., ITER operation scenarios), system requirements, and the functional breakdown of the PCS. It also captures specifications for individual functions—referred to as Functional Blocks (FBs)—including input and output port descriptions, performance requirements, and exception handling.

The PCSDB further documents the many simulation tests conducted to verify that design requirements are met and, importantly, records all assumed models. These models encompass complex actuator systems with which the PCS interacts, sensor models describing expected measurement signals, and plant and plasma models predicting system response to control actions. Because model validation is central to commissioning, the PCS commissioning plan is designed to systematically test all models, ensuring that each is rigorously verified against expected behaviour.

The PCSDB facilitates the development of a systematic commissioning plan. Artefacts within the PCSDB—such as FBs, models, and ports—can be directly linked to commissioning use-cases and procedures. This traceability ensures that all designed functions are scheduled for commissioning and that none are inadvertently omitted. Importantly, commissioning use-cases can also be traced to specific design requirements, supporting comprehensive verification. Accurate checklists are a critical component of any commissioning plan, and the PCSDB enables their easy creation. For example, a checklist for a commissioning use-case testing input ports can automatically include all ports of the relevant FBs, while another checklist can enumerate all design models associated with FBs that require validation.

The output of the PCS commissioning plan—including graphs, procedures, and use-cases—can be generated in various formats as needed. A complete plain-text version of the SRO PCS commissioning plan, including all use-case data and checklists, exceeds 400 pages. These checklists are automatically generated according to the specifications of individual commissioning use-cases. The PCSDB allows this output to be recreated at any time after updates or to optimize the documentation format. It also enables the creation of different views of the plan, improving comprehension of individual tasks and supporting detailed

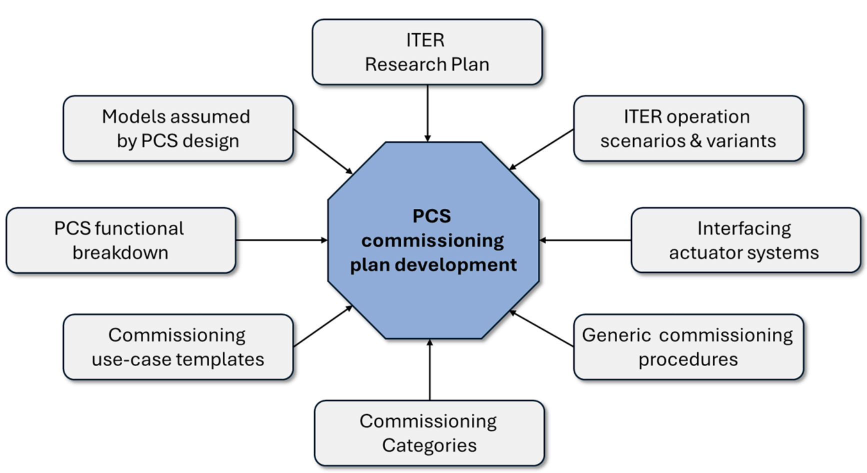

Fig. 1. Various guidelines, templates and frameworks that jointly provide the structures allowing a systematic development of the ITER PCS commissioning plan. From the top-down, the overall PCS commissioning plan should align with the IRP and ITER operation scenarios, while from the bottom-up each of its commissioning use-cases (or tests descriptions) should be structured by the use-case templates and generic commissioning procedure.

Table 3
Basic rules to be applied when developing the ITER PCS commissioning plan for SRO.

Test all PCS components or functions (i.e. FBs).
Check the required configurability of all functions.
Test all performance requirements for each function (FB).
Test all exception handling related to each function.
Validate all models assumed during its design.
Test all interfaces with actuators as early as possible.
Include plans to optimize functions by reconfiguration.
Group related tests together in procedures.
Compare procedures to templates to determine if any tests are missing.
Determine the operation scenario, or variants, for tests during IC and PO.
Do any tests as early as possible (at lowest risk, e.g. lowest plasma current)
Determine if tests need to be repeated under other circumstances or not.
Ensure the method statement (and possibly also operation scenario variant) is viable.
Aim to align with SRO IRP and flag any deviation

analysis of the PCS commissioning plan, as will be illustrated in Section 5. This commissioning plan will eventually have to be formalized as part of the ITER official commissioning and operation documentation.

Fig. 2a presents an example from the perspective of a commissioning use-case, showing the related artefacts. The use-case specifies the tasks to be performed and links them to the relevant FBs, associated models to be validated, and the plasma operation scenarios in which the test must be conducted. Fig. 2b illustrates the view from an individual FB, highlighting all tests required to commission that function, the procedural steps for execution, and the associated artefacts. Fig. 2c shows the commonly used perspective of a commissioning procedure, which groups multiple tests into specific steps and identifies the FBs involved. In all figures, only artefacts directly related to the commissioning work are displayed. However, the commissioning workflow can, if needed, be traced back to the system stakeholder requirements.

4. PCS commissioning plan for SRO

In this section the actual PCS commissioning plan for SRO will be discussed, obtained using the method described in the previous section (Section 3). As is clear from Figs. 2a-c, each commissioning use-case and each procedure contains significant amounts of information. Hence, it should be clear that it goes too far to show all procedural steps with all details. Here the main features are shown, describing how the main plan is broken down, indicating a few interesting features, and some statistics.

Fig. 3 shows the highest-level outline of the PCS commissioning plan for SRO. The plan contains, three main blocks that follow the principles of ITER commissioning: System Commissioning (SC) (i.e. mainly tests on the individual system done outside the standard ITER operation framework), Integrated Commissioning (IC) (i.e. tests that can be done pre-plasma operation but done as part of the standard ITER operation framework) and finally tests that require PO. Stepwise this increases the complexity of the PCS tests, from testing software of individual FB to use

