Strategy to systematically design and deploy the ITER Plasma Control System: a system engineering and model-based design approach

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Abstract

The paper details the process of developing the ITER Plasma Control System (PCS), that is, how to design and deploy it systematically, in the most efficient and effective manner. The integrated nature of the ITER PCS, with its multitude of coupled control functions, and its long-term development, calls for a different approach than the design and short-term deployment of individual controllers. It requires, in the first place, a flexible implementation strategy and system architecture that allows system re-configuration and optimization throughout its development. Secondly, a model-based system engineering approach is carried out, for the complete PCS development, i.e. both its design and deployment. It requires clear definitions for both the PCS role and its functionality, as well as definitions of the design and deployment process itself. The design and deployment process is shown to allow tracing the relationships of the many individual design and deployment aspects, such as system requirements, assumed operation use-cases and response models, and eventually verification and functional validation of the system design. The functional validation will make use of a dedicated PCS simulation platform that includes the description of the control function design as well as plant, actuator and sensor models that enable the simulation of these functions. By establishing a clear understanding of the interconnected steps involved in designing, implementing, commissioning, and operating the system, a more systematic approach is achieved. This ensures the completion of a comprehensive design that can be deployed efficiently.

1. Introduction

The ITER Plasma Control System (PCS) serves as the central control system responsible for operating the tokamak and controlling the plasma therein. A tokamak is a device that utilizes magnetic fields to confine plasma, allowing it to be heated to temperatures necessary for thermonuclear fusion. Currently being constructed in the southern region of France, the ITER tokamak is a crucial component of the global initiative to harness fusion energy as a viable and sustainable power source [ITER, Bigot2019]. The primary goal of the ITER plasma is to achieve a Q value of 10, indicating the production of ten times more fusion energy than the energy required to sustain the plasma [IPB2007].

A tokamak is operated in pulses, during which a hydrogenic gas can be ionized to form a plasma discharge, through which a current is generated. The plasma is confined by means of magnetic fields provided by external (super-conducting) magnets as well as the magnetic field generated by the current that runs through the plasma. In the case of the ITER tokamak, the plasma will consist of a mixture of the hydrogen isotopes Deuterium and Tritium. The system aims to attain a plasma current of 15MA, with a primary external magnetic field strength of 5.3T. The volume occupied by the plasma will be approximately 800m³.

During a plasma discharge, the plasma current is ramped up to its desired value, in ITER up to 15MA, then kept constant (flat-top) during which auxiliary heating systems heat the plasma to the desired thermonuclear temperatures, towards the end of the pulse, the current is ramped down again. This entire scenario is to be controlled fully autonomously by the PCS, meaning, without any outside intervention. This means, the pulse is prepared in advance, configured by the so-called pulse schedule, after which the pulse is launched under PCS control. The PCS is concerned with synchronous or continuous control, i.e. providing feedforward and feedback control to a multitude of plant and plasma parameters. Moreover, the PCS will act asynchronously on events that will require it to alter its path or control strategy, also referred to as event or better as exception handling. A tokamak pulse can be viewed as the flight of an aeroplane, with its take-off (i.e. plasma initiation), ascent (i.e. the current ramp-up), cruising at a fixed altitude (i.e. the current flat-top), descent and landing (i.e. the current ramp-down, and pulse termination). This is all done fully automatically following the prepared pulse schedule (the “flight path”) except if events require the PCS to change the strategy. At a higher level, tokamak operation involves the repeated execution of pulses with plasma discharges.

The many control functions that are required to provide the control actions needed for ITER plasmas, and, in more general, of pulses, have been the focus of many tokamak research studies and publications [Gribov2007, Humphreys2015, Walker2020]. This paper will, however, deal specifically with the strategy of how the ITER PCS software is designed and developed. The design process of a single control function can still be outlined with a certain simplicity. However, this will become increasingly more complex when considering the entirety of the ITER PCS functions with their interactions. Furthermore, ITER control design and deployment solutions are strongly driven by its nuclear mission, with tight commissioning constraints for which only a limited number of operational discharges are available. Hence, the commissioning and deployment of controllers should be more efficient relative to current devices.

There are a number of issues that need to be considered in this respect. Firstly, the ITER PCS is known to require a certain degree of functional integration. Hence, it is not simply a collection of a large number of independent controllers, but many control functions are coupled to some extent. The coupling is the result of the complex and non-linear plasma response to PCS control actions but is also due to the use of the same sensors and actuators for different control functions and to the availability of different sensors and actuators for the same control functions. At the same time, all PCS control functions will have to carry out a coordinated response in case of events. This paper will address various strategies and tactics to help to manage this coupling between functions, with respect to their design and deployment. A second aspect to consider relates to the uncertainty of the plant and plasma behaviour and sensor input models. The ITER tokamak will operate plasmas in a range, no previous fusion device has operated before [Ikeda2007]. The uncertainty of response models requires that a certain redundancy and robustness is built into the design, while also ensuring that the control functions remain configurable to allow tuning and optimization during their deployment in the early stages of ITER operation. The ITER plant, and thus the PCS as well, will be developed in stages, step by step expanding its operation range, and ensuring proper plant and plasma model validation, before going to full-performance operation. Development time scales of years and decades need to be considered. This differs from the development of controllers that have a faster turn-around time, between design and deployment, such that operation experience is fed back into re-design. Therefore, any design choices made at the early stage should still be understandable, in the many years, requiring a more stringent approach to the design documentation, allowing us to efficiently trace and justify design choices and requirements. In contrast to the design of simpler, singular control functions, the design description is not just meant as a reminder for the individual designer but aimed at larger or even different teams. The design description and commissioning plans should be such that they help a larger design team make sense of the overall design integration, provide efficient information for those who are involved with the implementation and clarity to those who will eventually commission or operate the system, even many years later.

This paper will first, in section 2, review the role and functions of the PCS, and the issues that may arise to design and deploy such a complex system. It will provide a brief introduction to the ITER PCS, its basic functionality and the plans to deploy it. Except for a few examples, this paper will not provide details on all its control functions and related design choices, because these are better described in previous publications. Nevertheless, a view of the multitude and interconnection of all these functions is needed to understand the complexity of the overall PCS design task. This includes complex functions such as the prevention and avoidance of discharge disruptions. Here a disruption is a very sudden, violent, interruption of the discharge that can lead to excessive heat loads and electromagnetic forces on the device [Hender2007, Lehnen2015]. In the comparison of a plasma discharge with the flight of an aeroplane, it can be considered a crash, thus something that should be prevented. A transparent design is not possible, if such definitions are not clear, which also counts for the PCS development process as a whole. Section 3 reviews those aspects that are to be considered the foundation on which the function design rests. It will introduce the ITER PCS implementation approach and discuss how interfaces with various other ITER systems are managed. Note that this paper focuses on the design of the PCS software, which is decoupled from the hardware design running real-time applications. The PCS architecture is outlined, explaining how this simplifies various aspects of the PCS functional design. Moreover, it introduces the platform that has been prepared to simulate PCS functionality. Section 4 discusses two pillars of the strategy to design the PCS; the system engineering approach [Devries2018] and the application of model-based design [Humphreys2015]. This section details the proposed design workflow. Firstly, the emphasis lies on the systematic and formalized description of the design of all functions in all its aspects, from its high-level requirements to detailed specifications, analysis, verification and validation activities and eventually the procedures to deploy the control functions [SEBoK]. Important is the ability to understand and document the relationship between the aspects considered during design and tasks that are to be done to commission the system, which is especially relevant for an integrated system such as the ITER PCS. Secondly, model-based design is systematically applied, and hence the selection of plant and plasma response models, as well as the ability to simulate the PCS functions play a central role in the design process. The choice of such models is crucial to the design and such choices should be well-founded and clearly recorded by the design description. Section 5 breaks down the PCS deployment process, from implementation, and commissioning to operation. It will be shown that each step in the deployment process can be more clearly defined by directly deriving them from design aspects, such as system requirements, but also response model assumptions. Thus it will be shown that the PCS commissioning plan is systematically derived from its design. Section 6 summarizes the ITER PCS development strategy, showing that its approach ensures a more systematic, transparent and flexible design description, that will ensure a more effective and efficient deployment of the system, even if lasting decades.

2. Review of the ITER PCS

Usually the emphasis on explaining the ITER PCS lies on its functions, but before that it is important to understand its role in the overall concept of ITER operation. To facilitate the system design, the role of the PCS as part of the overall ITER plant control and tokamak operation should be well defined, allowing high-level requirements to create a conceptual breakdown of its functions and interfaces with other ITER plant systems that act as actuators or sensors. This section defines the role of the PCS and reviews its functional breakdown, highlighting the complexities related to the required level of functional integration and the staged development of the system.

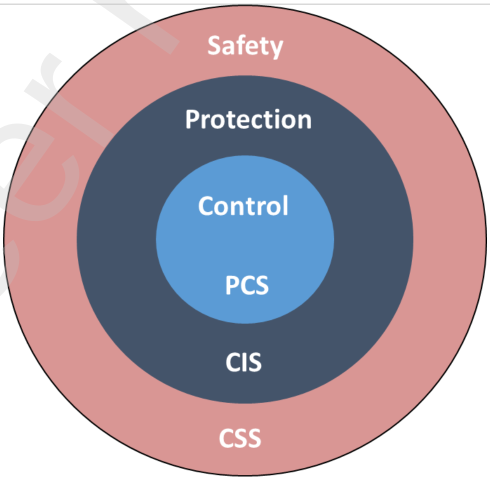
2.1 The role of the PCS

The ITER PCS is part of overall ITER plant control [Wallander2013]. Besides the PCS, this consists of the plant supervisory control, systems that ensure plant safety and those that protect plant components against damage. The PCS is, however, the core system relevant to ITER tokamak control.

Tokamak operation is done in pulses. During an ITER pulse, the PCS provides fully autonomous and integrated control of those systems needed to facilitate the pulse scenario. One could say that, PCS control and executing an ITER pulse are synonymous. An ITER pulse is often confused with plasma, although a plasma discharge can be, but is not necessarily, part of a pulse. Thus one can run a pulse (i.e. under PCS control) without a plasma discharge, for example, to test individually tokamak functions or sub-systems. An ITER pulse is prepared by the ITER plant supervisory control, by configuring the plant systems, including the PCS that are required by the pulse scenario or pulse schedule. For example, it ensures that those ITER actuator systems, such as magnets and their power supplies, or sensors and plasma diagnostics, as required for the pulse scenario, are in the right state and configuration. When all required systems are ready, the plant supervisory control will initiate the pulse by handing over control to the PCS [Wallander2013]. The pulse ends with PCS handing back control to the plant supervisory control and local plant system controllers. The Pulse Schedule Preparation System (PSPS) contains and allows the editing of the pulse schedule, i.e. all the information for executing an ITER pulse, with or without plasma. It includes general parameters, operation limits, plant system configuration parameters (including the PCS configuration), and an ordered sequence of tasks and targets that the PCS will aim to execute. In the context of the flight of an aeroplane, it can be considered the flight plan, and all the required attributes to carry out the flight plan, including often alternative paths. The pulse schedule differs from a physics operation scenario which an intended evolution of a tokamak discharge. The latter can be translated into reference signals for the PCS to control. Many possible physics operation scenarios have been simulated to assist the ITER plant and also the PCS design. Furthermore, such simulations are also done to design the pulses in preparation for their translation into a pulse schedule to be executed by the plant, reducing operational risk. Such simulations of physics operation scenarios are the first link to the model-based design of the PCS, discussed in section 4.

During a pulse, the PCS will have to avoid operation limits. Such limits are often related to the avoidance of damaging plant components. However, ITER PCS is not responsible for device protection. The ITER defence-in-depth strategy provides machine protection and safety, independent from the nominal Tokamak control, e.g. the PCS. Nevertheless, the PCS can be regarded as the first line of defense for machine protection aiming to avoid activation of the dedicated ITER machine protection provided by the Central Interlock System (CIS) [Vergara2011, Fernandez2018] that includes the Advance Protection System (APS). If the PCS limit avoidance is ineffective, and CIS or APS protection limits are exceeded measures can be taken to mitigate any impact on the device often enforcing the termination of the tokamak discharge and the ITER pulse. Figure 2.1 shows this multi-layered protection concept, which provides redundancy to the overall protection function, thus increasing reliability, though also enabling flexibility to the design and deployment of the ITER PCS.

Figure 2.1: Multi-layered concept of ITER machine protection and safety, during pulsed ITER operation, with PCS preventing and avoiding the plant and the plasma discharge to exceed the protection limits, which is separately guarded by the Central Interlock System (CIS), while above this the Central Safety System (CSS) ensures the plant safety. Outside pulsed operation, the plant supervisory control takes the role of PCS.



2.2 The PCS functional breakdown

The PCS will deploy continuous (feedback and feedforward) control as well as asynchronous control, later referred to as so-called Exception Handling (EH). The PCS can conceptually be broken down into the following high-level functions [Gribov2007, Snipes2014, Snipes2017]:

1. Magnetic control
2. Kinetic control
3. Instability control
4. First Wall Heat Load (FWHL) control
5. Control of some methods of wall conditioning
6. Exception Handling (EH)
7. Disruption prevention and avoidance

These high level functions can again be broken down further into specific control functions, which will be summarized below, while detailed design considerations can be found in the in the references.

2.2.1 Magnetic control: concerns the control of current in the ITER magnets, with the exception of those that generate the tokamak toroidal field. The control of the latter are outside the scope of the PCS, because these ITER magnets are to be charged for a duration significantly longer than an ITER pulse. However, all other magnets are under PCS control. This includes the 6 Poloidal Field (PF) coils, 6 Central Solenoid (CS) coils, the Correction Coils to reduce the so-called Error Fields (EF) and, finally, coils installed in-vessel to improve the response time. These in-vessel coils are used to improve the plasma Vertical Stability (VS) control and also to provide Resonant Magnetic Perturbations (RMP) that can be used control so-called Edge Localized Modes (ELMs). Magnetic control concerns steering the combined PF and CS coil currents such that a plasma is induced, after which these coils are used to control both the toroidal current flowing through the plasma and, importantly, the plasma magnetic equilibrium [Walker2020, Ariola2016, Detommasi2019]. The latter involves controlling the plasma shape in relation to the First Wall (FW) (e.g. exactly where it touches the FW and the gaps that are maintained elsewhere). Real-time information on the plasma magnetic equilibrium can be deduced, predominantly, by processing a large number of magnetic sensors that are installed close to the tokamak plasma [Vayakis2012]. The same set of magnetic coils are used as actuators to carry out multiple control functions. Hence, tokamak magnetic control designs often need multiple input multiple output (MIMO) approaches. The vertical position of an elongated tokamak plasma is not stable, requiring the PCS to actively maintain plasma VS. In-vessel poloidal magnets are to be used here, to guarantee marginal stability for possible highly elongated and high internal inductance plasmas [Humphreys2009].

2.2.2 Kinetic control: which includes the control of the fuelling, i.e. the plasma particle content or so-called plasma density control [Blanken2018, Ravensbergen2018], as well as control over the various means of auxiliary heating systems that ITER has available. ITER plans to heat plasmas by the injection of energetic Neutral Beams (NB) or high powered Radio Frequency (RF) waves resonant with either the ion or electron cyclotron frequency in the plasma, i.e. Ion and Electron Cyclotron Heating (ICH and ECH). However, the ECH system is not merely used to heat but also as an actuator for a large number of other functions, such as assisting the plasma initiation, current drive, temperature profile control, and, as will be shown later, instability control [Henderson2015]. With respect to kinetic control, it is important to realise, that in contrast to current tokamaks that operate at $Q<1$, for which the auxiliary heating systems dominate plasma heating, ITER aims to operate in a regime ($Q>5$) in which the impact of auxiliary heating systems is reduced and the plasma is predominantly heated by energetic α-particles resulting from the DT fusion reaction. This means that in such situations, auxiliary heating systems have a less direct effect on the plasma itself.

The ITER plasma can be fuelled by a large number of valves that can release different types of gasses, or by injecting cryogenically frozen pellets of H, D or T. However, ITER also requires more advanced functions such as the control over the distribution (i.e. profiles) of density and pressure inside the plasma [Joffrin2003, Laborde2005], the content of impurities in the plasma and eventually the control over the fusion burn [Pajares2019, Graber2021], i.e. ensuring that the plasma conditions are kept such that the amount of fusion energy that is generated remains stable. The latter requires coordinated control of the plasma temperature (i.e. by auxiliary heating), the density as well as the D and T mixture of the plasma (i.e. by combined fuelling of D and T), and possibly managing various instabilities that can be driven by high energetic fusion products, such as Toroidal Alfven Eigenmodes (TAE).