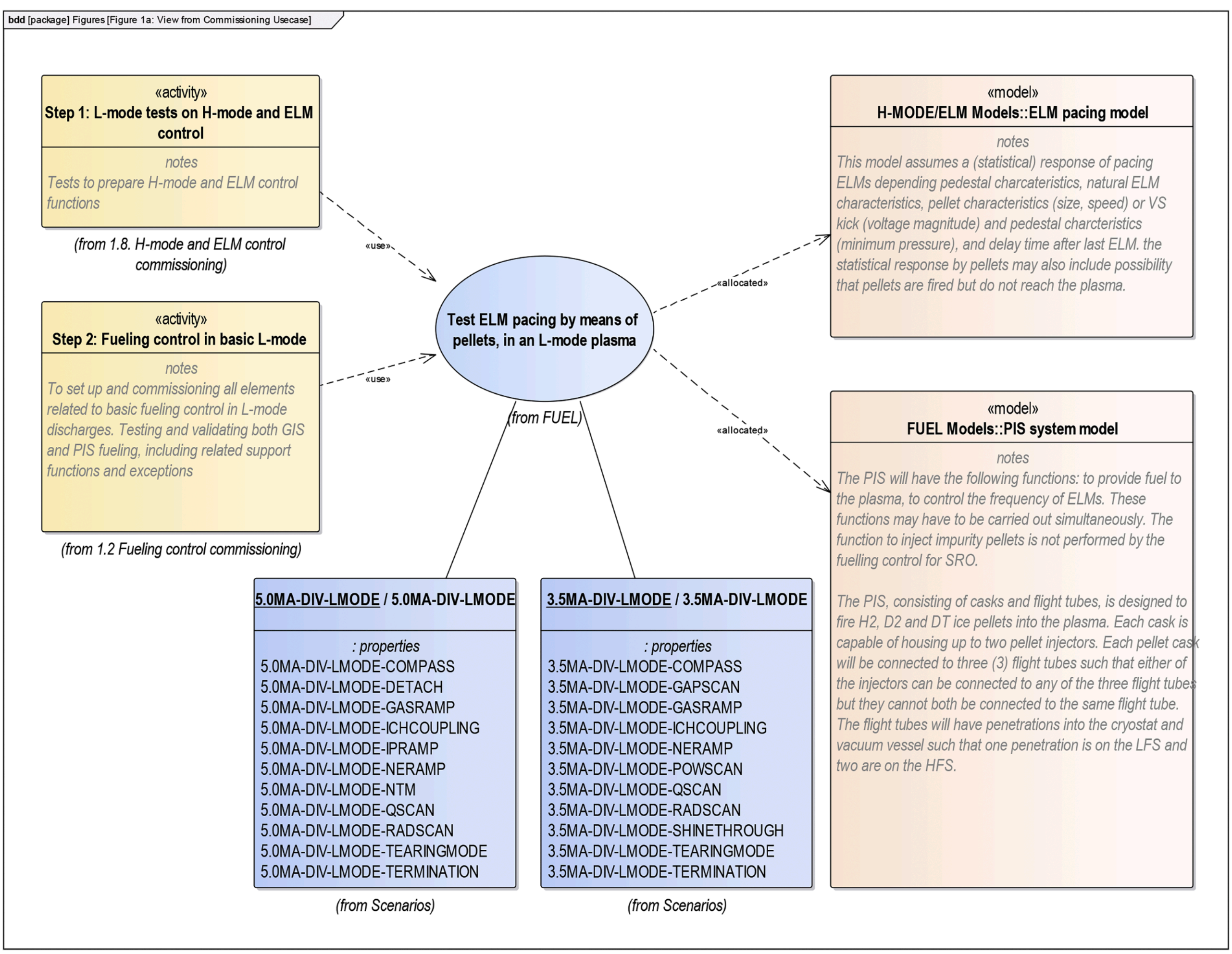

Fig. 2a. This view centres on a commissioning use-case (blue oval) and illustrates its relationships with key PCSDB artefacts. These include the operation scenarios (blue rectangles), the design models to be validated (beige rectangles on the right), and the commissioning procedure steps (yellow rectangles on the left) where the tests are scheduled for execution. Some tests appear in multiple procedures, reflecting their inclusion at different stages of the commissioning workflow.

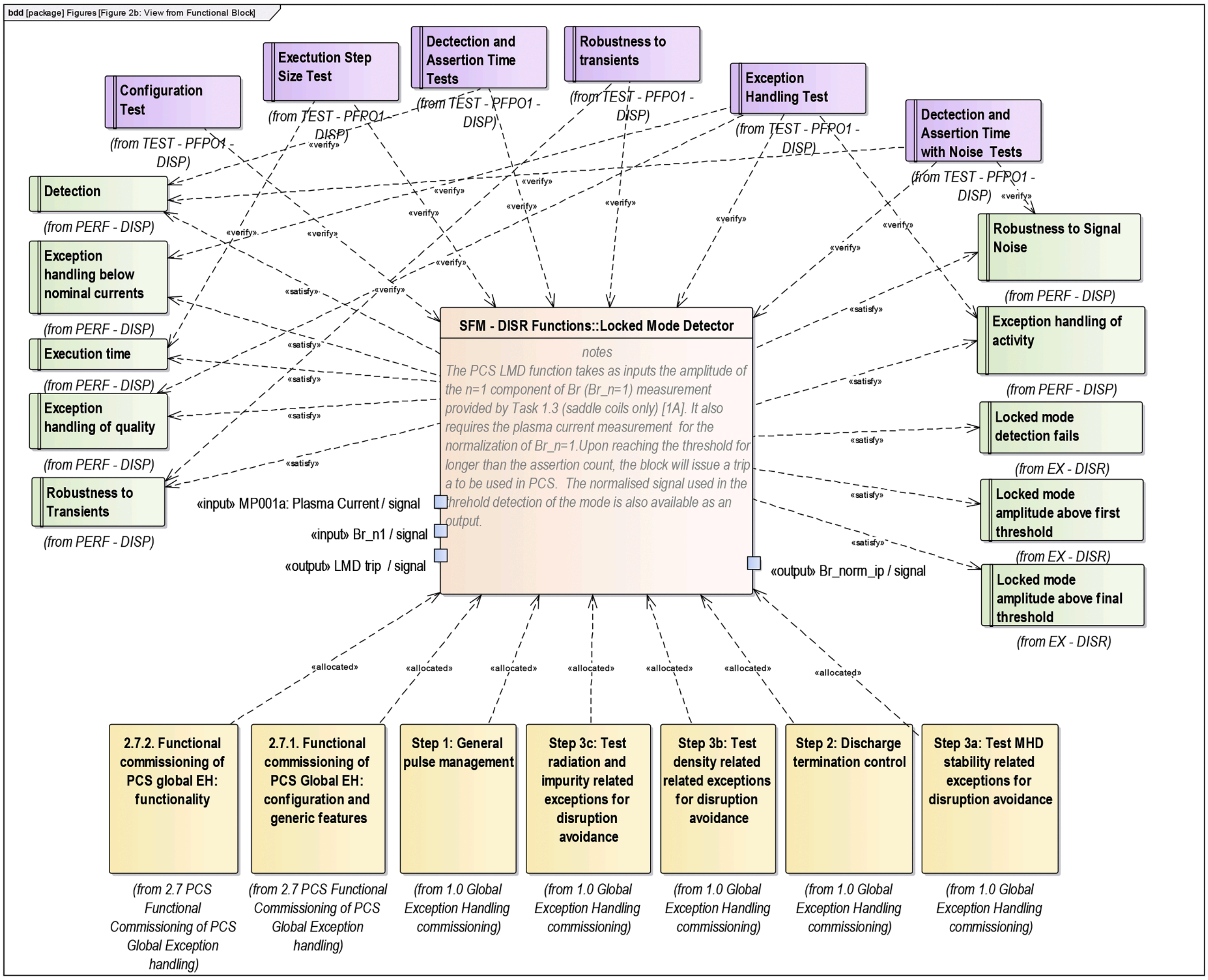

Fig. 2b. This view places a Functional Block (FB) at the centre (beige rectangle) and illustrates its relationships with artefacts relevant to commissioning. The FB's input and output ports are shown as light blue blocks. Above the FB, assessment tests conducted during design to validate performance are indicated in purple rectangles. On the left, performance requirements are shown in green rectangles, while related exceptions are displayed on the right, also in green. Below the FB, the procedural steps in which tests on this function are executed are depicted as yellow triangles. These steps are part of procedures spanning System Commissioning (SC), Integrated Commissioning (IC), and, ultimately, testing during Plasma Operation (PO).

of integrated PCS functionality facilitating plasma operation. Each of these parts can be expanded to show its own internal logic with respect to the various procedures, as shown in Fig. 4, as an example. And each of these procedures is further detailed in a similar way as shown in Fig. 2c, providing the procedural steps and the related commissioning use-cases.

PCS System Commissioning (SC) concerns two main aspects: the PCS Verification & Validation (V&V) and basic interface tests with available actuator systems. This means that the plan aims to verify that each function is implemented as intended (i.e. is it available, does it have the correct ports, etc.) and validated if it meets the required performance. The detailed design description of each function can be traced using the PCSDB, and the procedures may contain checklists such as ports, performance requirements, exemptions, etc., that need to be checked. The functional performance can be tested, by repeating exactly those tests that were done assessing the design prior to its implementation [16], however now using co-simulations with the real-time code [13]. The first part of PCS SC starts with the with a procedure focusing on the testing of the basic PCS functionality, that is: basic exception handling and pulse organization features. Thereafter the procedures break down along the lines of the PCS highest level functional breakdown for SRO, as shown in Table 4. At the end an additional procedure is added that is dedicated to testing the integrated functional performance (e.g. testing combined magnetic and fuelling control, etc.) [16].

The second, optional part concerns testing the interface between the real-time PCS and any available existing actuator systems. It does not concern applying actual actuation but the testing of the often-complex data exchange between the PCS and these systems. If this can be done prior to IC, it would make it easier to resolve any bugs. However, such tests are scheduled to be repeated during IC and PO. The procedures of this second part of SC are broken down per interfacing system.

With ITER IC the plant will be formally in operation. The PCS commissioning starts with the basic tests of ITER pulsed operation, to configure it, to execute it and to run basic (dry) pulses in which architectural features of the PCS, and interfaces with the Central Interlock System (CIS) are tested. The procedures are broken down with respect to the interfacing system (i.e. magnets, fuelling system, ECH). Dry pulses being pulses that do not contain a plasma discharge. Then step by step functionality is added and tested. Any function that can be tested without PO, should be tested during IC. The interfaces with all actuator systems are tested under (dry) pulse operation conditions, and operating actuators on dummy loads will allow validating actuator models as well. Key to the IC of a tokamak is the operation of its magnets that does not concern any PO. Thus, the full functionality of all PCS functions related to the operation of its magnets (e.g. Poloidal Field (PF) and Central

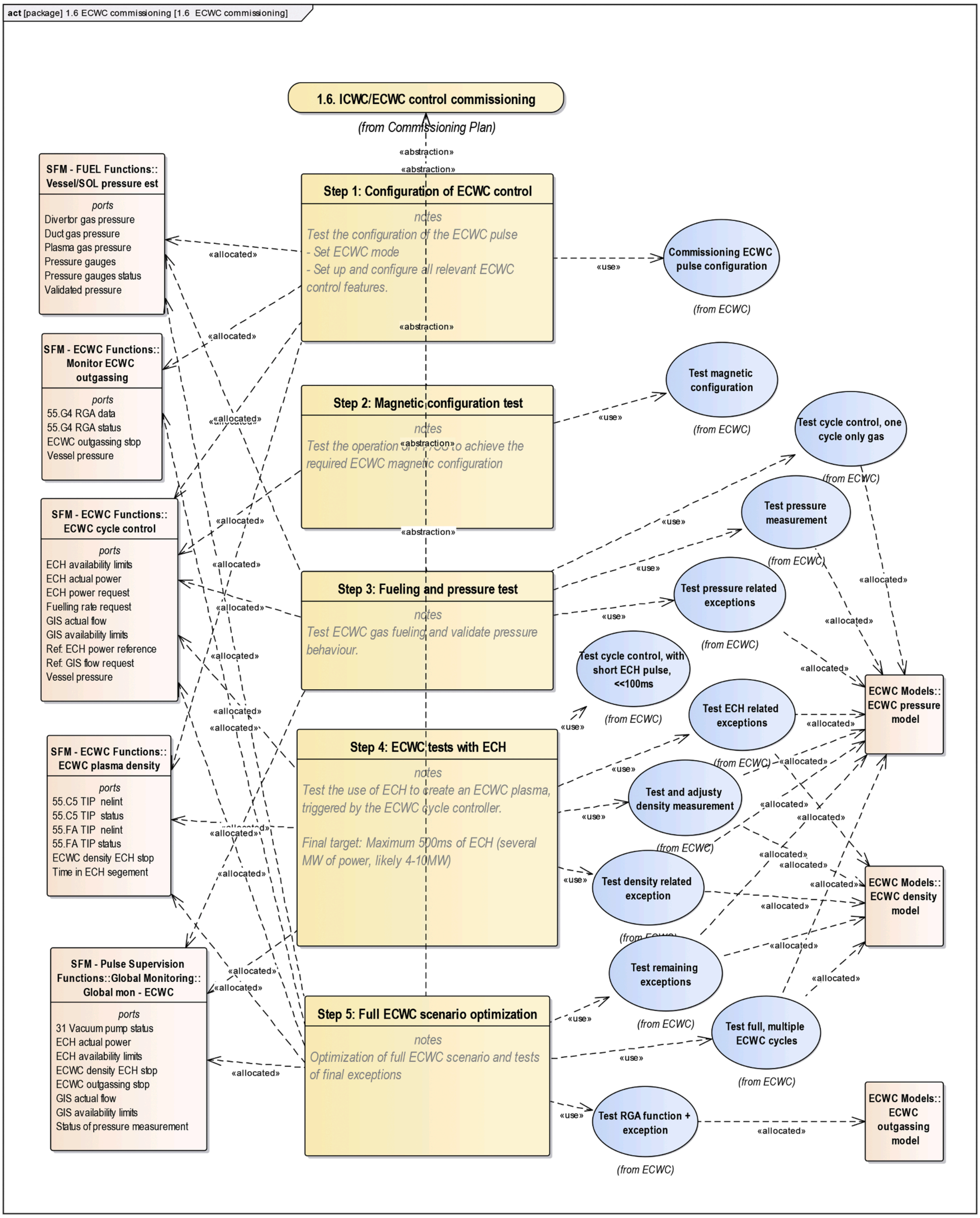

Fig. 2c. This view places a commissioning procedure at the centre and illustrates its relationships with key artefacts across the procedure's steps. It displays all steps within a single procedure, linking each to the corresponding commissioning use-cases and the Functional Blocks (FBs) to which the tests are applied. In this example, the operation scenarios in which the commissioning use-cases are executed are not shown. This procedure represents one of the simpler cases; other procedures involve many more artefacts—including FBs, use-cases, and procedural steps—making it challenging to create a clear figure suitable for publication.

Solenoid (SC) coils and those for the Correction Coils (CCs) and In-vessel Coils (IVCs) but excluding the toroidal field magnets as these are not under PCS control) will have to be fully commissioned. Basic control of part of the ECH plant and GIS (Gas Injection System) will be tested, because these two systems are, together with the magnets, essential for ITER plasma initiation. These tests will allow the validation of some (parts of) the actuator models but also the ITER plant itself (i.e. vessel currents when operating magnets, resistance of circuits, power supply behaviour, vessel fuelling by GIS, etc.).

A separate part is added to IC that combines the procedures that deal with the stepwise integration and optimization of all functions to prepare for ITER First Plasma initiation. This last stage usually seamlessly flows over into PO, hence overlap exists between the final IC procedure and the first steps in some of the PO procedures.

PCS commissioning with PO will focus on all functionality required for SRO. Control functions not required for SRO, such as NBI or burn-control, will be designed and commissioned later, following the ITER staged approach [5]. The procedures again break down predominantly along the lines of the higher-level PCS functionality (Table 4) breakdown. As noted before, this breakdown is not perfect and there are