2.2.3 Instability control: concerns the active and passive control of many types of instabilities that affect a tokamak plasma [Hender2007, Gribov2007]. In the first place, this concerns the VS control and EF control by means of ITER magnets, already mentioned above. Secondly, Tearing Modes (TMs) are to be controlled by means of the ECH system, especially those driven neo-classically, the so called Neo-classical Tearing Modes or NTMs [Lahaye2006, Henderson2015]. Furthermore, Resistive Wall Modes (RWM) and the above-mentioned TAEs all can have a detrimental effect on the tokamak plasma performance and measures need to be in place to avoid or regulate these instabilities [Ariola2014]. ELM control can also be seen as a form of instability control, though this function is usually listed under the control of heat loads.

2.2.4 First Wall Heat Load (FWHL) control: concerns the control of the heat flux from plasma to the FW [Pitts2011]. The actively cooled ITER FW is designed such that it can sustain very large heat loads and temperatures. Nevertheless, the PCS should control the main-chamber heat loads within the FW design limits, in the first place, by the above-mentioned plasma equilibrium and gap control [Pesamosca2023]. It will also require the PCS to interpret information from multiple camera systems that monitor infrared and visible images of the FW during a plasma discharge. The highest power densities are managed by the ITER divertor which is the part of the device that extracts the highest fraction of the power exhausted by the plasma. These power densities are regulated by the PCS via the plasma detachment, which is the simultaneous reduction of the divertor target temperature and particle flux. Such a reduction is achieved by dissipating power, momentum, and particle flux along the open field lines that connect the outer parts of the main-chamber plasma to the divertor. It requires control of high plasma densities in the divertor and the injection of low-Z impurities to regulate the radiative power dissipation [Pitts2011, Loarte 2007]. It should be clear that the FWHL control function in general couples various aspects of magnetic control and kinetic (fuelling and heating control) control.

ELM control can also be considered another aspect of FWHL control [Loarte2007, Loarte 2014]. ELMs occur during a specific high-confinement mode of tokamak operation (so-called H-mode in contrast to L-mode. These ELMs cause transiently large heat loads and hence this instability should be carefully controlled. To this end, ITER will mainly deploy the RPM coils but it can also do it by fast-paced injection of pellets that would increase the frequency of these events and minimized their impact.

2.2.5 Control of wall conditioning: concerns ITER pulses that are carried out such that a cold, high-density plasma is generated, by means of either ICH or ECH heating [Wauters2020]. Such Wall Conditioning (WC) pulses require the deployment of the ITER magnets, fuelling and RF heating systems and are thus done under PCS control. These plasmas differ from a full-blown tokamak plasma discharge and are specially created to enhance the outgassing (i.e. conditioning) of the FW, in preparation for further tokamak plasma operation [Wauters2020]. The execution of ICWC or ECWC pulses can be seen as a distinct PCS operation mode, separate from PCS tokamak plasma operation and PCS integrated system commissioning without plasma.

2.2.6 Exception handling: has come up several times already, and concerns the asynchronous response by the PCS to events that cannot be handled by continuous controllers [Walker2020, Raupp2012]. At ITER, exception handling (EH) is regarded as the response of the PCS to rare occurrences. Thus it does not merely concern the detection of events, but also the rules to respond and the selection of the most appropriate handling policy. It includes the response of the PCS to reported faults by actuator systems, sensors, or indicators from the plant or plasma itself. The PCS response to these events is to be managed fully autonomously, hence, events are not alarms to trigger external (e.g. human) interference, but the system will have to decide by itself what the best response is. Importantly, the EH requires in many cases a coordinated response from various control functions. This is for example the case, for terminating a plasma discharge which requires coordination of various aspects of magnetic, kinetic and instability control.

EH is an often underestimated aspect of a tokamak control system and its design requires some level of integration. The complexity lies in the scale of the overall EH component in the PCS, which can include a large amount of possible events, with different response rules and possible handling policies. For ITER First Plasma operation the number of events that can lead to exceptions, was several dozen, but the PCS design for first standard tokamak operation at ITER will require hundreds of events. The number of events for EH The investigation of all possible events under all circumstances (i.e. at any time during an ITER pulse), including how to deal with concurrency, i.e. handling the response of concurrent events, is a near-impossible task. The complicated coordination of responses by different control functions in response to specific events further exacerbates this problem. In the later sections, EH will therefore get special attention to ensure that its design and deployment avoid the ad-hoc nature that it traditionally gets. It requires a proper architectural layout, dedicated design description and careful management of the design tests and deployment plans, to keep this function manageable.

2.2.7 Disruption prevention and avoidance: concerns an important function for a tokamak to prevent and avoid disruptions [Strait2019]. The PCS prevents disruptions through its continuous control ensuring that disruption-critical parameters remain within their limits (the synchronous control aspect of PCS). For example, it will have to control the plasma density such that it remains below the empirical Greenwald-limit, or the normalized plasma pressure below the Troyon-limit, above which the plasma is known to disrupt

[Devries2011]. The PCS also provides active control over various instabilities that, when uncontrolled, can also lead to a disruption. Disruption avoidance concerns the asynchronous PCS response to events that may lead to a disruption. Hence, disruption avoidance can be seen as a sub-group, of general EH by the PCS. Clearly, PCS disruption prevention and avoidance concerns a sub-set of the control functions and exceptions, respectively, which are closely related to disruptive limits, instability control and the response to events most closely related to the onset of disruptions.

Disruptions can be caused by a complex chain of events that step by step lead to further destabilization of a tokamak discharge [Devries2011, Devries2015]. This may start, with events related to the actuator faults that lead to control errors that bring the plasma outside its stable operation range, triggering instabilities that can grow to disrupt the plasma. Figure 2.2 shows a generic tree of such event classes. PCS exception handling determines the appropriate response to such detected events, breaking the chain and avoiding a disruption. Some of the event classes shown in Figure 2.2, such as a simple actuator faults are not considered part of disruption avoidance, simply because significant escalation is needed to end up with a disruption, and an effective response by the PCS is easily achieved. Hence, the likelihood that they lead to a disruption is low and traditionally such events are not linked to disruption avoidance. While others, like the loss of VS control almost always lead to a disruption. Certain events are known to be clear precursors to a disruption. If a certain exception is to be considered part of disruption avoidances can be determined by; the likelihood of a disruption in case an event occurs, the length of the chain-of-events needed to escalate things to disruption and the relationship of the event to the detection of disruptive operation limits and precursor instabilities linked to disruptions. A nice example of a system that detects multiple events for disruption avoidance purposes is the DECAF code [Sabbagh2023].

It should be stressed that disruption avoidance is here defined as a set of many different responses to events that indicate the discharge may disrupt, which differs from the more generic concept of disruption prediction that aims to determine the likelihood of a disruption, by combining the information from a multitude of indicators or events. However, the fact that such predictors would amalgamate information on multiple, often non-linear, physics processes (e.g. different destabilizing events) shows that it complicates the interpretation of the prediction and thus also its use by the PCS.

At ITER, the utilization of disruption mitigation measures, by means of the so-called Disruption Mitigation System (DMS) [ITER-DMS], is not regarded as the duty of the PCS. As discussed in section 2.1, if the PCS cannot avoid a disruption any more, and a disruptive end of the tokamak discharge is (predicted to be) inevitable or detected to have started, a higher-level protection system, is responsible for triggering the ITER DMS [Devries2016]. A clear separation between the function to avoid (i.e. by the PCS) and the one to mitigate the impact of an ongoing disruption (i.e. by the ITER CIS), following the approach shown in Figure 2.1, prevents possible fault propagation between the different systems and adds redundancy to the overall function to manage with tokamak discharge disruptions, making it more robust.

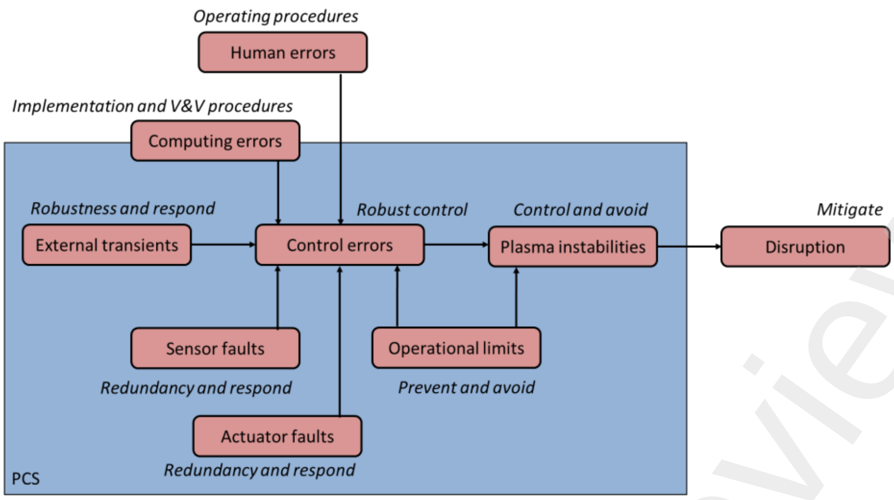


Figure 2.2: Classes of events that can escalate and further complicate of the tokamak discharge control, eventually leading to a disruption. This is a generalization of the analysis developed in ref. [Devries2011, Devries2014]. Those classes that will be managed within the ITER PCS, fall within the box. Human errors can occur due to the erroneous configuration of the plant or the PCS, prior to a pulse. In italic text a general indication is given of the response to these event classes that prevent them, avoid propagation or mitigate their impact.

2.3 Functional integration

The functional breakdown, shown above, aids the design as often different disciplines and knowledge of plasma physics, actuators and diagnostics is needed, resulting in different design teams working on these functions. Traditionally many of these functions were developed individually, however, the level of required functional integration needed for ITER operation is significantly higher than in current tokamaks.

It should already be clear from the summary in section 2.1, that there is considerable overlap and coupling between functions. There are different degrees of functional coupling and also different reasons for this coupling. To a lesser extent this is due the fact that control functions may make use of the same sensors or diagnostics, but a stronger coupling originates from both the fact that the plasma or plant response to actuation due to different controllers is coupled, while also multiple control functions may have to share the same set of actuators (actuator sharing). As an example, pacing ELMs with pellets also fuels the plasma with these pellets, hence the plasma particle content (density) control and this type of ELM control are coupled. A further example concerns the control of the plasma position and the exact plasma shape done by changing the current in the set of 6 PF and 6 CS coils. The behaviour of the currents in these coils is coupled, while they also will have to control the current at the same time, requiring more complex multiple input multiple output control schemes. The need for actuator sharing is evident when the role of for example ECH for plasma control is considered, which will be used to assist plasma initiation, used to heat the plasma, drive current and mitigate NTMs. Clearly the ITER ECH system is not merely a single actuator to provide auxiliary heating to the plasma but a highly complex system that allows various ways of actuation [Henderson2015]. This is reflected in a complex interface between the PCS and the ITER ECH system. Various means of actuator management need to be in place, both in the PCS as well as in the ECH system local controller, to allocate the right actuator capacity to each control function.

Another example of the need for integration is the important aspect of a coordinated response, of various control functions to specific events, which was already mentioned when discussing EH in the previous section. Terminating a tokamak discharge will require a coordinated ramp-down of the plasma current, while maintaining control of the magnetic equilibrium, VS, simultaneously reducing the plasma thermal energy (heating) and particle content (fuelling), while at the same time avoiding various stability and control limits [Devries2018b]. Without possible control coordination, the development of a robust and stable discharge termination will be significantly more complex.

Figure 2.3 compares the concept of a single control function, with a set of coupled control functions. The single feedback control loop considers the plant response, due to actuation by an actuator, as requested by a controller, based on measurements of this plant response by specific sensors as shown on the left (in Figure 2.3a). Pure feedforward control may concern only the regulation of actuator based on predefined waveforms (i.e. the left side of the loop), however, the sensor input may be needed for EH related to the feedforward control. This can be compared the more complex picture on the right (Figure 2.3b). Here the plant and plasma can be considered as a collection of simple or more complex models that are coupled, although the degree or strength of this coupling may vary. The response is measured by a set of sensors that diagnose various parameters, and in some cases, carry out data processing that again may require input from other sensors. The actuators each differently impact the plant or plasma, and in some cases, the internal control of the actuator system may assist the PCS by interpreting the controller actuation request to optimize the use of the actuator system. In other cases, this actuator management is done on the controller side. It can be seen that the set of controllers, shown in Figure 2.3b, deal on one side with the sensor information processing and on the other side with the management of the actuation requests. This breakdown of control functions will come back when describing the ITER PCS architecture, in section 3.4.

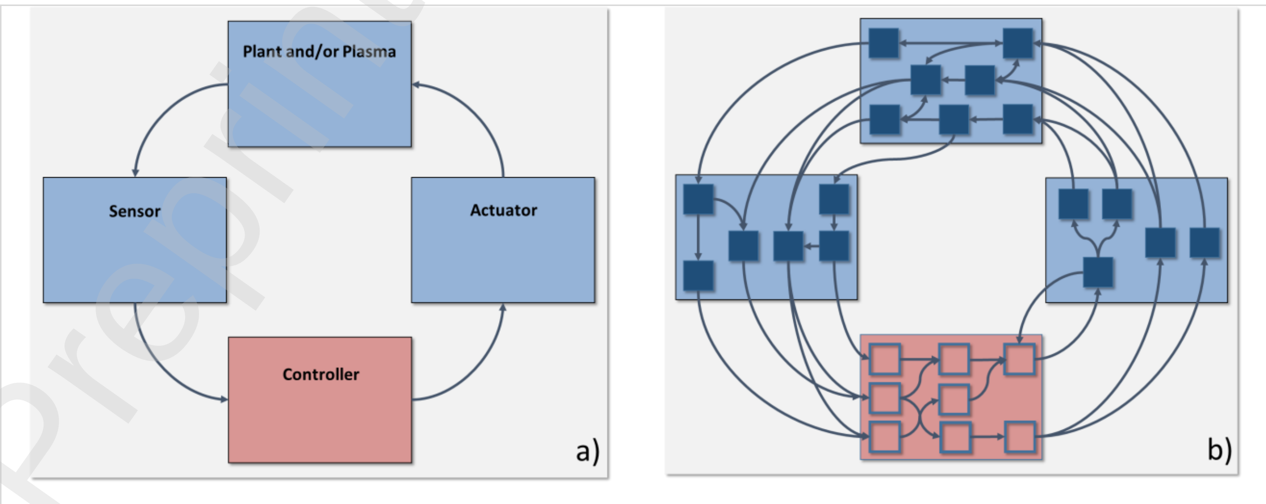


Figure 2.3: a) an individual control loop to be considered when designing a control function, linking the control function, via actuators to the plant, and sensors providing the data needed for the regulation. b) a representation of a still simple picture of a control system, not just one function, that is linked to multiple actuator and sensor systems, and a plant making up of many individual response models, that might be linked by different degrees of coupling. All closed boxes represent models, either plant models, or actuator or sensor system models. The open boxes represent control functions, not necessarily only feedback controllers, but also those dealing with exception handling, data processing or actuator management. Feedforward control could be considered

If a functional breakdown is carried out, similar to that discussed in section 2.1, and the coupling between each function is indicated, this can be developed into the sketch shown in Figure 2.4. It goes too far to discuss here each element of this study but it illustrates the level of complexity of the PCS. This analysis was used to provide an understanding of the architectural requirements for the PCS that will be discussed later in section 3.4. One node with a high level of connectivity can be identified, as the waveform generator, while two other nodes, relate to magnetic control (equilibrium reconstruction) and fuelling control, which are listed in section 2.1 as the highest level functions needed for tokamak control. Special analysis techniques can be applied to identify nodes of high coupling to aid the designs of complex systems [Beernaert2023].