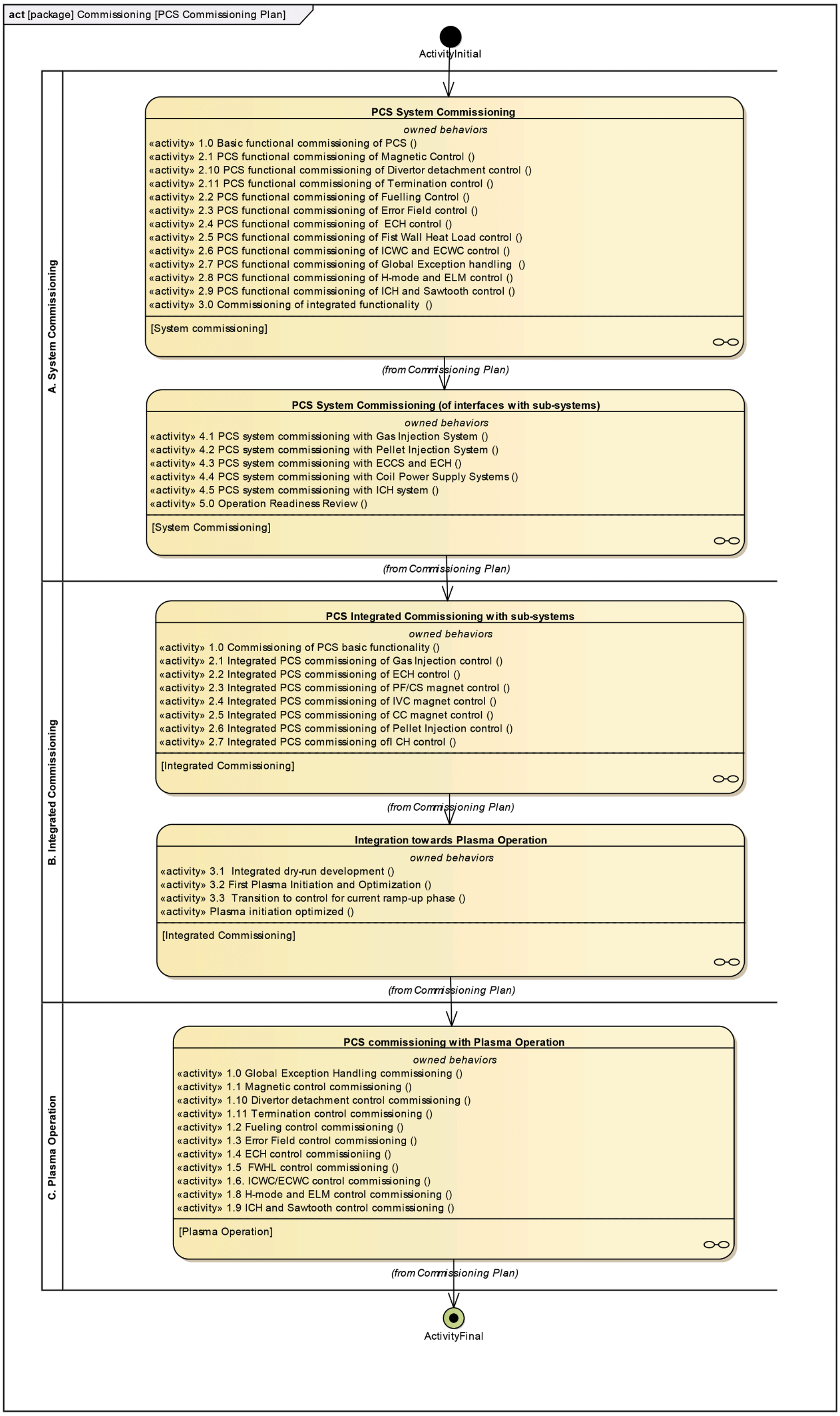

Fig. 3. The highest-level breakdown of the PCS commissioning plan for SRO, with each line in the blocks referring to a specific procedure, like the one shown in Fig. 2c and each part being a plan with its own first-level logic as shown in the next Fig. 4.

various areas of overlap, mainly concerning the control of Magneto-Hydro-Dynamic instabilities and high-level exception handling. The latter is therefore also given its own dedicated procedure which focusses specifically on PCS functions related to disruption avoidance (i.e. commissioning those exceptions with the highest risk-priority number linked to the requirements to avoid disruptions [5]). During the PO phase of PCS commissioning will enable the validation of further details of actuator models but especially now also the

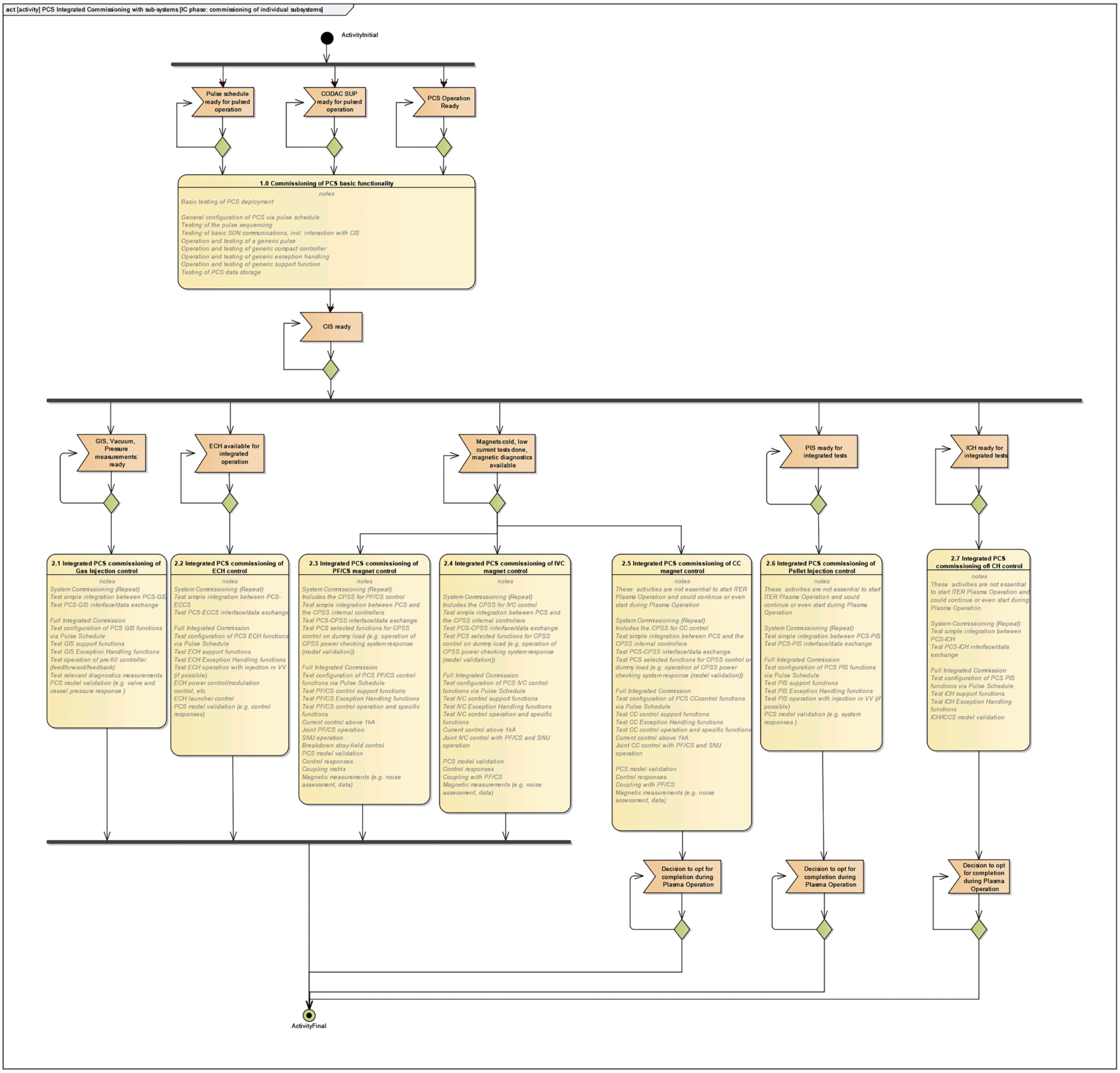

Fig. 4. Example of the current part that describes the logic for the part that deals with the IC of the PCS with its subsystems, indicating those procedures that must be completed before the start of PO and those that may continue during the initial stages of PO. The optionality indicated by the flags, gives information on the prerequisites. The procedure starts with testing basic PCS functionality (1.1) and then (in parallel) commissions the PCS functionality with sub-systems, from left to right, (2.1) gas injection system, (2.2) the ECH system, (2.3) the PF/CS magnets, (2.4) the in-vessel coils, followed by (2.5) correction coils, (2.6) pellet injection and (2.7) the ICH system.

assumed plasma models (i.e. fuelling responses, plasma position control responses, ELM characteristics, etc.) the highest stakeholder requirements for the PCS, that are capability to facilitate SRO operation scenarios, can be validated, including the integrated application of multiple PCS functions.

Fig. 3 shows there are five main parts to the PCS commissioning plan. As is clear from Fig. 4, each of these parts of the PCS commissioning plan contains a basic, first-level logic. Fig. 5 is an attempt to visualize this logic in a cartoon sketch of the PCS commissioning plan. The SC procedures, except for its initial one, follow a generic pattern for all PCS functions and each can be executed independently from each other. The same is true for the procedures that commission the interfaces with other ITER sub-systems and thus also the initial IC procedures. The structure changes, however, towards the end of IC and for PO. Procedures are broken down differently, some organized by functionality, others by the progressed complexity of the tests, while it is also possible that the procedure is organized by ITER operation scenario. It should be reminded that this plan provides all commissioning tests specifically for the PCS and not the overall IC or PO for the ITER. The PCS commissioning workflow is overall guided by the SRO plan and the proposed sequence of its operation scenarios. In some cases, a single procedural step may be executed several times, each time using a different plasma (e.g. operating at higher plasma current, different shape, different heating powers). Individual steps from the different PO procedures shown in Fig. 5 can therefore be executed in parallel. Therefore, the detailed logic of the PCS PO commissioning plan is significantly more complex than shown here and better described by the IRP itself [9,10].

Table 5 shows the breakdown of the different parts of the PCS commissioning plan. It gives the number of procedures, and the number of commissioning use-cases currently used. The latter could change, as it

Table 4
The highest-level PCS functional breakdown for SRO. Note that each of these will concern many independent functions (i.e. FB) that jointly enable the required control for SRO and that some of these FB can be used by more than one of the functions listed here. Hence, this functional breakdown is not perfect, and overlap exists.