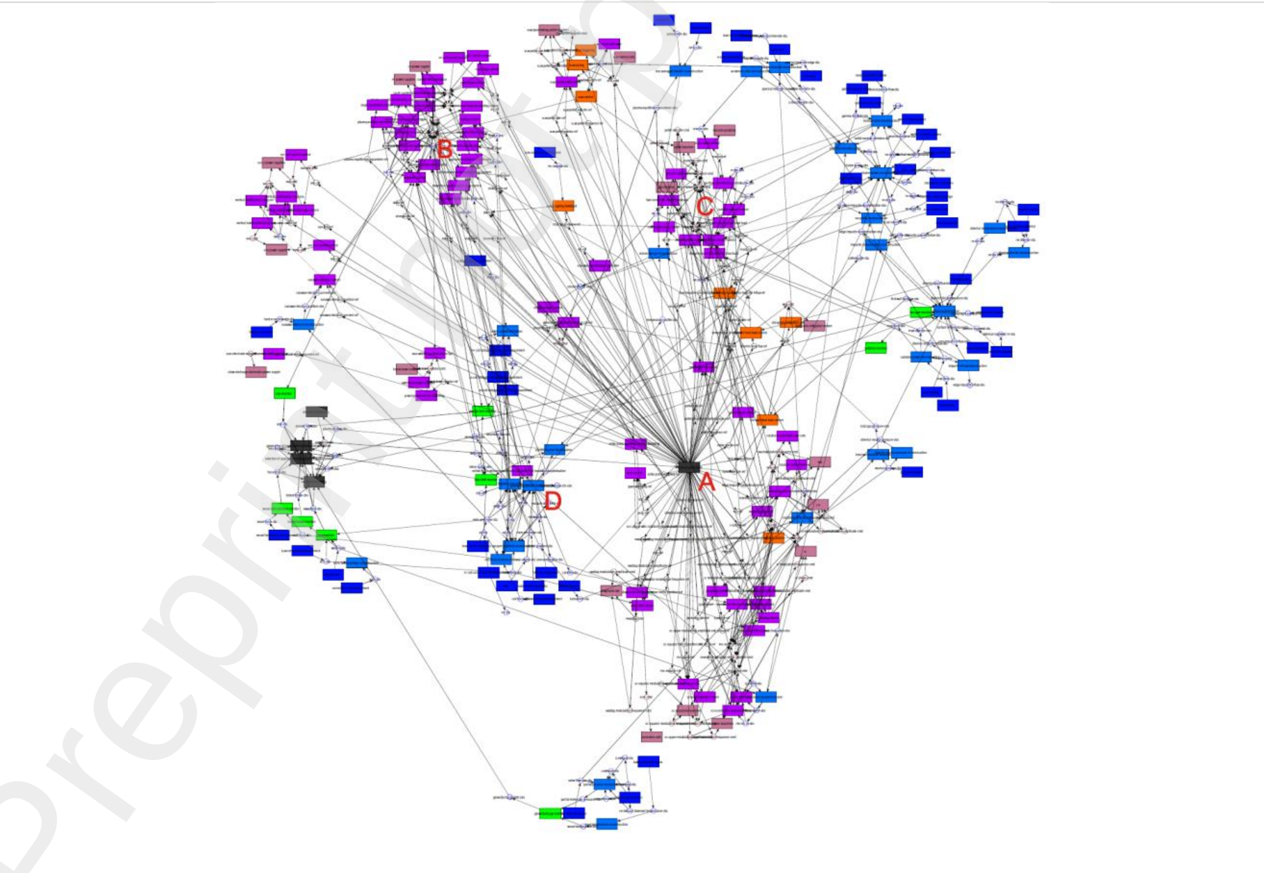


Figure 2.4: Sketch highlighting the complexity of the ITER PCS by showing a dependency graph of ITER PCS control functions, as defined by the PCS conceptual design [Treutterer2014]. The colours indicating different types of control functions such as: support functions managing diagnostic data input (in blue), monitoring support functions (in green), basic control functions such as controllers or exceptions (in purple) and functions that manage the interface with actuators (in pink) and supervisory components such as waveform generation functions (in black). One of the key central notes in the web of connections is the PCS function that manages the generation of waveforms to all other control functions. Important nodes with high levels of connectivity between PCS functions can be identified as: the waveform generator (A), functions needed for magnetic control (B), fueling control (C) and the support function providing equilibrium reconstruction (D).

Although a lot of the PCS functions described above have been tested to some extent in current tokamak experiments, ITER will be the first device for which these functions will have to be fully integrated into the design and to be deployed simultaneously during its pulses. ITER will be the first tokamak that truly requires the control of ELMs and detachment control while putting more stringent requirements on instability control and disruption avoidance. Actuation capacity at ITER is also relatively more restricted. The capacity of available fuelling and heating systems is a balance between the needs and the size and cost of such systems. Moreover, specific issues could also affect the capability of these actuators. For example, the penetration of gas particles and pellets will be shallower in the hot ITER plasma edge than in current devices, making fuelling less efficient. While operation at Q>5 means that the plasma is heated predominantly by the energy released from fusion reactions, hence relatively less auxiliary heating is required. This however contradicts applying such heating systems for other control needs, such as current drive or NTM control. This adds to the already complicated balancing act the ITER PCS has to conduct with respect to actuator management.

2.4 The staged development of the ITER PCS

A strategy, as described in this paper to design the PCS, is not equivalent to a plan but allow one to optimally planned development of the PCS in relation to the overall development of the ITER plant itself. ITER operation is broken down into stages. The ITER plant capabilities are progressively extended, adding new heating, fuelling and diagnostic systems at each stage, expanding the operation range of the device each time, to reach the project target. The ITER Research Plan (IRP) is aligned with this staged approach, ensuring that sufficient knowledge is obtained at each stage, to ensure a smooth and effective path towards high-performance tokamak plasmas that create sufficient fusion energy to dominantly heat itself [IRP2019, Campbell2023].

This means that at each stage new functionality will have to be added to the PCS, or the performance requirements of existing functions will change. Therefore the PCS development is also aligned with the ITER staged approach and a new version of the system is designed and implemented for each stage. On the other hand, the PCS will also benefit from the knowledge obtained from ITER operation itself. Such knowledge may come from, for example, new plasma physics insights, the validation (or invalidation) of plant or plasma models assumed by the PCS design) or practical information, such as the actual characteristics of diagnostic signals (e.g. noise) and actuator behaviour (e.g. reliability), that allow one to optimize the PCS. Especially at the early stage of ITER operation, the experiments that are planned as part of the IRP focus specifically on control studies. This staged development ensures the PCS design is focussed avoiding development of functions that are not yet required and are better designed at a later stage.

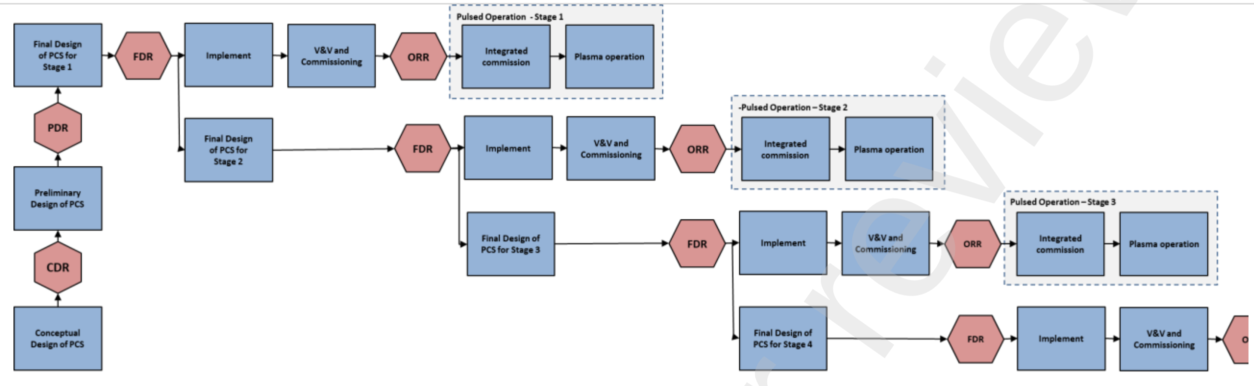


Figure 2.5: The staged development of the ITER PCS, with new versions designed and implemented for each stage. This can mean improving existing functions based on operation experience in earlier stages, or creating new functions due to newly available actuators, sensors, or new performance requirements as the tokamak plasma performance increases progressively at each stage.

This process is shown in Figure 2.5, initiated with the ITER PCS Conceptual Design, its Conceptual Design Review (CDR), its Preliminary Design and Review (PDR), after which the Final Design of the PCS functionality needed for the first operation stage is carried out which is completed with a formal Final Design Review (FDR). After the design review and approval, this specific version of the PCS can be implemented, i.e. coded and deployed on target hardware. This aspect is further discussed in section 3.3. The PCS deployment then continues with System Commissioning (SC) that allows verifying that the system is ready for ITER operation, the so-called Operation Readiness Review (ORR). At that point this specific version of the PCS can be used for ITER pulsed operation, initially executing so-called ITER Integrated Commissioning (IC), running pulses without plasma, to integrally test all required systems, including the PCS, before commencing ITER Plasma Operation (PO). As shown in Figure 2.5, the PCS design for the next operation stage will be carried in parallel, with the ongoing implementation, commissioning and operation of the previously design version. This process is repeated for each of the ITER operation stages. Of course, certain PCS functionality can only be fully commissioned during actual plasma operation itself. The PCS design and commissioning process should minimize the risk that the required functional performance is not met during plasma operation. In Figure 2.5, illustrates a highly structured and rigid workflow, a crucial requirement within large projects such as ITER. This level of structure is vital for efficiently managing work that encompasses a multitude of individuals, diverse groups, and intricate interactions with other concurrently designed and deployed ITER systems. However, as we delve into Section 4, it becomes apparent that the PCS design thrives when an agile approach is employed. A delicate balance should be achieved between the necessary agility and rigidity. The first steps of the PCS development, following the process shown in Figure 2.4, have already been completed. The ITER conceptual [Snipes2014] and preliminary designs [Snipes2017] were finalized out in 2012 and 2016, respectively. The final design for what is currently defined as the first operation stage, ITER First Plasma operation, was completed and reviewed in 2020 [Snipes2021] and is currently (in 2024) been implemented and commissioned.

In the analogy of a pulse being similar to the flight of an aeroplane, ITER plant operations and the organization of an operation stage could be considered managing an airline or an airport. ITER operation stage may consist of roughly a year or more of operation and concerns hundreds of pulses. This may sound a lot but is generally significantly more constrained compared to current tokamak experiments. The ITER operation space is planned to expand relatively quickly, also pushing operation into a range, in which no tokamak has yet operated, i.e. burning fusion plasma operation. Thus, all tests and experiments during each stage should be focussed on obtaining sufficient information to allow, for example, operation at a higher current. For the PCS deployment this means, that the system should be fully prepared for all possible operations planned in that operation stage. Moreover, its design should incorporate possible uncertainties by allowing the control functions to be configurable. This in contrast to redesigning and recoding functions during operations. The latter carries risks of loss of operational time or may generate control errors that in the worst case could result in an increased number of disruptions. The ITER PCS design should mitigate this risk by:

1) imposing a systematic design method to all PCS functionality,
2) providing a clear set of requirements to be met at each stage,
3) planning configurability by designing different possible options for control functions,
4) developing behavioural models to allow a systematic simulation of functionality,
5) anticipating model uncertainties and external perturbations when assessing functions,
6) preparing an efficient system deployment (e.g. commissioning),
7) ensuring all design and deployment information is documented in a structured way.

To clarify these points, it should be noted the design of PCS functions for current tokamak experiments can follow various strategies. Some have been modelled in detail prior to the start of tokamak operation. For example, no tokamak can be designed without understanding the VS control capabilities [Humphreys2009]. However, other functions, such as ELM or detachment control, are usually developed in a more ad-hoc trial-and-error fashion, with the risk that the understanding of certain design choices is lost, or the coupling with other functionality is not fully understood. A trial-and-error approach allows one to easily adapt finding for example more suitable sensor signals or thresholds based on experimental evidence, but is time-consuming and clearly allows control errors as part of its approach that cannot be tolerated at ITER. To reduce the risk of losing time, and finding sufficient information to optimize functions during the operation stage, the ITER design will have to ensure, that for all control functions, clear knowledge is available on what sensor data is to be expected and also be able to estimate what the actuator response might be. As will be discussed in section 3.2, this is not an easy task. It means that a model-based design approach is to be imposed on the complete PCS, and not only a few functions, allowing simulations of these functions to assess their performance, as will be presented in section 4.3. Furthermore, all functions need to have a clear plan on how to be commissioned. The means one has to understand, how to systemise the commissioning, to ensure more effective and efficient deployment of the function. This is closely linked to design verification and model validation while also supporting control optimization by re-configuring control functions, as will be outlined in section 5. The final point relates to the fact, that individual control functions are often designed by small teams that deploy them over short periods of time. Smaller teams or sometimes individual designers may not record all design aspects. Certain design choices are regarded as common knowledge, or ad-hoc tests are not recorded, while only the results of a final working function are published. If larger teams of people are involved in the long-term design and deployment of a system like the ITER PCS, all design aspects (e.g. requirements, specifications, assumed models or executed tests), and, importantly, the relationships between them, should be easily traceable at all times during its development by all who are involved. How this can be achieved will be the topic of section 4.2.

3. The basis of the PCS design

During the conceptual and preliminary designs of the ITER PCS [Snipes2014, Snipes2017], several specific features were iteratively developed that provided an important basis for the further, final, design of the system. In the first place, this concerns the strategy of how the design and deployment are to be carried out, which is the topic of this paper. But it also concerns the detailing of physics operation scenarios, which on one side will be input to the PCS design, while on the other side, the development of physics operation scenarios themselves requires knowledge of control capabilities as well. The conceptual and preliminary designs also provided a first indication of a possible functional breakdown and an assessment of the degree of coupling between functions. The result of this conceptual and preliminary design work is a detailed list of high-level, so-called stakeholder requirements imposed on the PCS that dictate what the system should be able to do for each operation stage. But these requirements are still rather coarse and further detailing is needed as part of the final design as will be discussed in section 4. Furthermore, the interface description between the PCS and other ITER systems was iteratively improved, and the implementation strategy and hardware requirements were determined. While also various tools were prepared to aid the design and development process (e.g. simulation capabilities). These features were all developed such as to enable a smooth final design of the PCS functionality for each operation stage, and hence are considered important boundary conditions or constraints to the functional designs.

3.1 ITER pulse or physics operation scenarios

Determining the requirements for the PCS functions starts with conceptual views on how the ITER tokamak is operated, as is also the case for all other systems that make up the ITER plant. These can be presented in the form of pulse or physics operation scenario, which is a time-ordered set of objectives and/or plasma states that define an intended pulse or discharge history over time. Many detailed physics operating scenarios of ITER discharges have been simulated, taking concept operation limits into account. Designing an ITER operation scenario also takes into account the capabilities of power supplies, heating, fuelling and other plant systems [Kim2017, Kim2018, Polevoi2023]. The IRP identifies specific operating scenarios to be achieved per ITER operation stage [Campbell2023]. Importantly, these operation scenarios are a target to be achieved by the detailed design of the PCS functions for each stage. In other words, these provide a complex set of high-level requirements for the PCS design. One should not only consider standard ITER plasma discharges but also include pulse scenarios without plasma used to commission plant operation, and other use-cases, such as the operating scenarios to carry out RF wall conditioning for example. Operation scenarios may provide details on specific plant and plasma dynamics (e.g. transition from L to H-mode, expected instability growth rates or required shape changes) which will dictate control function capabilities. The relevance of effects to certain failure modes may differ from one operation scenario to another indicating the need for different response to such failure modes by the PCS. Moreover, the accuracy of plasma diagnostics may vary across different time intervals within a given operation scenario and across various scenarios. In all, detailed performance requirements for PCS functions are derived from these operation scenarios.

It is sometimes incorrectly perceived that high-performance operation scenarios (i.e. high plasma current or using full heating powers, etc.), may provide the most challenging requirements to the system design. But control performance may also be compromised when considering plant operation at the low-performance range of the systems. Flying an aeroplane very close to the ground may be more difficult than that at a higher altitude. The design of the PCS should not take into account not only scenarios involving plasma discharges but also consider pulses without discharges. Such pulses are used to commission the ITER plant operation, for example. It is crucial to consider this aspect when selecting use cases for the PCS function design, choosing appropriate tests, and planning its commissioning.

3.2 Interfaces between the PCS and other ITER systems

By its very nature, the functional control system interfaces with a large number of other ITER plant systems. As part of the ITER design process, these interfaces are documented and controlled, to set clear boundaries for the design of all ITER systems. The interface description gives all requirements placed by the PCS on each other system and visa-versa. This can include the required exchange of information between the systems (i.e. PCS command signals and triggers or system fault status information), the operational constraints of the other system (e.g. operation range of an actuator, or measurement range of sensors), and, important for a control system, requirements on response times, time resolution and latency, etc.

Up to this point in the paper, no distinction has been made between PCS sensor input and so-called diagnostics. At ITER diagnostics are considered a set of systems designed to measure specific, predominantly, plasma parameters. Diagnostics are developed to measure the magnetic configuration or to measure the kinetic (density and temperature) profiles of the plasma. But diagnostics are not the sole sensor input to the PCS. The PCS sensor input (as indicated in Figure 2.3) is to be considered as a combination of ITER diagnostic measurements and other data, such as measurements coming from actuators. The ITER PCS interfaces can be broken down into four groups:

1) interfaces with actuators,
2) interfaces with diagnostic systems,
3) interfaces with passive systems,
4) interfaces with other control systems,

Actuator interfaces concern the required actuator response times, details on the PCS commands, actuator fault status reporting or actuator operation capabilities and limits. Diagnostic interfaces, specify measurement parameters, measurement accuracy, time resolution and latency and diagnostic fault reporting. Passive systems are considered, for example, the FW, vacuum vessel pumping, etc. that are usually not directly used in the control function design, except that these may set operation constraints that must be considered by the PCS design. The final set of interfaces define the role of the PCS in relation to the overall ITER plant control, for example, its interaction with the CIS or relationship to the ITER plant supervisory control.

The PCS interfaces have been identified and consolidated at the time of the PCS conceptual and preliminary design [Snipes2012, Snipes2014, Zabeo2017]. The maturity of the interface description can vary, depending on the state of the interfacing system design. For some, the design may still be ongoing while others may have completed construction. The varying state of maturity of the system design, when the interface description is developed, means that often sufficient margin needs to be included. Obviously, for each ITER operation stage, the PCS design should consider only the interfaces of those systems that are available for that specific stage. The interface may also indicate that the system capability changes per operation stage, which is another consideration to take into account.

The interface description also has to clearly define the boundary between what is to be considered the PCS and the actuator and diagnostic systems. This may sound straightforward but in practice, this boundary may not be always very clear. For example, ITER actuator systems can be complex, consisting of multiple actuation capabilities. The gas and pellet injection system, consists of many different valves and pellet injectors, while the EC heating systems will make use of a multitude of options to launch the high-powered waves into the plasma [Carannante2023]. Thus these actuator systems require management by means of an internal control system, to which the PCS will have to interface, without compromising on the functionality requirements. Similarly, an extra layer can be present between the PCS and diagnostic systems [Zabeo2017]. The PCS can use diagnostic input and process this, in real-time, to obtain the required control parameters. But in many cases, it is more practical that such data processing is already done on the diagnostic side. In this case, the processing time is clearly constrained by the latency requirement set by the PCS. A careful eye may have spotted such internal actuation management or diagnostic processing functions, in the actuator and sensor part of Figure 2.3b.

3.3. The PCS implementation approach

As explained in section 2.1, The ITER PCS is one of the many applications that make up the ITER CODAC Control, Data Access and Communication (CODAC) system [Wallander2013]. The implementation of the PCS functional design (as shown in the work flow in Figure 2.1) is envisaged as the realization of real-time code that enables those functions, that are to be deployed on CODAC hardware (i.e. computers) and are connected to the CODAC data communication networks [Winter2015, Lui2018, Lee2021, Lee2023]. The ITER Real-Time Framework (RTF), on which CODAC real-time applications, like the PCS, are realised, allow a configurable, modular implementation that can easily be adapted and expanded [Winter2015, Lee2021, Lee2023]. Most of the communication to-and-from the RTF (and thus the PCS) runs via the Synchronous Data Network (SDN), on which all necessary real-time data, including PCS commands to actuators, actuator status information and diagnostic measurements, are published [Lui2018]. Together with the already mentioned Pulse Schedule Preparation System (PSPS) that allows configuring the PCS to execute specific pulses, this implementation strategy allows one to decouple the PCS function design from the hardware or data communication design and simplifies the interface between the PCS design and its actuators and sensors. The PCS specific requirements placed on the RTF, SDN and PSPS, are detailed in the interface between the PCS and the ITER CODAC system.

3.4. The PCS architecture

The basic architecture of the ITER PCS was developed during the system's conceptual and preliminary designs [Treuterrer2014, Treutterer2017]. The architecture of the ITER PCS reflects the need to manage the coupling between different PCS functions (as discussed in section 2.3) and create an environment that simplifies reconfiguration of the deployed PCS, prior to pulses, and system upgrades (e.g. additions of functions) at each ITER operation stage. The latter is achieved by abstraction and standardization of key PCS functions, such as controllers, exceptions and actuator management functions. Abstraction focuses not on the detailed functionality, but on all the possible capabilities certain functions need to possess, and how such functions are generally being composed. This can then be converted into an architectural component which is a standardized decomposition that can be used to build up any possible ITER PCS function of that kind. It is not in the scope of this paper to go into detail about the architectural design of controllers, exceptions and actuator managers. However, an example of such an abstraction, is shown in Figure 3.1 which shows the breakdown of a typical EH function, detailing each step in the process, from detecting the event, processing the information and the decision processes that eventually may lead to it choosing a handling policy [Raupp2017]. In a similar way, the ITER PCS architecture also uses abstractions of controllers, so-called Compact Controller (CC) [Treutterer2014]. It enforces the designers, to systematically design their functions following prescribed concepts. An ad-hoc design approach may sometimes over-emphasize certain steps, such as only dealing with event detection. This architecture ensures that for each exception all facets are covered equally.

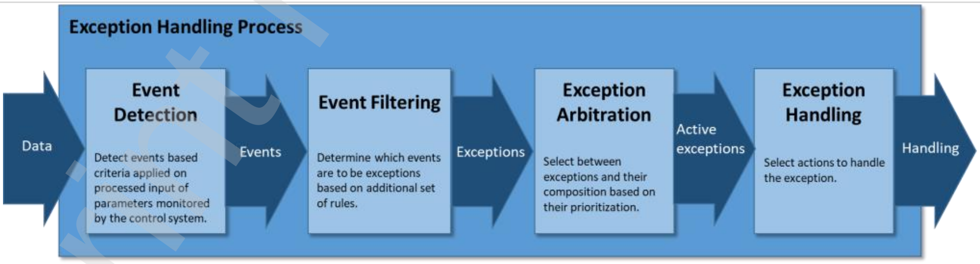


Figure 3.1: The architectural decomposition of EH: detecting an event (e.g. a parameter exceeds a threshold), filtering the response based on rules (e.g. do not respond because another parameter is below another threshold), arbitration or prioritization (e.g. do not override the execution of an earlier more important one) and finally selecting the appropriate handling policy (e.g. in one case reduce the heating but under other conditions terminate the plasma discharge).

The PCS architectural concept aims to ensure its efficient deployment and simplifies the management of the various degrees of coupling that may exist between the control functions. Figure 3.2 shows a general outline of the ITER PCS architecture. It consists of a Pulse Supervisory Control (PSC) layer, that provides the main coordination of the different PCS control functions [Raupp1997, Treutterer2017, Blanken2019]. The PSC is responsible for the generating of appropriate reference waveforms based on the planned pulse scenario, as dictated by the ITER pulse schedule (PSPS) and also manages so-called global exceptions that require a coordinated response of many different controllers [Raupp2017]. It is important to note the difference here between a PCS control function, and a controller. A controller is a PCS control function, but there are also other control functions, such as the EH functions, the waveform generation, and the so-called support functions. The latter make up an important part of the ITER PCS. Already in the basic sketch, shown in Figure 2.3b, a degree of decoupling is achieved in the PCS block, by two layers that manage the PCS sensor input and the link with the actuators, and this is also the case in Figure 3.2. On the left various support functions manage the monitoring and processing of diagnostic data, providing robust information to the actual controllers. These support functions could have various degrees of complexity, from simple filtering or diagnostic status monitoring to multiple diagnostic input processing, validation and Kalman filtering, for as could, for example, be done to estimate the density control parameter [Pastore2023]. On the right-hand side, support functions manage the link with the actuators. These functions convert generic actuation requests, such as providing a specific flow of gas to fuel the plasma, to actual actuator commands, that request a specific set of valves for each to provide specific flows. The complexity of ITER actuator systems, and the need to properly allocate the right actuator requests based on actuation requests from different controllers, requires the design of complex actuator management functions. Actuator management functions have proven to simplify the control system design that has to manage multiple tasks while also making the control system response more effective [Maljaars2017, Kudlacek2019, Vu2019, Vu2021, Pajares2021]. Note that, as shown in Figure 2.3, EH can take place at all levels in the PCS, either in the PSC, the so-called global exception handling, or locally, inside the controller or support functions themselves [Raupp2017].

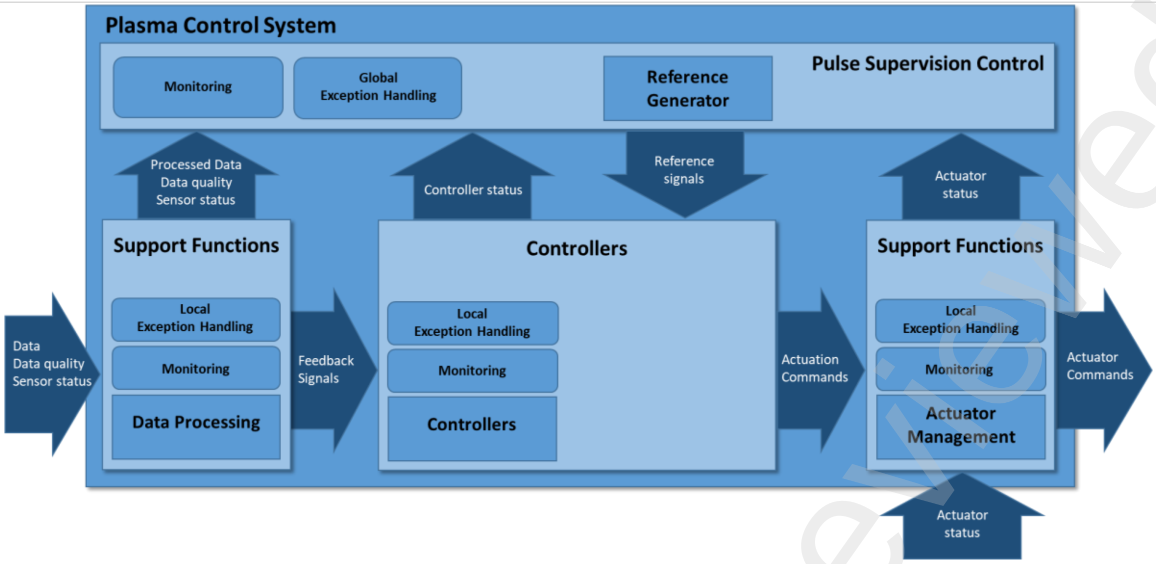


Figure 3.2: The general outline of the ITER PCS architecture, with the arrows indicating the information flow, with on the top the PCS Pulse Supervision Control (PSC) layer, on the left support functions that manage data processing, on the right those that manage the interaction with the actuators, and in the middle the actual controllers. Exception handling is present in all these layers, in the form of so-called global exception handling, executed by the PSC, or on the local level, internally to the control functions.

This architecture not only makes the control system itself more effective but also allows for a more focused and efficient design of the functions. To illustrate this, it allows the design of a generic controller that is independent of the complex interface with sensors and diagnostics because controllers only have to consider synthesized measurements and provide generic actuation commands. Hence, it is easier to reconfigure controllers or even to slot in an upgraded design. And the design work itself can be focused, for example, by separating the design work, with one team focussing on the controller, while others with more expertise on ITER diagnostic or actuator systems, develop the data processing or actuation to actuator conversion.

4. PCS functional design

This section will outline, how the design of the PCS functions is done. Firstly, it will look at the design workflow and what steps are usually taken when designing control functions and formalizing these. Secondly, it will focus on these individual steps, and the design information they create, It will be shown that the design information or so-called design artefacts created by each step are linked, creating a multiple-dimensional design description. Thirdly, the central role of models in the ITER PCS design is discussed. Two main design tools are introduced; the PCS Database (PCSDB), which organizes all the design information (introduced in section 4.3) and the PCS Simulation Platform (PCSSP), which provides the capability to simulate the PCS behaviour (detailed in section 4.5). Important is that the approach is applied systematically to all functions or sub-functions of the ITER PCS, ensuring that a consistent design is provided, that allows straightforward implementation and deployment.

4.1 PCS design workflow

The fundamentals of the PCS design workflow are based on standard practises but for the PCS it is further refined based on many years of experience. The design workflow of PCS functions can be broken down into the steps, or activities, shown in the table below (Table 4.1). These will be further described and discussed below and also indicated in the workflow diagram shown in Figure 4.1.

1	Determine the stakeholder requirements.
2	Specify the functional (incl. exceptions) and performance requirements.
3	Breakdown in, and detailed specification of, functional blocks (FBs).
4	Select or develop required control-oriented models.
5	Design implementation.
6	Specify test cases associated with the performance requirements.
7	Design assessment by simulation.
8	Design improvements in response to the assessment results.
9	Develop a plan to deploy or commission the function
10	Document the design.
11	Manage design integration.
12	Design review and acceptance

Table 4.1: Activities that are part of the ITER workflow for the final design of PCS functions. These activities are also shown in the workflow diagram shown in Figure 4.1.

Determine the stakeholder requirements (activity 1): agrees on the high-level PCS stakeholder requirements, for the ITER operation stage relevant to this particular PCS design. This is in part, linked to detailing the aspects described in section 3. It concerns creating a concise set of high-level system requirements and physics operation scenarios that are expected to be executed during the concerned operation stages. It also involves determining the exact actuator and diagnostic capabilities for this operation stage, and thus, the relevant interface requirements between the PCS and active and passive systems that apply for this stage. From this one can create a breakdown of required PCS functionality for this specific stage. The work breakdown for the design project can then be organized accordingly, grouping functions that have similar high-level functionality. This allows specialist teams of control engineers and plasma physicists who are experts on specific control functions to work on their design. But applying such a breakdown carries the risk that possible coupling between high-level functions is neglected, hence, a continuous process of design integration, is needed, running in parallel to these design tasks, which is covered by activity 11 in Table 4.1. In Figure 4.1, shows this workflow, following the steps in Table 4.1, for a specific PCS function (e.g. magnetic or fuelling control), combined with the integrating activities indicated in red.

Specify the functional and performance requirements (activity 2): determines the detailed functional requirements. These requirements or specifications contrast to the higher level ones, by determining details on all sub-functionality needed to achieve the required control. Thus, specifying the required data processing, real-time calculations, input and output ports, further functional breakdown and control logic, needed for the function to do its job. This step will also have to determine or derive the required performance, i.e. the quality of the control. At the higher level, the required performance is provided in the form of physics operating scenarios, interface requirements or various operating limits that need to be translated into precise requirements, on the capabilities of each function or even sub-functionality, such that these can be checked and tested. The interpretation of the operation scenario and the derivation of performance requirements from it usually requires some iteration and optimization during the design process. Furthermore, the exceptions that relate to these functions need to be specified. One will often see that the design of the required exceptions can be a rather daunting task that can easily get out of control due to the sheer amount of exceptions that need to be considered. Moreover, coordination is needed to properly rationalize the overall exception requirements for all functions. Failure Mode and Effect Analysis is one way to determine which exceptions are required. Tactically, exceptions are first collected per high-level function, ensuring that all possible events are covered, especially various ways how sensors and actuators could fail, and control errors, systematically determined based on operation limits, either of the plasma but also again limits to actuators and sensors. But note that not all exceptions are linked to fault scenarios, some can be used to initiate an optimization of the control or the goal of the pulse. The entire list of exceptions and especially the allocation of handling policies is to be rationalized (i.e. all exceptions are to be described in the same logical manner to form a single list for the entire system, not just per high-level function). And crucially, an effort is to be made, to reduce the complexity of the overall EH design, by removing those exceptions that are already effectively covered by others. The design of the PCS for First Plasma operation [Snipes2021] existed of only 38 individual exceptions, however the system that is needed for normal tokamak operation likely hundreds of exceptions are required. Each exception is assigned a Risk Priority Number (RPN), based on the multiplication of the severity, occurrence and detectability, i.e. respectively, the severity of the impact if the event is not handled properly, the likelihood the event may happen and how difficult it might be to detect a certain event. The RPN may help emphasise the design effort on those exceptions that have a specific relevance. High severity is usually linked to those exceptions that are deemed to be part of the disruption avoidance function (see Section 2.2.7). Exceptions related to disruption avoidance should be labelled such that these can be given special treatment when carrying out the design assessment (e.g. extra tests) or when developing the commissioning plan for the PCS.