1	Magnet and plasma magnetic control
2	Fuelling and plasma density control
3	Error field control
4	Electron Cyclotron Heating and Neo-classical Tearing Mode (NTM) control
5	First Wall Heat Load (FWHL) control
6	Ion or Electron Cyclotron Wall Condition (ICWC/ECWC) control
7	Disruption avoidance
8	H-mode and Edge Localized Mode (ELM) control
9	Ion Cyclotron Heating (ICH) control and sawtooth control
10	Divertor heat load and detachment control

is easy to remove, replace or add use-cases. However, the plan is presently well consolidated thus major adjustments are not expected. Note that certain commissioning use-cases are generic and can be used multiple times. For example, commissioning use-cases that indicate that all ports need to be tested, or that local exception handling should be verified and validated. Thus, such use-cases are counted each time they are used in different procedures. Nevertheless, each time it means the test described by the commissioning use-case should be executed. Hence, this doesn't concern double-counting work. This is also evident from the fact that the total numbers of different use-cases, models and scenarios in the PCSDB, as shown in the bottom row of Table 5, does not equate the sum of the times they are used by commissioning procedures.

As the method described in Section 3 explains, the commissioning plan identifies the operation scenarios, either dry or with plasma, that are required to carry out the test. Or it determined a specific variant of one of the basic operation scenarios. Fig. 6 gives an overview of all the operation scenarios that are currently linked to the PCS commissioning plan for SRO. Obviously, the simple identifiers or names used here only give a rough indication about the scenario, but each of these can be linked to entries in the ITER scenario database that provide simulations of these pulses and plasmas in detail [17]. More background on these ITER operation scenarios and the logic on how they will be executed is provided by the IRP [9]. Note that in some cases more than a dozen dedicated variants have been determined for PCS commissioning tasks, most of these being at plasma currents of the level of 3.5MA. The PCS design team will have to determine how certain tests are done in detail with the future ITER operation team. In some cases, this means perturbative tests are done in a standard operating scenario (e.g. gas puff step response tests or VS control stop-and-start tests) but in other cases a new variant of an operation scenario needs to be designed (e.g. scenarios with different shapes, closer to the wall to execute FWHL control tests, or scenarios that trigger NTMs such that NTM control can be assessed). The fact that the requirements of these variants are determined early, means that the design of such new operation scenarios and the development of the PCS commissioning plan can be optimally prepared. SRO PCS commissioning continues up to the maximum plasma current of 15MA. Further simulations are needed to design and assess these operation scenario variants in preparation for the start of SRO.

Models play a central role in the design of the PCS [5], and hence, the commissioning has the task to validate these models. The design takes model variations into account to ensure it is robust against any model uncertainties. The model validation during the commissioning stage then allows the correct configuring of the PCS function, based on the actual plant behaviour. For example, setting the correct gains, thresholds, filter settings, etc. The latter is not always an easy task, especially when dealing with complex models and integrated

Table 5
Breakdown of the PCS commissioning plan for SRO, showing the number of procedures and commissioning use-cases, models and scenario variants, to date, for the two parts of System Commissioning (SC), two parts of Integrated Commissioning (IC) and commissioning with Plasma Operation (PO). Note that some generic commissioning use-cases can be used multiple times and here each time one is added to a procedure is counted. Similarly, the same models can be linked to different procedures, hence, they can be double counted. The total, listed at the bottom, is the number of individual use-cases, models and scenarios in the PCSDB which does not equate the sum of their usages in each procedure. The current PCS design for SRO is nearly complete, but at a few points it is possible that additional features will be added. This may result in possible additional commissioning related artefacts (i.e. commissioning use-cases, models, etc.) at certain places in the plan. Hence, numbers have been marked with an asterisk if these may increase slightly in the next two years.

Part of the SRO plan	Procedures	Use-cases	Models	Scenarios
SC functional performance	13	78*	0	0
SC interfaces with sub-systems	5	24*	37	0
IC control of sub-systems	8	133*	79	35
IC integration towards PO	3	68	54	36
PO	11	285*	95*	180*
Overall individual elements	40	246*	49*	54*

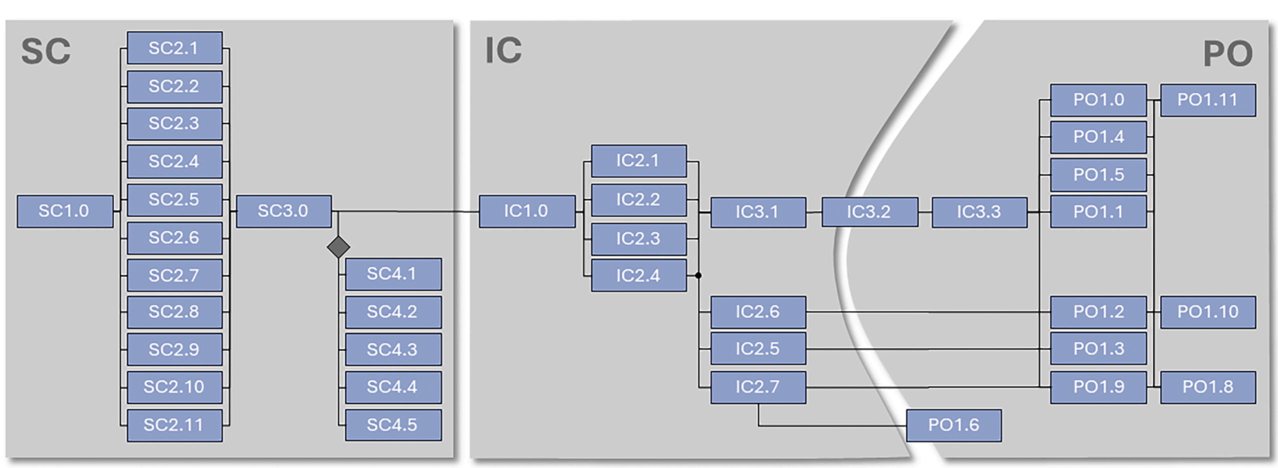

Fig. 5. A cartoon of the basic logic and workflow of the main procedures that make up the PCS commissioning plan. The numbering relates to the PCSDB procedures listed in Fig. 3. The plan starts on the right with System Commissioning (SC), for which the second part with the SC4.X procedures is optional after which PCS Integrated Commissioning (IC) can commence. Note that from the PCS commissioning point of view, the transition from IC to PO is less clear, hence the fuzzy division. First Plasma is aimed for in IC3.2. PO1.6 concerns the commissioning of ICWC and control. The first-level logic of the PO commissioning hides the actual complexity of the organization of the work.