Breakdown in, and detailed specification of, functional blocks (FBs) (activity 3): starts with the breakdown of into the sub-functionality (or so-called functional blocks (FB) based on the detailed requirements determined in the previous step. Functional blocks are components that can be individually implemented and tested. These can be controllers but also support functions such as data processing or actuator management functions. These components combined should fulfil the high-level requirements of the high-level function. Some will consist of a small set of functions, one or more feedback controllers and a few support functions to manage data monitoring and actuator management. While others will consist of functions that implement MIMO controllers (to manage higher degrees of coupled behaviour), internally optimized control by event-based switching between controllers or tuning controller configurations, and a multitude of support functions, such as the case for ITER magnetic control [Mattei2023]. For each FB, their individual specifications such as input and output ports are to be specified. The design integration activity relevant at this step relates to the coordination of the definition of support functions. For example, the support function to monitor the plasma density, may not be only used by the fuelling or density control, but also by others, such as the function monitoring the amount of unabsorbed ECH power. Equilibrium reconstruction is one support function that is found to have links to most PCS functions. It is important to realise that for the ITER PCS, the number of FBs that are considered support functions can easily outstrip the number of FBs that concern pure controllers.

Select or develop required control-oriented models (Activity 4): concerns the selection or development of specifically control-oriented models, which are needed to test or assess the functions. For the ITER PCS, this often turns out to be the most complicated step. In some cases, rigorously validated control-oriented models are available, while in other cases, only high-fidelity models allow the accurate simulation of the process, however, these may not be suited to assess the control loop, efficiently. As shown in Figure 4.1, this is also seen as an integrating activity. The aspect of the model choice and how this is linked to the design integration is further explained in section 4.4.

Design implementation (Activity 5): is done for the ITER PCS by creating entities of each function and model in Matlab/Simulink © on the so-called ITER PCS Simulation Platform (PCSSP), which will be further detailed in section 4.5. Note, that this concerns the design implementation, and not yet the actual implementation of the PCS functions on the RTF, as discussed in section 3.3. The design implementation will have to make use of all the requirements, which were specified earlier and could make use of knowledge contained by the selected models as well. It is important that the design implementation follows the proposed

PCS architecture concept as mentioned in section 3.4. It is important to remark that there is not necessarily a one-to-one correspondence between FBs and PCSSP components that implement the corresponding functionality. Single components on PCSSP could include functionalities from more than one FB, as well as the functionality of a single FB can be distributed among various PCSSP components. This is not an issue as long as the link between FBs and PCSSP components is traceable.

Specify test cases associated with the performance requirements (Activity 6): determines all test cases that allow the validation of the performance requirements. The tests should be developed such that these challenge the functional performance, while the number of tests should be limited to keep the whole assessment process efficient.

Design assessment by simulation (Activity 7): ensures that functions meet their performance requirements, by executing the related tests, by simulation on the PCSSP. As will be further detailed in section 4.6, this will start with the assessment of individual units, followed by the combined function for this specific task and eventually fully combined PCS functionality, taking into account more complex coupling as well. Hence, the preparation of these assessments requires coordination and is an integrating activity.

Design improvements in response to the assessment results (Activity 8): shows the iterative aspect of the design. If the assessment proves successful, the design stops with activity 7, however, in reality, the simulation of the control functionality brings up issues, that require changes to the design, either debugging the design implementation in PCSSP or in some cases a redefinition of the functional, models, performance and test requirements or adding new FBs. Sometimes multiple iterations are needed to get the design of the function right, while at the same time these design modifications do not compromise the integration with the overall PCS functionality. The agility of the design process to such iterations is crucial to achieving the required correct design detail and level of integration. One may also perceive a hierarchy in requirements, from high-level stakeholder requirements that state what the function must achieve, to detailed requirements on its performance under test scenarios and lower-level input and output port specifications.

Develop a plan to deploy or commission the function (Activity 9): is an often forgotten task, related to the planned deployment, or better, the commissioning plan of the respective PCS function. A system cannot be designed, without considering how it is being deployed. This is not straightforward for some of the PCS functions. While designing a control function, the designer will have to have some inclination on how it will be deployed to full performance. The effective deployment of each function benefits from the development of a systematic plan, which is an activity that starts at this stage of the design, often related to the tests developed around the design simulation and assessment, as will be further discussed in section 5. This activity is to be done for each function. However adding an integrated activity, as shown in Table 4.1 and Figure 4.1, ensures a more efficient overall PCS commissioning plan.

Document the design (activity 10): is done in two parts. Firstly, this is achieved simply by providing the design implementation on the PCSSP. This description will provide the first outline to the PCS implementation team, on how to realise the functions as code on the ITER RTF. Secondly, the justification of all functions on PCSSP should be clear, and thus all artefacts that are developed at each design activity should be recorded as well. Thus for each function, it should be clear, what its functional specifications, performance requirements, output and input ports are, as well as listing all relevant models, test cases and assessment results. This is at ITER achieved by storing this information in the PCS system engineering database (PCSDB) as will be discussed in detail in the subsequent sections of this paper. It should be clear that this activity is necessary even when considering a single function (when no integration coordination is needed). However, when considering multiple high-level functions, this activity has an important role in the overall design coordination.

Manage design integration (activity 11): ensures that certain aspects of the design are coordinated such that all parts of the design can be properly integrated into the design (description) of the entire PCS. It might be perceived such integration activities are only needed because of the multifaceted functionality of the PCS system, and the fact that the design work is broken up into different high-level functions that are to be designed by different design teams that have the appropriate expertise for this function. But even a single person designing a single control function, would benefit by breaking down the work as in Figure 4.1. Carrying out the integrating activities ensures these tasks obtain the focus that is required, rather than being treated in a more ad-hoc matter (e.g. determining the exceptions related to a certain control function). Hence, the overall design will be developed more systematically.

Design review and acceptance (activity 12): is a formal step at ITER that reviews and approves the system design prior to its implementation, assembly or deployment.

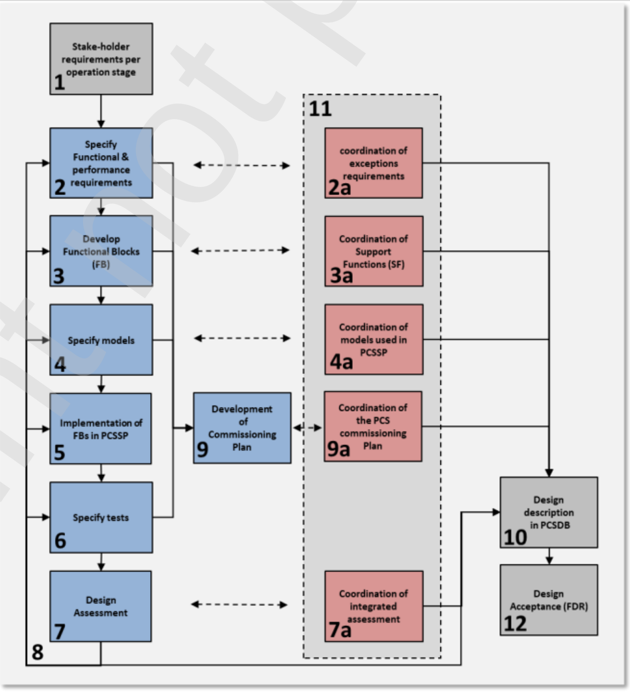


Figure 4.1: Schematic view of the PCS design workflow, assuming two different design tasks (that focus each on a specific high-level function), within the middle, the various activities that coordinate the integrating design activities, which are shown in red. The design starts on the top left with the specification

of the design basis for an ITER operation state, determining the so-called stakeholder requirements and flows to the detailed design description and eventually the design review. The design is documented by the description of the functions in PCSSP and the record of all design artefacts created by the different design steps, in the PCSDB. Those activities in blue are generally considered the standard for the design of a control function. Activities shown in red are viewed as integrating activities (activity 11) that together coordinate the design of a single PCS function with the design of other functions (with coordination indicated by the dashed double arrows). Activities shown in grey and not necessarily integrating, because these play a role even for a design workflow for a single function. However, these activities require an integrated view of the entire system, rather than a single function and thus play a coordinating role. The numbers of each step or activity, correspond to those listed in Table 4.1.

4.2 System engineering approach

The design of the ITER PCS should cover many different aspects, which are not limited to the design of control algorithms alone but also for example verification and validation tests, models and commissioning procedures. All these so-called artefacts are the output of each step of the design process, as shown above in Figure 4.1. It is important that the overall design ensures that the contributions that come from different design teams adopt a heterogeneous description of all these aspects. To homogenize these contributions and to keep track of the PCS life-cycle throughout various stages of ITER operation, a specific system-engineering approach has been adopted on top of the standard ITER life-cycle and the requirement management process [Cinque2019, Cinque2020, Detommasi2022].

Systems Engineering is an integrative approach to enable the successful realization and use of engineered systems, using systems principles and concepts, and scientific, technological, and management methods [SEBoK]. Importantly it assumes that all design artefacts (that what is determined at each design step) are interlinked. This is often expressed by depicting the design process in the form of a so-called V-diagram. Such a diagram, for the PCS design, is shown in Figure 4.2.

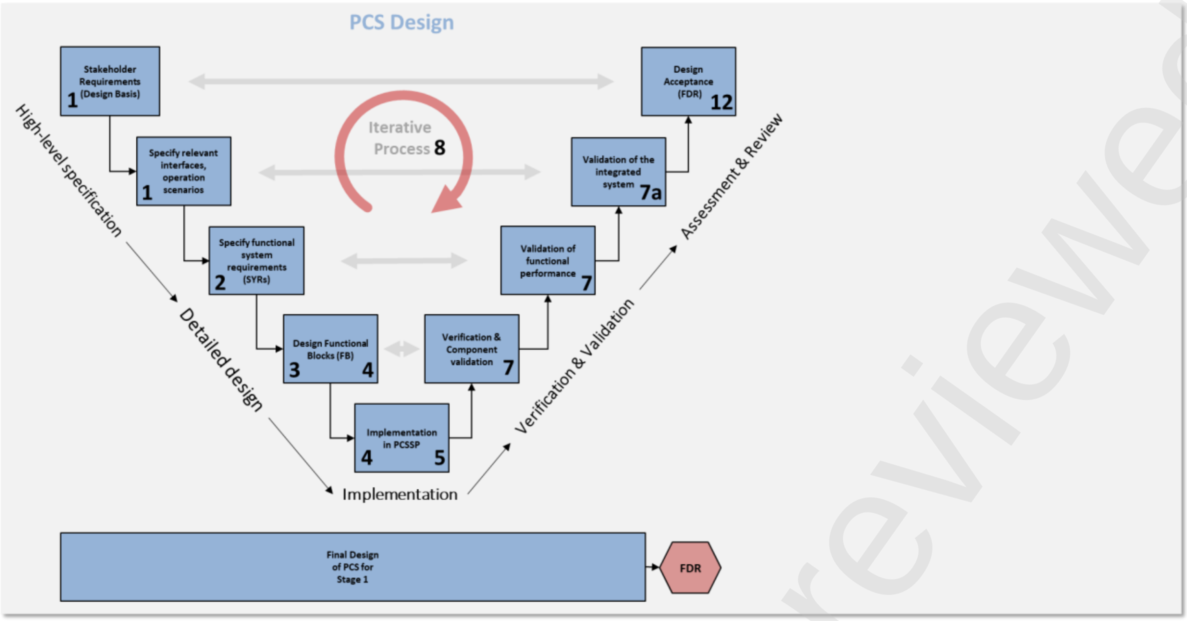


Figure 4.2: PCS design system engineering V-diagram. The numbering allows one to link the steps to those shown in Figure 2.5, and Figure 4.1. Note that the final step of this diagram is not a fully deployed system, but the acceptance of its design, and the central activity, is the design implementation (in PCSSP) and not yet the actual PCS implementation (on the ITER RTF).

The system engineering V-diagram puts the weight of the process not just on the design implementation step as is often done when attacking controller design in an ad-hoc manner. In the first place, it places more weight on the preparatory steps, the specification of the detailed requirements, which is often stated as being 50% of the design work. Secondly, it also emphasizes the work needed to verify and validate that the design meets these requirements.

Another feature of the V-diagram, changes the normally linear design process, into one, in which the initial stages of the design process, that is the high-level specification and detailed design are coupled to the later stages of the design process, which concerns the verification, validation or design assessment. Formally, linking these design stages, means a more systematic design is carried out, that ensures completeness (i.e. nothing is forgotten) and detects errors early, preventing costly redesigns later. As was already indicated when describing the ITER PCS design process in the previous section (section 4.1), the whole process is iterative, hence there should be a continuous consultation and review at one step with the aspects that were developed at earlier design steps. The V-diagram shows this by linking the initial design steps with the later ones. This ensures that all requirements of the design that is being implemented, are systematically verified and validated (V&V). The iterative process might suggest that the design can change its initial requirements which might suggest one could eventually obtain a flawed view of the system's needs. However, in reality, especially high-level requirements may be formulated rather abstractly by the stakeholder. Hence, the design team will have to re-formulate information of abstract requirements, such as “ensure density control in a specific physics operation scenario by means of gas injection as actuator”, into a more precise formulation of specifications that determine the design of this function. The PCS design team will have to re-formulate these abstract requirements into those that matter specifically for a control system, hence derive from them exact control performance requirements. Choices have to be made on the required diagnostic input and actuator combinations that are going to be used, or the type of controller (e.g. proportional, integral, multiple-input-multiple-output control, etc.). High-level requirements may suggest which ones to use, but the exact combination to be used might be determined by the required control optimization that is the outcome of the design itself. The assessment of the first implemented function may reveal that performance optimization is needed, control errors may occur under certain circumstances that need to be prevented, or the design can be economized and simplified, by changing its architecture (e.g. adding additional support functions or logic internal to the function design). Hence, changing design specifications is a natural part the design optimization.

The design process, shown in Figure 4.1, is not transformed one-to-one to the breakdown shown in the V-diagram in Figure 4.2. The former shows the practical breakdown of distinct tasks, while the latter puts more emphasis on the breakdown of the V&V work, which in the design workflow is shown as a single step. It is recognised here that the V&V process can be broken down into distinct parts that assess the design validity to various degrees of complexity. This concerns in the first place the design verification. Verification is defined as the process that evaluates if the design contains the elements it should have (specified requirements), showing that one has designed the right system or that it is as it should be [IEEE2016, Devries2018]. It verifies if all design artefacts (e.g. sub-functions, support functions, exceptions, ports), that are derived from the stakeholder requirements and developed during the design specification, are implemented correctly and none are forgotten. Verification shows the design is complete. Verification begins before validation and then they run in parallel until the design is finalized. Validation determines if the designed system is right, and that it does what it should do [Devries2018]. It is the process that evaluates whether the designed system meets its high-level stakeholder requirements [IEEE2016]. For the ITER PCS this would mean, showing that the designed functions operate correctly to control the proposed operation scenarios for a given ITER operation stage. Validation is of course of special importance for a control system, hence this is broken down into different levels of functional validation or design assessment, which go from unit tests that determine if a FB works without basic errors, to the fully integrated simulation of multiple coupled PCS functions [Walker2019]. This important process will be further discussed in the next section (section 4.3). The PCS design cumulates to its FDR at the top of the V-diagram, and not full deployment of the system as will be detailed further in section 5. Besides V-diagrams for the entire PCS, such diagrams can also be drawn for the design of individual functions or V-diagrams of the PCS can be combined with those for the design and deployment of other related systems.

A systematic design of the PCS starts with understanding the process and importantly applying this evenly to all functions: not just a few or one function of the entire system. Contributions to the overall PCS design can come from different design teams that focus on different PCS functionality, according to their own expertise, or focus on specific design steps, such as the simulation and assessment effort. Hence, the ITER design description consists of a large set of design artefacts that are all interconnected in various dimensions. Design artefacts concern information on the high-level system and interface requirements, physics operation scenarios, functional use-cases, behavioural models of the plasma, actuators and diagnostics, functional (performance) requirements, functional breakdown, the FB specification with their data input and output ports, simulation models, validation tests and their results and commissioning use-cases that describe how each function is to be deployed. The system engineering approach relies on the capability to trace the links between each artefact in various dimensions. Thus tracing integrated simulation tests, to the various functional performance requirements that the test validates, or how FBs are justified by various system requirements. Key aspects of this approach are the traceability of design aspects and that this can enable one to determine if all aspects for all PCS functionality are fully covered. Thus requirements, at each level, have been implemented, design choices are justified and all functionality has been systematically validated, thus also justifying design completeness.

4.3 PCS system engineering database

For this purpose, all PCS design artefacts are stored in a central repository, the so-called PCS Database (PCSDB). The PCSDB is implemented using Enterprise Architect © [Sparxsystems], a commercial software that fully supports the system-engineering approach and SysML modelling of the design. SysML is a graphical, human readable, modelling language developed to support systems engineering, specification, analysis, design, verification, and validation of systems [SysML]. It provides the structure of PCS design in hierarchical entities, named package diagrams. A package is a model artefact that acts as a container for other artefacts stored in the PCSDB. The PCSDB is broken down into packages, following the rationale of the system engineering V-diagram, as shown below in Table 4.2:

Environmental	Includes artefacts that describe the high-level input to the design, including all artefacts that concern project or stake-holder requirements, physics operation scenarios and interface requirements with other ITER systems.
Specifications	Includes all the artefacts concerning the detailed specification of the PCS functions as developed by the design. PCS architectural specifications can also be considered part of this package.
Functions	Includes design implementation of all the FBs of the PCS, along with needed structural diagrams and data flow. PCS architectural components can also be considered part of this package.
Simulation	Includes all the artefacts concerning the assessments specifications, functional models, tests and their results.
Commissioning	Commissioning, which includes all the artefacts about the planned commissioning.

Table 4.2: The main packages that build-up the ITER PCS Database.

Importantly, the Enterprise Architect © PCSDB at ITER has created a link to the repository of functions and models that are implemented on the PCSSP. Hence, any design implementation of PCS functions in Matlab/Simulink © on PCSSP can be traced by artefacts in the PCSDB (thus, how the function is justified, specified, interfaces with other ITER systems and how it is to be commissioned) while simulation models and test results from PCSSP can be fed back to the PCSDB as well [Cinque2019, Cinque2020, Detommasi2022].

Figure 4.3 shows an example of how, using SysML, some high-level and detailed functional requirements can be used to justify specific functions (i.e. FB) and how functional performance is defined, which requires the definition of specific test cases. All these artefacts are linked together, and hence can be traced up to the results obtained by carrying out the assessment tests on the PCSSP. Tactically, the design will have to ensure that each FB is justified by system requirements (SYRs), either identical or derived from higher-level system requirements. Each FB should be assigned exceptions and one or more performance requirements. Each exception and performance requirement should be assigned at least one test case. If test cases make use of a model, this should be recorded in the PCSDB as well. Each test case is coupled to simulations in the PCSSP, of which the results are again recorded in the PCSDB. It is important to remark that the FB is an artefact in the PCSDB that focuses all relevant information related to a certain function that is to be designed, but that this does not necessarily represent a single implementation of such a function. The FB could indicate different possible configurations of a function may be required or it may incorporate different possible design solutions that could be deployed, or not, enhancing the resilience and adaptability the of PCS design more in the face of uncertainties.

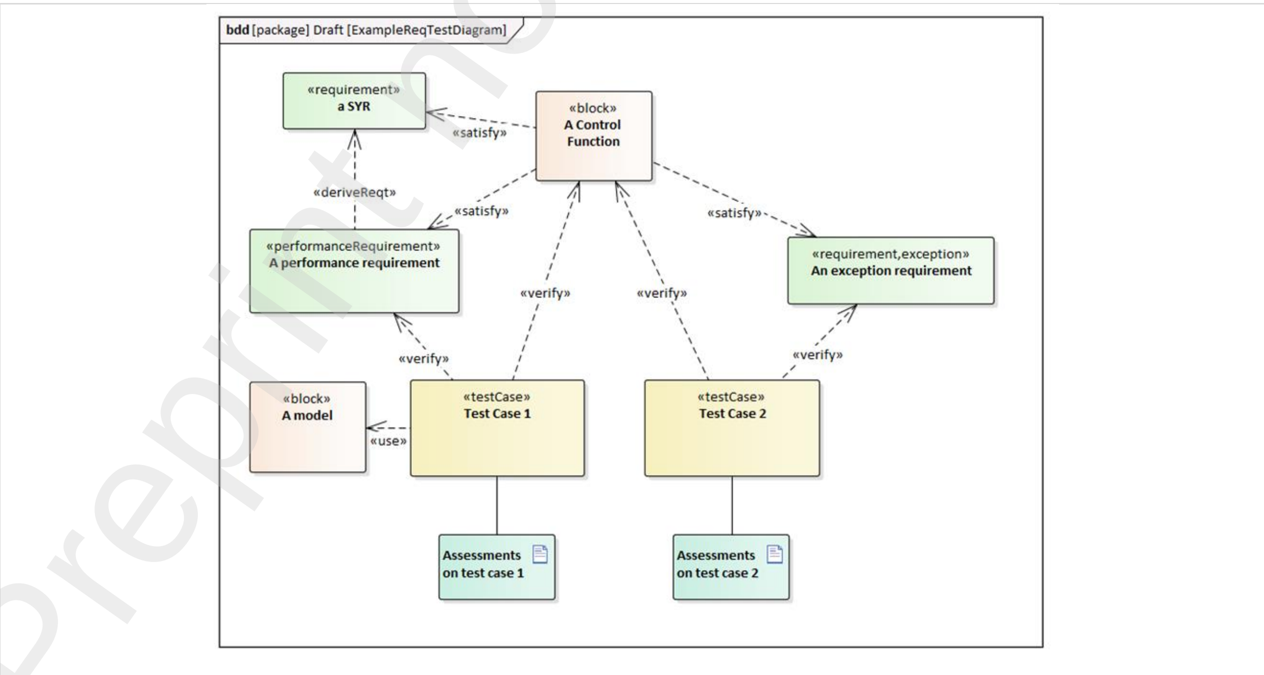
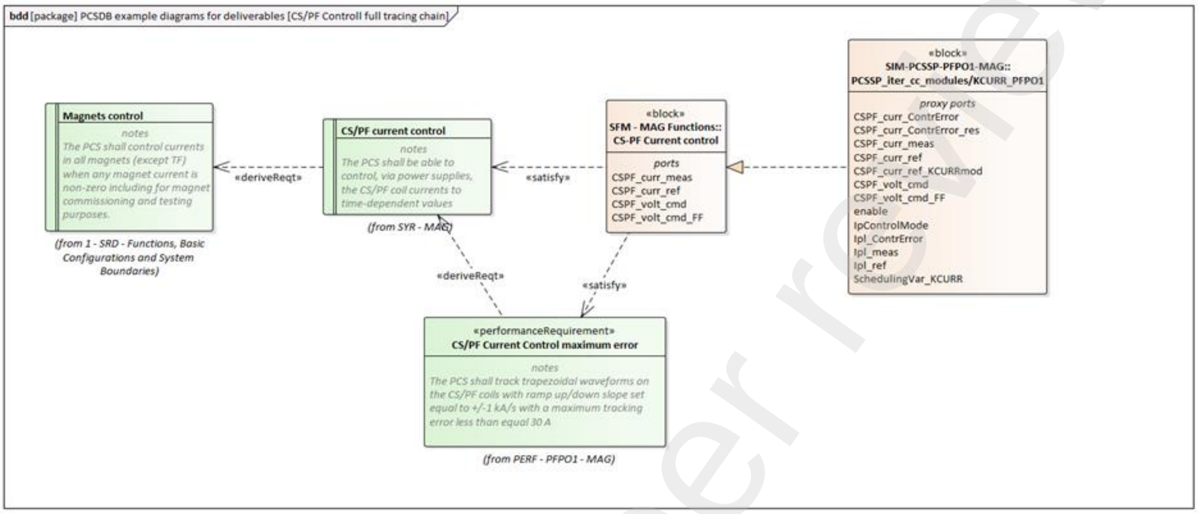


Figure 4.3: a) A schematic view, using the SysML formalism, how the main artefacts for the design of a function are linked, with the functional block, being satisfying system requirements (often derived from higher level stake-holder requirements), performance requirements and requirements related to the function exception handling. These last requirements are verified by at least one test case, and some of these test cases, may make use of models. The assessment result for each test, carried out on the PCSSP, is ported into the PCSDB and stored together with the respective test case.



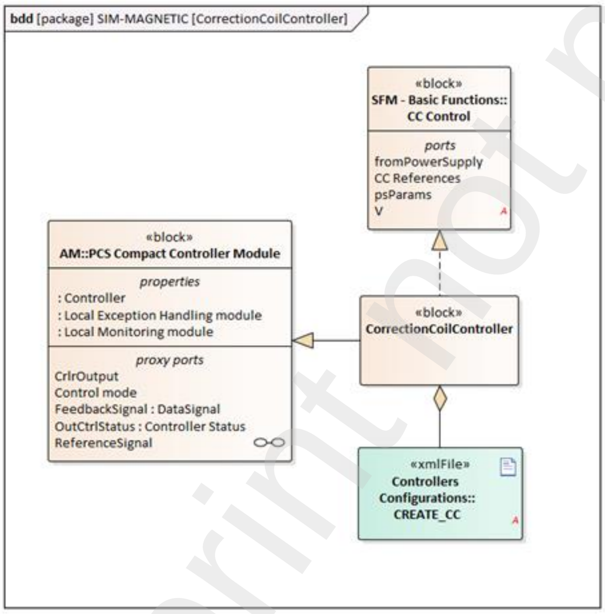


Figure 4.3: b) Example of SysML description that shows the derive, satisfy, realize chain for the CS/PF Current Control function. c) Another example showing the realization of the CC functional block depicting the architecural aspect of the Compact Controller along with its configuration.

A new PCSDB is created for each PCS version per ITER operation stage. For the PCS design of one of the first ITER operation stages, the number of artefacts runs in the hundreds of requirements, FB, use-cases, models and even more different types of dependencies [Cinque2020]. The PCSDB can provide the multi-dimension design in different views, for example, showing the overall design structure, but also views on the lower level FB description, data flow between FB, requirement justification, lists of test results, or the commissioning procedures for certain FB, etc. It goes too far to show and discuss each of these views, but one example is shown in Figure 4.4. Important is that the Enterprise Architect © PCSDB is flexible in creating various views and different output documentation if deemed necessary. Output documentation can be providing a specific view of the design for review, but can also be created to support the work to implement the design on the RTF or its commissioning, or be in the form of checklists or commissioning procedures.

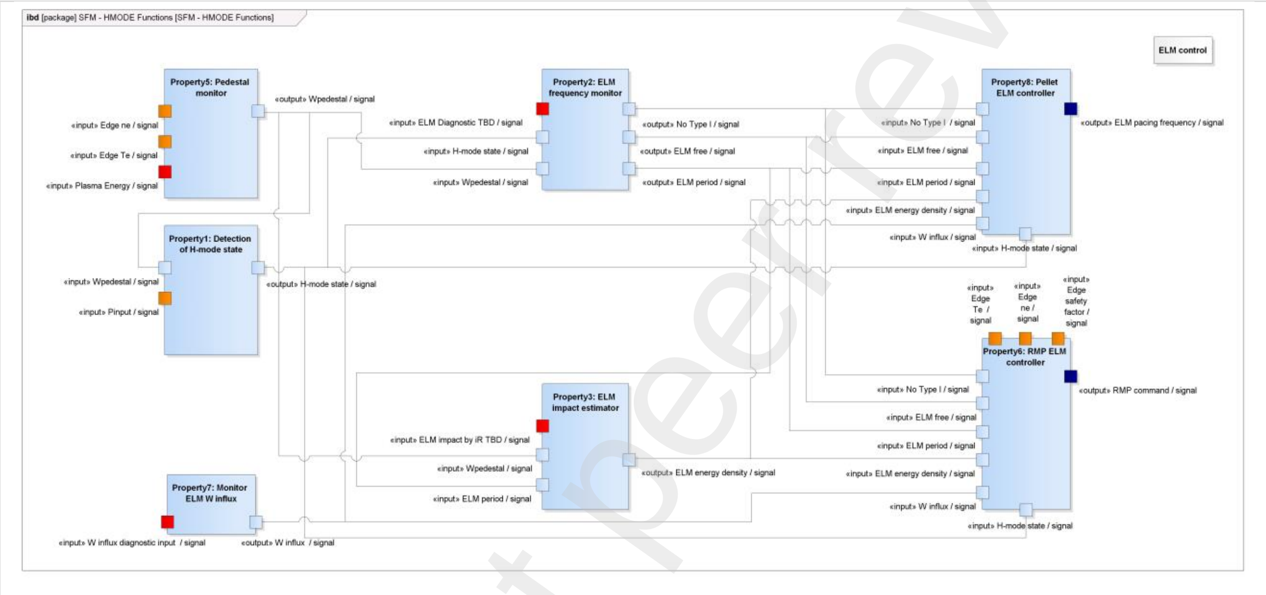


Figure 4.4: Example of another view of a PCS design aspect by Enterprise Architect © showing a SysML description of the input/output ports and data flow for a set of functions (controllers and support functions) that enables ELM control. In this example, ports with direct input of diagnostic signals are assigned red, ports that output actuator commands are dark blue, input from other PCS support functions are shown in orange, and those internal to this scheme are light blue. Other views can be created, what the requirements and justification for these functions are, or how these functions are assessed, tested or deployed.

4.4. Model-based control design approach

In the previous section, the design V&V has already been highlighted, as the component that determines if the system design meets its requirements. The validation determines if the system functions as required, and, for a complex functional system such as the PCS, this will require simulations of its functions to various degrees of complexity. In model-based design of control systems, development is manifested in these four facets: modelling a plant, analysing and synthesizing a controller for the plant, simulating the plant and controller, and integrating all these by deploying the controller design. The central role models taken in the model-based design approach to develop the PCS is illustrated in Figure 4.5, with the model being part of the iterative specification and optimization of the PCS function, essential to the simulation process to validate or assess if the function meets its specifications, but also, as will be discussed further in section 5, related to the systematic commissioning of the function. Model-based design has shown to be able to reduce the risk of design errors and allow a speeder deployment of new PCS functions on tokamaks [Humphreys2015]. Although ITER control deployment will require high reliability and nuclear licensing, in contrast, to present tokamaks, there is high confidence that the mature design tools and preparation approaches under development or available now on existing devices will enable efficient and rapid deployment of reliable control for ITER within the planned commissioning time [Humphreys2015]. Model-based design allows the knowledge of the model to be used to design the controller and one might view the controller to be, or to include, an inversion of the model. Model-based control can assist in complex decoupling of control, such is done to properly regulate the PF and CS currents to obtain the correct control over the plasma current, plasma position and the plasma shape. It is important to differentiate between the model-based design approach and model-based system engineering for which the modelling of the design focusses only on the SysML description.

The model-based design and system engineering approach is applied systematically to the entire PCS development, and not only to the design of a select set of PCS functions. The model-based design approach improved the understanding of the functionality, helps understand system complexity and reduces the risks by detecting errors earlier, improving the design quality and easing the system deployment. Note that at ITER, control functions cannot be developed solely based on experimental experience, for example, by watching various diagnostic signals that show ELMs, and selecting the best candidate for the input of an ELM controller, which is then tuned and optimized empirically. Not only is this time-consuming and prone to error, but it also is impossible as it would imply that uncontrolled ELMs are needed to initiate this development.

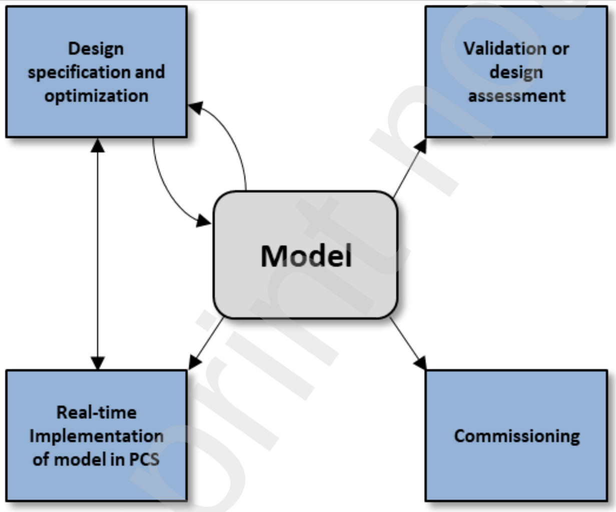


Figure 4.5: The model is shown to be central to the system design, its assessment and deployment (commissioning) as part of the model-based design approach, or can be implemented as a real-time application contributing to the PCS functions.