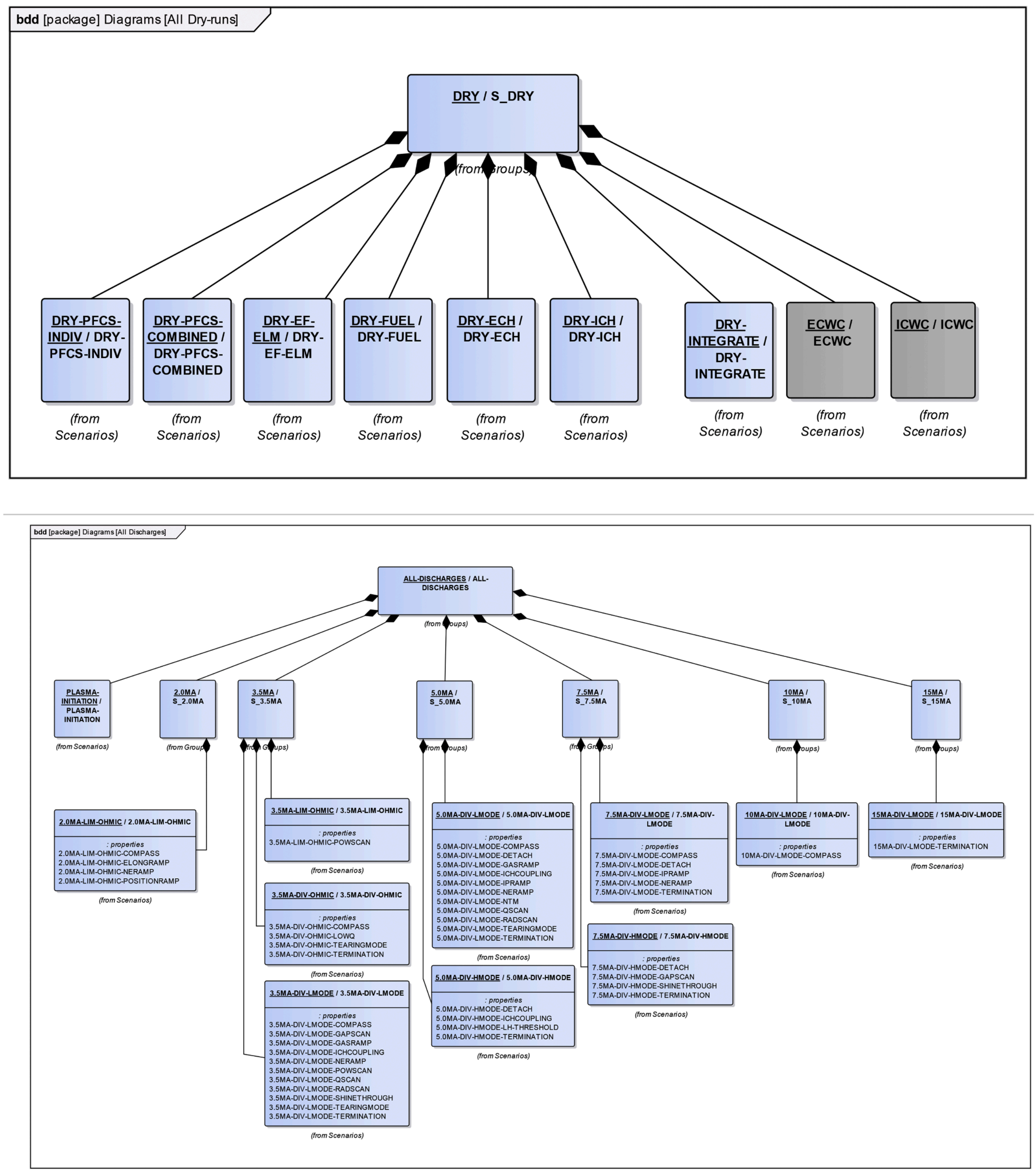

Fig. 6. PCSDB overview of the current list of the ITER SRO operation scenarios, and their variants, identified as necessary for a) dry IC scenarios, also containing references to scenarios for Ion and Electron Cyclotron Wall Conditioning (ICWC & ECWC), and b) PO, which lists all discharges needed to commission the PCS. Operation scenarios can be grouped, as is shown in the figure, with the highest level, the group according to plasma current and toroidal magnetic field.

multiple-input-multiple-output control functions. Hence, the optimization of the configuration should be done, by updating model descriptions used to simulate the PCS behaviour during the design (PCS Simulation Platform: PCSSP), and re-assess the functions with their new optimized configuration, before applying it to the plant. This loop between model validation and PCSSP optimization is especially important to efficiently optimize the ITER magnetic control and features in the generic commissioning procedures shown in ref [5].

The completion of each of the parts of the commissioning plan can be regarded as a PCS commissioning milestone. Specifically, the completion of the SC, can be considered as the Operation Readiness milestone, here meaning the PCS to be ready for ITER pulsed operation. An important second milestone concerns the completion of IC, with achieving First Plasma initiation at ITER. It is however more complicated to set PO milestones. Obviously, completing SRO PO could be considered a milestone as well but this is unlikely to be very relevant to the PCS system. Important PO milestones to PCS commissioning are better linked to the completion of commissioning of specific PCS functions or its application to specific ITER operation scenarios. This will be further discussed in the next section.

5. First analysis of the plan

That the PCS commissioning plan is broken down in its constituent elements doesn't only make it easily correct or adapt the plan but also makes it analytic. Various analysis can be applied that may shed light on deficiencies thus allowing these to be corrected, however, it can also help to understand the plan better and identify areas of complexity that require attention. It is not easy to assign metrics to aspects of criticality or complexity of a workflow or a plan. Complexity can be perceived as something which has many interconnected components. Complexity may also arise due to variations in its structure and arrangements (e.g. differences in the procedural breakdown or organization of procedures themselves), interactions, either external (e.g. interfaces with other system (commissioning plans) or internal (i.e. the relationship or logic between the various parts of the plan). It also allows one to identify milestones. Milestones are significant points in the plan, often indicating a major transition in the plan. Some of these milestones are obvious, such as the transition from SC to IC and later from IC to PO. However, the analysis also may find additional milestones, based on completion of bottlenecks or complex parts of the plan (i.e. parts with significantly higher levels of tasks or use-cases).

Fig. 7 shows how many FBs, commissioning use-cases, models, operation scenarios and interfacing actuator systems, are referenced in each procedure that is part of the current PCS commissioning plan. Ultimate complexity involves commissioning procedures that deal with functions that are part of different higher-level functionality (see Table 4) (i.e. combined testing of both magnetic and fuelling control). High numbers are an indication of complexity. Clear elevated levels of complexity are notable for SC procedures such as SC2.1 (: ①), SC2.7 (: ②), concerning the SC of the PCS architecture and its general function, PCS magnetic control and PCS exception handling, respectively. However, the most complex SC procedure concerns the validation of the integrated functionality (SC3.0: ③), simply because of the sheer number of FB involved and the fact it combines all different PCS high-level functionalities. More interesting are the procedures for IC and PO, for which the complexity in general is already elevated. But clear outliers during IC are: IC2.3 ④ being the magnet control Integrated Commissioning (labelled as number 4 in Fig. 7), and IC3.0 ⑤, the control integration required to achieve ITER plasma initiation. With respect to this last point, the target is not only to have breakdown and burn-through but also to obtain a well-controlled tokamak discharge (i.e. at least basic shape and position, plasma current and density control) [18] which is the most complex task to achieve from the PCS commissioning point of view. During PO, both the commissioning of ITER magnetic control (PO1.1: ⑥), the commissioning of fuelling and density control (PO1.2 ⑦) and the important case to commissioning of advanced exception handling and disruption avoidance functionality commission (PO1.7: ⑧). The identification of these most complex procedures means that these may require additional reviews aiming to further optimize them.

Besides ordering PCS commissioning tasks per procedure, the work during IC and PO can also be ordered by ITER operation scenario. Fig. 8 indicates levels of commissioning complexity, i.e. numbers of planned commissioning use-cases and FBs on which these are applied. For simplicity these operation scenarios are here simply grouped by their highest plasma current (in MA) although Fig. 6 shows that these contain many possible variants. This time there are fewer clear outliers, but a few important observations can be made. The complexity of PCS commissioning decreases for ITER operations with plasma currents larger than 3.5MA, and only a few commissioning use-cases require operations above 10MA. Up to a plasma current of 3.5MA 63% of all commissioning use-cases can be done in operation scenarios up to 3.5MA, and 80% is done with plasma currents at or below 5.0MA. This means most of the ITER PCS commissioning can be executed in operation scenarios that carry little risk, such as damage caused by disruptions [9,19].

The above knowledge can be used to expand the PCS commissioning milestones, to those shown in Table 6. It can be noted that these milestones do not merely indicate the start and end of the SC, IC and PO parts of the PCS commissioning. A key milestone during the PCS SC is the completion of the test on the integrated functionality. Further tasks such