One should distinguish models to be used for the PCS design from those used to carry out high-fidelity physics simulations, for example, to predict and design physics operating scenarios or to study detailed physics phenomena in tokamak plasmas. The plant models required for the PCS design should be control-oriented. Control-oriented models should be time-dependent and allow simulations to be executed in quick repetition to facilitate design optimization. And, if a feed-back loop has to be simulated, these models should be self-consistent. Such models describe appropriate plasma and system responses with sufficient accuracy to enable a practical design of feedback algorithms. The need for plasma response and machine system models to design controllers, demands significant and specific physics knowledge of the actuator and diagnostic behavior [Humphreys2015, Walker2018]. These models should only reproduce the behavior of interest without necessarily make use of exact physics descriptions. Assumed models can be heuristic emulators of expected response, such as setting a simple time delay in the response of the gas to arrive from the valve to the tokamak vessel, rather than simulating exactly how the gas travels through the pipe. Control-oriented models can be derived from high-fidelity models by simplification or linearization. The level of accuracy of control-oriented plasma models is usually below that associated with good physics understanding, although the design is improved by more accurate models.

The selection or development of models used for the PCS design is a design choice and should play an important role in the design process, in table or Figure 4.1 done by activity 4. If a PCS model is chosen, there are requirements imposed on the initial implementation of this simulation as well as long-term consequences for its continued development and maintenance [Walker2018]. Issues that may arise from this could relate to, their availability, validity, accuracy and possibility to integrate them. For example, a good model might not be available which means the basis of the design is very thin. Another complication might be the model validity, as ITER plans to operate in a range no tokamak has operated before. Thus the PCS design could be compromised by the uncertainty of the assumed plant model. And the development of such models can take up a significant portion of the design work. This contrasts often with the design of other control systems that can make use of well-established and accurate plant models, but where the design problem is more concerned with the robustness, performance or accuracy of the system. The quality or accuracy of the available models also affects the confidence that the design would function correctly and may require building in additional configurability or optionality into the design. The capability to integrate the model with others to carry out integrated assessment is of course important for the higher-level testing that is foreseen. The choice of model and the assumed parameter range over which the model is valid should be recognised as a risk to the design and taken into account during the design assessment and commissioning. For example, if the response time is not accurately known, the design assessment should assume a range of possible response times, and hence the control design is shown to be robust to model variations over that range.

4.5. Platform for control-oriented simulations

The ability to carry out simulations of the designed control functions and ITER plant models is the cornerstone of the PCS model-based design approach [Humphreys2015, Walker2018]. The focus lies here on the simulation of control functions using control-oriented models of the plant. This differentiates from the simulations carried out to design physics operation scenarios, discussed in section 2.1, that might make use of higher fidelity models. For control-oriented simulations solver stability and time-to-solutions are factors that often weigh heavier than model complexity and accuracy. For this purpose, a dedicated Plasma Control System Simulation Platform (PCSSP) has been developed [Walker2014, Walker2015].

A schematic view of the Plasma Control System Simulation Platform (PCSSP) is shown in Figure 4.6, with at the top, modules, from which one can select the required tokamak, plasma, diagnostic and actuator models, while the specific PCS configuration of functions is configured in the bottom box. These communicate, by simulating the ITER communication networks to form the control loop that is to be simulated. Events can be generated both on the tokamak and PCS side [Raupp2014].

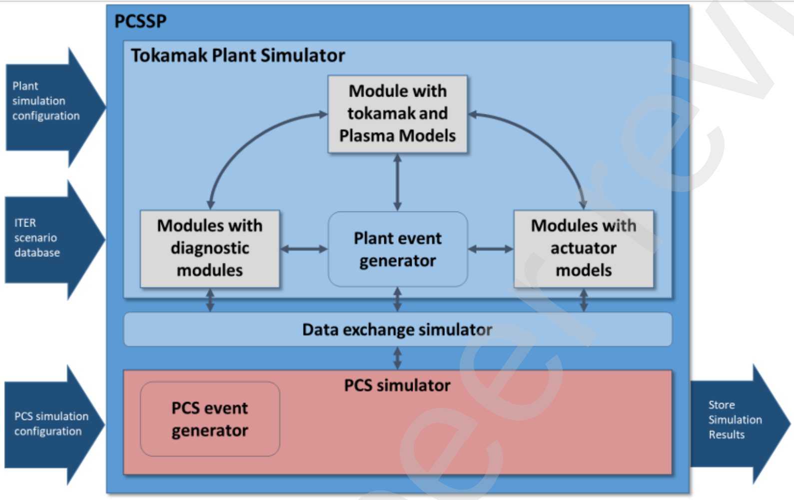


Figure 4.6: Schematic of the Plasma Control System Simulation Platform (PCSSP), with at the top, modules, from which one can select the required tokamak, plasma, diagnostic and actuator models, to simulate a specific set of PCS functions in the bottom box. These communicate, by simulating the ITER communication networks. Events can be generated both on tokamak and PCS side. The PCSSP can input information from earlier simulated physics operation scenarios, stored in the ITER scenario database.

All models for the design of the PCS are to be implemented on the PCSSP. In the first place, one thinks here of plasma response models, like how neutrals fuel the plasma, or how magnetic flux drives the current through the plasma. However, accurate simulation of entire functional loops also requires creating models of the actuators, such as for example models that describe the behaviour of the magnet power supplies, and the complex behaviour of the ECH plant, while at the same time, synthetic diagnostic models need to be created to allow closed-loop controller simulations. The actuator models will not only be used to simulate the exact response to a PCS actuation request but can also be used to study system fault scenarios (e.g. changes to the ECH plant status). The constraints in ITER operation time do not allow one to base controller designs on empirically obtained knowledge on diagnostic signal response. Synthetic diagnostics are needed to explain how expected changes to the plasma are actually viewed by the diagnostic (e.g. a change in density due to a request for additional fuelling by the PCS, may, depending on other parameters, like plasma shape and position changes, not necessarily result in an increase in line-integrated density as measured by density interferometer diagnostics). Synthetic diagnostic studies can for example explain what exact measurements can actually be made, in real-time, under challenging circumstances, and how these can be used for control [Sinha2021]. In section 5 it will be shown that the PCSSP also plays a role during the commissioning of controllers.

4.6. Design assessment

The system-engineering V-diagram, as shown in Figure 4.2, gives an indication of the process to assess the design (i.e. providing confidence that the system will work as intended and proof that the design meets its requirements). This process can be broken-down into differently named steps, however, the main feature is that the level of functional integration increases towards the end of the design assessment process. Important artefacts that provide the basis of this process are high-level physics operation scenarios, system or function use-cases, function performance requirements and (simulation) test cases that validate these performance requirements [Walker2019, Pangione2023]. All these artefacts are stored in the ITER PCSDB [Cinque2020].

Figure 4.7 shows another representation of the PCS design assessment, starting off with unit tests, for which one can consider the unit a FB (as defined by the PCSDB). The verification justifies the existence of the FB per requirements, the validation shows that the basic functionality of the block is correct. Note that often the basic functionality may not always require complex simulations or models, and simple input/output response tests may suffice. For example, the support function that monitors the plasma density is tested, to see how it responds if the diagnostic fault scenario is communicated to this function in the PCS. The next level carries out the functional assessment integrated with several FBs and/or control-oriented models to test the control performance by simulation. For example, the performance of the density control function is simulated for a certain physics operating scenario, assuming a plasma fuelling model and actuator response models. As mentioned above, the tests may have to be carried out to show that the control is valid taking into account model accuracy. For example, if the exact fuelling efficiency is not known accurately, tests are done assuming a range of fuelling efficiencies (i.e. model variants). This is followed up, by integrating more functionality, up to a level, in which it is shown that high-level PCS functionality, such as magnetic, fuelling and error field control is carried out successfully to execute all assumed physics operation scenarios.

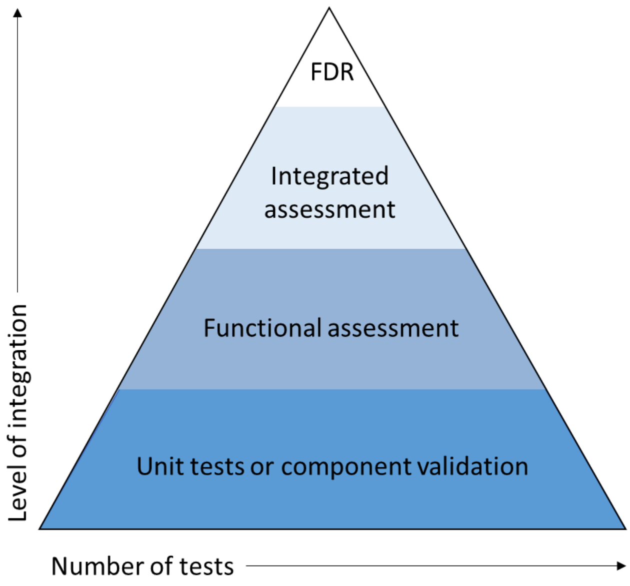


Figure 4.7: Overview of layering of the PCS design assessment [Pangione2023], starting with testing of individual components, such as FB, with the level of system integration increasing, which would require progressively fewer tests. The FDR can be considered as the pinnacle of ITER design assessment, when it is thoroughly reviewed before it can be implemented and deployed on the ITER plant.

Note that the design assessment process has to make choices and that each choice carries a risk that a certain aspect is not tested, hence could develop as a non-conformity when deploying the PCS. Choices have to be made, selecting models and the range of model variants (to take into account the perceived model accuracy), the physics operating scenarios and use-cases. For example, one could test the PCS for all planned physics operating scenarios for a given ITER operation stage. But it might become unmanageable to test all possible discharge termination scenarios. Especially, the task of testing EH could easily blow up if one considers testing all possible fault scenarios under all possible conditions, and even more so if concurrent exceptions are considered as well. The PCS can never be tested for all eventualities, for all combinations of model variants, and all combinations of possible configurations of its functions. The choices that are made to achieve the design assessment, either the assumed model or the assigned tests, are key to the design quality.

The layering of the assessment (as shown in Figure 4.7), with the number of tests decreasing with the level of integration, makes this process more efficient and manageable, without being ineffective [Pangione2023]. Low-level unit tests, ensure correct basic functionality of individual functions implicitly assuming that the effects that are tested are decoupled from other control functions. Such a decoupling is reasonably assumed based on existing tokamak operation and plasma physics expertise. Therefore, individual unit tests (and the related performance requirements) used during component validation are expected to remain valid during full PCS implementation and integration testing. Additionally, to mitigate control errors introduced by the integration of various control functions, focussed tests, especially challenging possible functional coupling, should be carried out. For example, testing control performance during the complex dynamic termination phase of a tokamak discharge or under extreme conditions (e.g. actuator or sensor failures). Carrying out tests that do not challenge the performance of the system, would be ineffective and the design assessment task may become inefficient if too many of these are being carried out. Thus the development of effective assessment tests is an important part of the PCS design assessment process. The approach requires the creation of a smaller but targeted set of integrated assessments tests. The obvious focus lies here in the known nodes of coupling between the different PCS functions (see Figure 2.4).

At the lower level, the design focuses on individual functions, and interactions with diagnostic or actuator systems, for which each design team that focuses on specific high-level functionality, develops models. The real challenge to the work proposed by Figure 4.7 lies in the need to integrate models from different high-level functionality to achieve integrated assessments. It requires integration of both magnetic control, fuelling control and other models, into a control-oriented system of models that still allow one to efficiently assess the control performance. Such approaches are available in the form of so-called flight-simulators that aim to provide an integrated control-oriented simulation of an entire tokamak discharge, such as Toksys or Fenix [Walker2015b, Walker2019, Janky2021, Fable2022].

5. PCS functional deployment

As per Figure 2.5, after the PCS design for a given stage has been reviewed and approved, it will be deployed [Devries2018]. The deployment process, concerns, the implementation of the functions on the ITER RTF, and the commissioning of the system. At ITER the commissioning of each system is broken into three parts: 1) the System Commissioning (SC), which can be done, would the need for any integration with other systems, 2) the Integrated Commissioning (IC), which tests how the system functions in conjunction with other systems, however, without the need of plasma operation and finally 3) a continuation of the integrated commissioning but now while also carrying out plasma operation (PO) (i.e. tokamak discharge). It is obvious that the latter is a very important part of the PCS commissioning. It means that both for IC and PO actual pulsed operation is needed, although only making use of so-called dry-pulses during IC, i.e. pulses without plasma discharges. To come back to the aeroplane analogy, SC is testing the control system individually, IC tests the system linked to all other components that make up the plane eventually even with the engines running but without taking off, while PO is analogous to testing the plane control system in flight. If PCS functions are fully commissioned, i.e. have been proven to capable to perform as required, under all planned ITER operation scenarios, these functions can be considered operational. If this is the case for all PCS functions, the whole PCS can be considered operational, although this is a feat unlikely to be ever achieved.

5.1. Systematic commissioning

As stated in the previous section (Section 4) a complete system design should provide a plan for the commissioning of this system. This commissioning plan should be developed systematically, while the considered commissioning use cases may themselves impact the design again. For example, the commissioning of Error Field control requires the identification of the Error Field by carrying out specific plasma scenarios (i.e. so-called compass-scans) that could be disruptive. To avoid disruptions, these scenarios place additional requirements on the fuelling control function [Pazsoldan2022, Piron2023].

The system engineering approach guides the development of such a commissioning plan. More traditional system engineering V-diagrams concern the entire design and deployment, but the V-diagram shown in Figure 4.2 focuses specifically on the PCS design process. In Figure 5.1 this is extended by an additional branch to also include the steps to deploy the system, forming the ITER PCS development V-diagram or better a W-diagram. One can observe that an agile and iterative approach can be applied as part of the PCS design, but this agility does not necessarily extend to the deployment process, which is bound by the more rigid organization as explained in section 2.4. Importantly, this diagram indicates two levels of V&V. The first level is the V&V done to show that the design meets its requirements, while the second level concerns the V&V done on the implemented PCS, the commissioning of the actual system. In Figure 5.1, it is clear that the activities shown in the PCS development plan at the bottom, do not necessarily map one-to-one to those in the V-diagram. The V-diagram often provides more detail and different breakdowns are possible. Nevertheless, the main strategy to develop the deployment plan is to base it on the design assessment tests, which again are linked to the design requirements. And the level of integration increases as the process progresses, similar to the assessment process. But, although the design V-diagram suggests an iterative optimization process (by design specification, design implementation and assessments), this iterative process is to be avoided between the deployment leg of the diagram shown on the right in Figure 5.1, and the design process on the left. This would mean active trial-and-error, testing controllers during tokamak operation and then redesigning them based on empirical input.

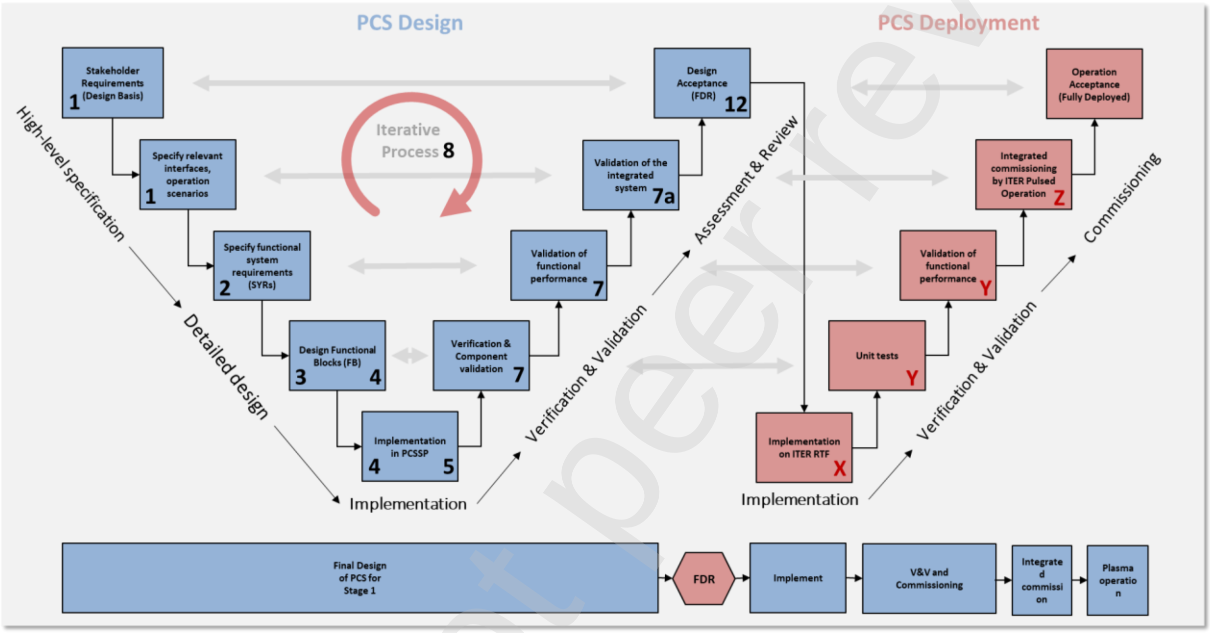


Figure 5.1: The system engineering V-diagram for the process to design and deployment the ITER PCS for a given operation stage. The link to the PCS development plan, as shown in Figure 2.5 is shown below. Step X concerns the system implementation, step Y, the ITER PCS System Commissioning, which is followed by Step Z, the Integrated Commissioning of the PCS.