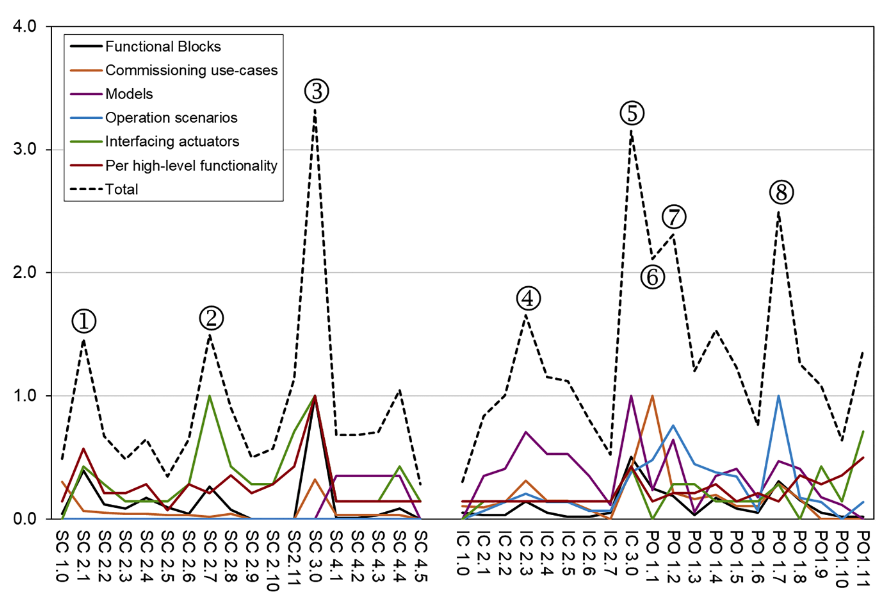

Fig. 7. showing how many FB, commissioning use-cases, models, operation scenarios and interfacing actuator systems, are referenced in each procedure that is part of the current PCS commissioning plan. The final case concerns the number of different higher-level functionalities related to each procedure. The total numbers for each procedure have been normalized to the maximum case, which makes it possible to compare each of the different cases (i.e. number of FB, use-cases, models, etc.). Most illustrative is the total given by the dashed line which is the sum of all the others together. Each procedure is referenced by its number and if it is part of System Commissioning (SC), Integrated Commissioning (IC) or Integrated Commissioning by Plasma Operation (PO). The numbering for the procedures relates to those listed in Fig. 3 and Fig. 5. Those procedures with a critically high complexity have been numbered as referenced in the text.

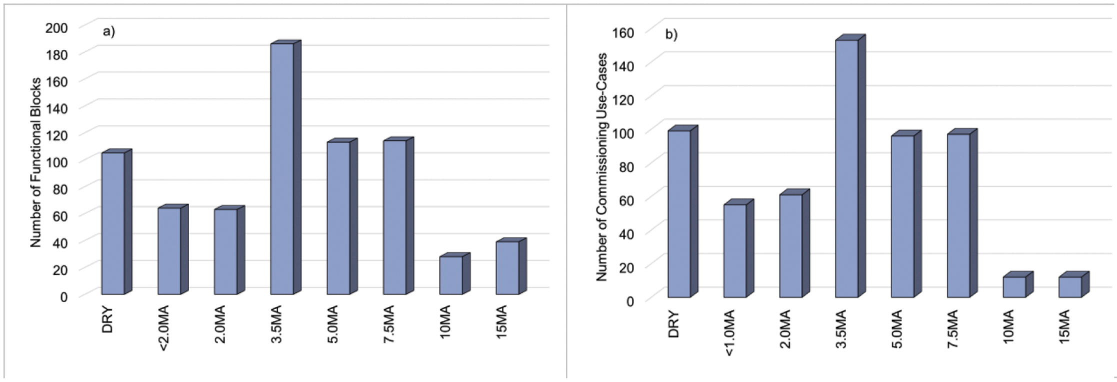

Fig. 8. showing a) how many FB and b) how many commissioning use-cases make use of an ITER operation scenario with a specific plasma current, including also dry-operation (i.e. pulses without any plasma current).

as initial tests of the PCS interfacing with other plant systems are optional, because such tests must be repeated anyway during IC and PO. ITER IC-I will commence with the preparation of the tokamak for operation [10]. A milestone for the PCS commissioning is the start of ITER pulsed operation, later in IC-I, being the start of the IC of the PCS (not IC-I). The start of the PCS commissioning related to the integrated tokamak operation in preparation of PO (start of IC3.1), is an important milestone. ITER First Plasma operation has been added here for obvious reasons as it separates IC and PO. However, for PCS commissioning First Plasma on its own has lesser relevance. After this follows an intense part of PCS commissioning, optimizing its magnetic and fuelling control, to achieve a controlled tokamak discharge for which the plasma current can be ramped up and its position and shape are controlled such that a diverted configuration can be obtained. During this part, ITER operation scenario development and PCS control optimization will go hand-in-hand. The completion of this crucial milestone for PCS commissioning, set at the point when ITER operation exceeds a plasma current of 3.5MA. At this point it will be known that its basic functionality performs adequately. After that the PCS commissioning becomes less integrated (i.e. concerning optimization of multiple PCS functions) and more the testing of individual testing of more advanced control functions. A final milestone is the overall completion of PCS commissioning which takes place towards the end of SRO, although it does not necessarily coincide with it. Achieving ELMy H-mode operation is known to be a key SRO milestone [9,10], however, notwithstanding the complexity to adequately control ELMs, this is not identified as a specifically complex PCS commissioning phase.

6. Summary

Commissioning activities may be undertaken in an ad-hoc manner, whereby a test plan is constructed around the features that are most readily identified. While such an approach can be effective in addressing the principal aspects of the system, it is not without risk. Specifically, certain components or functions may remain untested, while less critical functions could be overlooked and subsequently exhibit unexpected behaviour as the operational domain is expanded. Furthermore, ad-hoc testing may result in duplicated efforts or an inefficient sequence of execution, thereby diminishing overall effectiveness. An additional concern arises when the intended outcomes of the tests are insufficiently defined. For instance, a system's performance may appear adequate within the context of the operational scenario under which it was tested; however, it is uncertain whether this adequacy can be generalized to other operational scenarios. The critical question, therefore, is how test results can be extrapolated with confidence to future operational scenarios, such that a single set of tests provides assurance of correct functionality across an expanded range of conditions. In this regard, the development of commissioning use-cases with greater precision is essential. Such use-cases should ideally be authored by the teams responsible for the design of the respective PCS functions, rather than by those who, as in the ITER project, may be tasked with executing the commissioning plan many years later.

To address these challenges, a systematic methodology has been applied to develop a commissioning plan that ensures comprehensive, effective, and efficient testing of all PCS components. The PCS commissioning plan is directly linked to the PCS design description contained in the PCSDB, with commissioning use-cases authored by the designers of the respective functions. This approach guarantees completeness and focuses on verifying that the original design has been correctly implemented and performs according to its intended specifications, even when several years may separate the design phase from commissioning execution. Completeness in this context means that the commissioning description of each PCS functional block has been developed following the methodology presented in this paper. This methodology ensures that all components of the PCS design are described in a comprehensive and consistent way.

Firstly, comprehensiveness and consistency are achieved through the systematic use of templates when defining the required commissioning tests. The paper provides several such templates. For instance, the component commissioning tests must address all points indicated in Fig. 1. The commissioning use-case template (Table 2) ensures that every test is described in the same way, including the same key elements. Each aspect listed in Table 1, needs to be covered by at least commissioning use-case, for each PCS component (i.e. FB). The ITER commissioning framework, i.e. the SC and IC phases, and the IRP, with its planned operation scenarios, provide another template, ensuring each PCS component has at least one test in each phase, and that the PO tests are carried out in viable operation scenarios. Moreover, for each model, used to assess the PCS design performance, there should be commissioning tests to validate them. This also includes models of the behaviour of auxiliary systems that interface with the PCS component, thus ensuring that each such interface is systematically tested. Finally, generic commissioning procedures provide a template of how several commissioning use-cases or tests are to be sequenced, thus making sure that procedures of different PCS components follow the same pattern. Secondly, ensuring consistency across the entire PCS design (i.e.,

Table 6
Milestones in the ITER PCS commissioning plan for SRO.

1	Completed PCS SC of integrated functionality
2	PCS SC completed / Operation Readiness
3	Start of PCS IC / Start of ITER pulsed operation
3	Start of IC integration towards Plasma Operation
4	First Plasma / Start of Plasma Operation
5	PCS commissioning up to or at 3.5MA completed
6	Completing PCS commissioning for SRO

between different PCS components or FB) requires regular design-integration discussions. These meetings help prevent duplication of tests across functions and allow coordinated planning of integrated tests involving multiple functions.

Finally, the PCS system engineering database (PCSDB) supports systematic completeness checks. The PCSDB contains all commissioning use-cases, describes how these are linked to the procedures and how these procedures are combined to a plan. The are also tagged to indicate, for example, the commissioning task category (see Table 1). It also links the use-cases to the individual PCS components (FB) to which the test applies, which in turn links them to further relevant artefacts, such as the design models, interfaces, input/output ports, performance requirements, etc. The PCS commissioning plan development is a continuous, iterative, process that runs in parallel with the PCS design project. Routine PCSDB analyses verify whether all commissioning-plan elements required by categories, templates, ITER phases, operation scenarios are present for every FB. This helps identify missing tests—for example, when PO tests exist but the corresponding SC tests are absent. The PCSDB also maintains dynamic checklists that automatically evolve with the design; for example, when a new input port is added to the design, it is automatically included in the relevant checklists for the corresponding commissioning stages. As shown in Section 5, more comprehensive analysis can identify planning complexity or other issues that then are addressed during the PCS design-integration discussions to further optimize the plan.

The model-based methodology employed in the design of the ITER PCS further supports this process by explicitly identifying all assumed behavioural models. These models can subsequently be validated in a systematic manner as part of the commissioning plan. The structured method used to document the PCS commissioning plan integrates it with the actual PCS design description, allowing one to trace commissioning tests back to design requirements or specifications. It creates automatic checklists and logically defines those SRO plasma operation scenarios required for the PCS testing. It also facilitates multiple levels of analysis of the plan such that gaps or inconsistencies can be identified. Hence, the plan can be efficiently corrected and easily updated as future design modifications arise. Additionally, it provides the means to detect critical stages or potential bottlenecks within the plan that may pose greater implementation challenges and thus warrant additional attention to optimize the commissioning process. The systematic method, that is further supported using templates and generic procedures, ensures a more consistent plan. Consistency strengthened by carrying out PCSDB analysis as described in section 5 and most importantly regular design integration discussions. Finally, the output of the commissioning plan can be created into many possible formats. These range from a comprehensive, detailed printout—potentially spanning several hundred pages—to more concise documents and checklists focusing on specific test procedures. This flexibility ensures that the plan is accessible and practical for different stakeholders and use-cases. The plan developed here will ultimately support the creation of the formal documentation, as required by the ITER commissioning and operations procedures. The responsibility for the execution of the PCS commissioning, especially during ICI and SRO, lies with the ITER operations team.

The current PCS commissioning plan provides an overarching structure and first-level logical framework; however, more detailed information regarding the precise sequencing of individual tests is contained within the commissioning use-case descriptions. At present, access to this information is limited, preventing a comprehensive assessment of the detailed test logic. Such access would enable analysis of the lower-level logic of the plan and potentially support automatic sequencing based on this logic. This capability could also facilitate the coordination of PCS testing with more complex interdependent activities, such as those involving the ITER protection system or the commissioning of various actuator systems scheduled during SRO. While the plan enumerates the tests to be conducted, the relationship between the planned tests, the associated testing duration, and the required number of tokamak pulses remains ambiguous. Consequently, future enhancements to the PCS commissioning data will focus on improving both the resolution of lower-level logical sequencing and the accuracy of assessments regarding time or number of pulses needed to carry out the tests. The large amount of data that make up the PCS commissioning for SRO also may benefit from further detailed analysis than those that have been presented so far.

Although the PCS commissioning plan presented in this paper is specific to ITER and its Start of Research Operation, many of its features are generic to tokamak systems in general. Consequently, the methodology and insights described here can also be applied to support the development of commissioning plans for other future fusion devices and their respective sub-systems. Although the exact method likely needs to be adapted for the device and sub-system specific.

CRediT authorship contribution statement

P.C. de Vries: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **S. Rosiello:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **M. Cinque:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **T. Ravensbergen:** Writing – review & editing, Methodology, Data curation, Conceptualization. **L. Zabeo:** Methodology, Data curation. **M. Ariola:** Data curation. **I.S. Carvalho:** Writing – review & editing, Data curation. **G. De Tommasi:** Writing – review & editing, Methodology, Data curation, Conceptualization. **I. Gomez:** Methodology, Data curation. **O. Kudlacek:** Data curation. **M. Mattei:** Data curation. **I. Nunes:** Methodology, Data curation. **L. Pangione:** Writing – review & editing, Data curation. **F. Pesamosca:** Data curation. **L. Piron:** Data curation. **A. Vu:** Data curation. **D. Weldon:** Data curation.

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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The views and opinions expressed in this paper do not necessarily reflect those of the ITER Organization.

Data availability

Data will be made available on request.

References

[1] J.A. Snipes, et al., Overview of the preliminary design of the ITER Plasma Control System, Nucl. Fusion 57 (2017), https://doi.org/10.1088/1741-4326/AA8177.
[2] Y. Gribov, et al., Progress in the ITER physics basis: chapter 8: plasma operation and control, Nucl. Fusion 47 (2007) S385. http://doi.org/10.1088/0029-5515/47/6/S08.
[3] D. Humphreys, et al., Novel aspects of plasma control in ITER, Phys. Plasmas 22 (2015) 021806, https://doi.org/10.1063/1.4907901.
[4] M.L. Walker, P. de Vries, F. Felici, E. Schuster, Introduction to tokamak plasma control, in: IEEE American Control Conference (ACC), Denver, CO, USA, 2020, p. 2901. http://doi.org/10.23919/ACC45564.2020.9147561.
[5] P.C. de Vries, et al., Strategy to systematically design and deploy the ITER Plasma Control System: a system engineering and model-based design approach, Fus. Eng. Des. 204 (2024) 114464, https://doi.org/10.1016/j.fusengdes.2024.114464.
[6] M. Cinque, et al., Requirements management support for the ITER Plasma Control System in view of first plasma operations, Fus. Eng. Des. 146 (2019) 447, https://doi.org/10.1016/j.fusengdes.2018.12.088.
[7] M. Cinque, et al., Management of the ITER PCS design using a system-engineering approach, IEEE Trans. Plasma Sci. 48 (2020) 1768. http://doi.org/10.1109/TPS.2019.2945715.

[8] P. Barabaschi, et al., 114990 ITER progresses into new baseline, Fus. Eng. Des. 215 (2025), https://doi.org/10.1016/j.fusengdes.2025.114990.
[9] A. Loarte, et al., The new ITER baseline, research plan and open R&D issues, Plasma Phys. Control. Fusion 67 (2025) 065023, https://doi.org/10.1088/1361-6587/add9c9.
[10] The ITER Research Plan, ITER technical reports (2025) to be published. https://www.iter.org/scientists/iter-technical-reports.
[11] P.C. de Vries, et al., Preparing the Plasma Control System final design for ITER first plasma operations, Fus. Eng. Des. 129 (2018) 334, https://doi.org/10.1016/j.fusengdes.2017.12.020.
[12] L. Zabeo, et al., Work-flow process from simulation to operation for the plasma control system for the ITER first plasma, Fus. Eng. Des. 146 (2019) 1146, https://doi.org/10.1016/j.fusengdes.2019.02.101.
[13] T. Ravensbergen, et al., Strategy towards model-based design and testing of the ITER plasma control system, Fus. Eng. Des. 188 (2023), https://doi.org/10.1016/j.fusengdes.2023.113440.
[14] M. Mattei, et al., Recent developments in ITER magnetic control algorithms, Fus. Eng. Des. 222 (2026) 115492, https://doi.org/10.1016/j.fusengdes.2025.115492.
[15] L. Piron, et al., Error field detection and correction studies towards ITER operation, Nucl. Fusion 64 (2024) 066029, https://doi.org/10.1088/1741-4326/ad3fcd.
[16] L. Pangione, et al., Workflow for the assessment of ITER plasma control system design, IEEE Trans. Plasma Sci. 52 (2024) 3842. http://doi.org/10.1109/TPS.2024.3376955.
[17] S.D. Pinches, Progress in the iter integrated modelling programme and the iter scenario database, in: the proc. of the 27th IAEA Fusion Energy Conference, Gandhinagar. India, 2018. TH/P6-7, https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/FEC%202018/fec2018-preprints/preprint0741.pdf.
[18] P.C. de Vries, Y. Gribov, ITER breakdown and plasma initiation revisited, Nucl. Fusion 59 (2019) 096043, https://doi.org/10.1088/1741-4326/ab2ef4.
[19] M. Lehnen, et al., Disruptions in ITER and strategies for their control and mitigation, J. Nucl. Mat. 463 (2015) 39, https://doi.org/10.1016/j.jnucmat.2014.10.075.