Commissioning is a risk mitigation strategy that aims to detect and correct faults by systematically assessing the system without the possibility that the fault detection could harm the plant. Commissioning is often used to show that the system works, but that is not sufficient, especially if such testing only applies to very specific operation scenarios, it does not guarantee operation in the entire range foreseen by the design. Hence, it should try to understand why it behaves as such and validate the design models. Each commissioning test can be assigned to a specific category, as shown in Table 5.1. And the full deployment of a PCS function may comprise tests of all of these categories, as will be highlighted in the next sections.

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	Step-wise expansion of the system operation range

Table 5.1: Categories that can be assigned to each commissioning task/step

The model-based system engineering approach also places the design models, central to the commissioning of the PCS [Ravensbergen2023, Zabeo2019]. It is therefore best that the plan to commission the system is detailed during the design of the system. Hence, the PCS commissioning plan is outlined in the PCSDB, from the high-level structure (i.e. the SC, IC and PO breakdown), up to lower-level procedures and lowest level commissioning use-cases. And design artefacts that are part of the PCSDB design description play a direct role in the definition of specific commissioning activities. Generic of procedures can be created that outline the basic process, how the PCS is to be commissioned during SC, IC and PO. A good commissioning plan contain procedures that covers all the categories as shown in Table 5.1. These generic procedures are described in the sections below.

Commissioning use-cases detail exactly, what to do (description), how to do the test (method statement), the prerequisites (what should be done prior to it), it is done. Commissioning use-case provide a method statement (how to do it), prerequisites to the work (what should be achieved before) and information on risks to execute the tests but also how to interpret a test failure and determine the consequences of such a non-conformity with the design. It is crucial that test failures that require correction by changing the PCS implementation should be prevented because this may result in an interruption of ITER tokamak operation. These use-cases are developed by the teams that design each PCS function, often because they have a good view of how these functions are to be deployed and can be tested. Thus if the procedure states, a model needs to be validated, the PCSDB can trace which exact models these are. Commissioning use-cases can be assigned (in the PCSDB) to a step in one of the many PCS commissioning procedures.

Hence, the commissioning plan, is developed from two directions. From the highest level downward, breaking it down into SC, IC and PO, and creating generic procedures, and by developing commissioning use-cases that are to be grouped to a logical order and thus a commission procedures.

5.2. PCS system commissioning

As discussed in section 3.3 the ITER PCS is implemented onto the RTF, which is the first step in the deployment process (step X in Figure 5.1). This is followed by the V&V of implemented units (step Y). In practice, this activity is often integrated with the implementation or coding work. However, to do this systematically, the verification should confirm that all functions required by the design have been implemented (Category A) and that these are validated, i.e. they work as per design (Category B). Checklists can be formed from the PCSDB that determine the required FB and basic function tests for each of them, as were performed previously as the lowest-level unit tests carried out during the design assessment. This process is eased by allowing functions implemented onto the RTF to be traced by artefacts in the PCSDB.

Thereafter, it is confirmed that the functional performance of the implemented PCS function is as its design as per the generic procedure shown in Figure 5.4a. [Devries2018, Ravensbergen2023]. Besides verifying the function's configurability (Category A), it confirms the implemented function has the performance as per design (Category D) by systematically repeating the same test cases as done during the design assessment but now using the implemented functions on RTF. For this, co-simulation of the implemented PCS on RTF, linked to models on the PCSSP is established. Thus the implemented functions can either be connected, via SDN to the actual plant, or models in PCSSP as is shown in Figure 5.2. The PCS SC plan and procedures in the PCSDB indicate what tests to do for which function (i.e. FB) as is discussed further in section 5.4b.

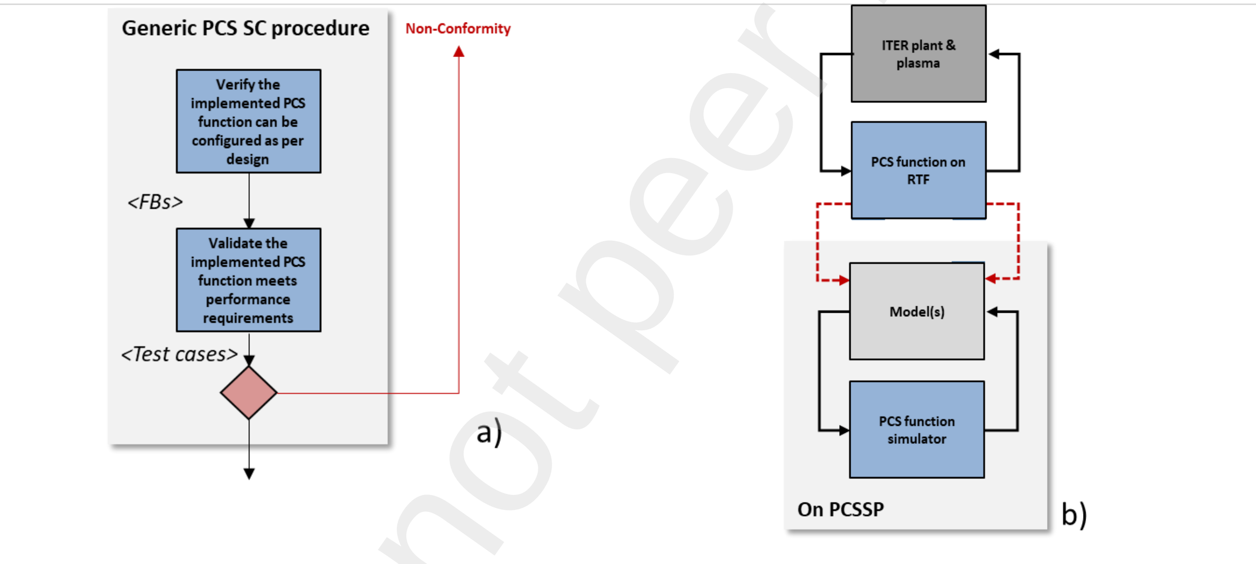


Figure 5.2: a) Generic procedure to be carried out to validate the performance of all PCS functions (i.e. FBs) that have been implemented onto the RTF. The PCSDB artefacts that relate to the commissioning steps are indicated in brackets. b) Figure showing how the simulations of PCS functions implemented in Matlab/Simulink© onto PCSSP, coupled to plant models, can be repeated by carrying out the same simulations, now using the same functions but implemented on the ITER RTF. The latter will later be actually deployed, thus connected to the actual plant (i.e. actuators, sensors, tokamak and plasma)

5.3. PCS integrated commissioning

Up to this point, the deployment process so far all focus on the functions of an individual system functions, at ITER identified as the SC phase (i.e. Step Y in Figure 5.1). It is an important process that ensures that the implemented code that makes up the PCS functions without errors and performs according to the requirements. The next activity is to deploy the system operationally, i.e. via ITER pulsed operation, and integrate it with other plant systems. This is shown as a single activity (labelled Z) in the V-diagram (Figure 5.1), however, a significantly more complex process that the SC of the PCS, involving the step-wise integration of the PCS with ITER operation in general, and other ITER systems in particular. Hence, category C activities are key during the PCS IC.

As explained in section 2, ITER pulsed operation is key to the deployment of the PCS. Hence, prior to starting the commissioning of the PCS itself, or in other words, the PCS functionality, the ITER CODAC applications that orchestrate pulsed operation, such as ITER plant supervisory control, the SDN, the Pulse Schedule and the testing of the ITER pulse sequence, have to be commissioned to enable execution of pulses. Then PCS IC can start, by initially executing basic pulsed operation, which does not test particular controllers. Instead, basic pulsed operation is used to test features such as pulse initialization and hand-over, basic generic waveform generation, generic exception handling and hand-back of control back to the plant supervisory control at the end of the pulse. These all fall under category B. Importantly the interface between the PCS and the CIS will have to be tested, showing that the ITER interlock system (CIS) can intervene and request a stop of the pulse execution (Category C).

This PCS basic integrated commissioning is shown as the first activity in Figure 5.3. This is followed by a set of procedures that validate the interfacing of the PCS to each interfacing actuator, e.g. the magnet and power supply system, the gas injection system or for example the ITER ECH, etc. This work follows the generic procedure shown in Figure 5.4a. This is followed by the validation of control functions that make use of these actuators. This is to be done for control functions that can be tested without the presence of a plasma discharge, such as the control and energization of the magnet system and the control of the vessel pressure by means of GIS, which follows the generic procedure shown in Figure 5.4b. IC is completed by integrating the various aspects of an ITER pulse in preparation for plasma initiation, thus switching to PO. However, this is more related to ITER pulse development than PCS functional commissioning, although it could be seen as the first step of PCS functional integration, the latter is something that will really take off during PO. The schematic shown in Figure 5.3, shows how the test procedure that aims to validate PCS functions can lead to different outcomes. It can allow the expansion of the plant operating space (e.g. increase the amount of ECH power and pulse duration used in the test or, the current at which the magnets are energized). The expansion of the operation space is here not only driven by the result of the PCS tests, but also by others, such as the validation of actuator system operation itself, and importantly the functioning of the ITER protection system (CIS/APS). The test result may require optimization of the PCS control function, by reconfiguring. This means that the actual controller that was designed on the basis of a model with a certain range of validity, is now tuned on the basis of the actual identified model. For example, controller gains and integration times can be adjusted. Input data ports can be adjusted by deselecting certain sensors or tuning data processing filtering. This shows how important the capability to reconfigure a PCS function is. Configurability of PCS functions should be considered when designing each function, taking into account the accuracy of the assumed models. Note again that here the model that is assumed during the PCS design could be a complex assumed behaviour of a coupled set of magnets and power supplies, but also the assumption that a diagnostic provides a certain, jet unknown, number of input channels, and the exact number is still to be decided when the systems are being deployed. As noted in Figure 5.3, PCSSP can be used to aid the reconfiguration of the controller, by simulating its behaviour with updated model information.

If the model identification shows that this is out of the range assumed during the design, a non-conformity is identified. This does not necessarily mean pulsed operation has the cease but operation limits may have to be adapted. In the worst case, it would require a re-design (and thus also reimplementation) of the PCS function, which can be a very time-consuming affair, delaying operation progress and, if not done systematically, also able to introduce further errors.

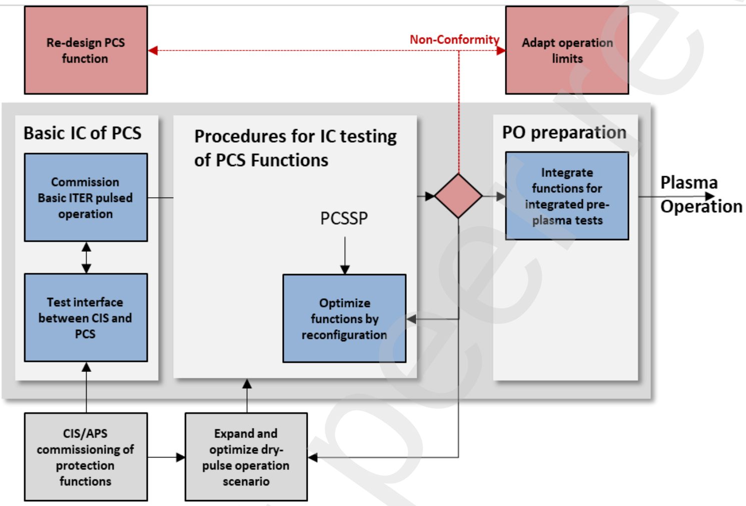


Figure 5.3: Schematic outline of the PCS Integrated Commissioning activities.

The generic procedure to test the interfacing of the PCS with any of its actuator systems (as shown Figure 5.4b) can be broken down as follows: For each of these, the pulse schedule configures the PCS to add the required controllers for these actuators (This can be considered category A). This is followed by a systematic test of the interface between the PCS and the actuator system (category C). This is followed by the activity to test basic control of the actuator system acting on dummy loads which allows the validation of the assumed actuator system models (category E). Thus without necessarily injecting gas of microwaves into the tokamak yet. A limited amount of tests on the functional performance of the control can be tested at this moment, which is a category D. Note that at this point, all action was on dummy loads, and for many actuator systems this is also sufficient during IC, or often the only possibility. This process is done for all PCS functions that command specific actuators.

Prior to PO, actual feedback control is not tested, except for two functions, the control of the ITER magnet systems and the control of the pre-fill pressure of the vacuum vessel, in preparation for first plasma initiation. The complexity of the ITER magnet systems makes the first a complex activity that is also combined with the commissioning of the ITER magnetic diagnostics, while the prefill control is easier to test. The generic procedure to carry out these tests is outlined in Figure 5.4b. Key activities that relate to this work, focus on the validation of the plant models related to these control functions, thus models on the magnet energization and the vessel pressure behaviour to gas injection (category E) often jointly with the validation of the control performance (category D).

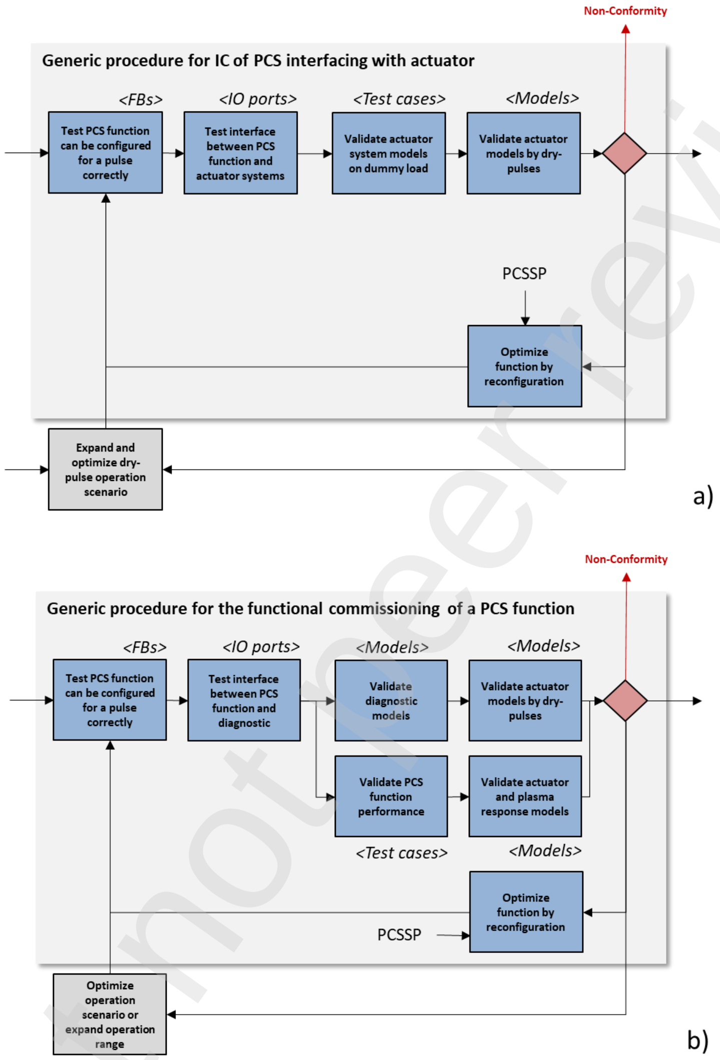


Figure 5.4: a) Generic procedure, to test the PCS interfacing with actuator systems, where for each activity the relevant PCSDB artefact is identified that helps to carry out this test systematically. b) A similar generic procedure that test PCS control functions. As shown in Figure 5.3, non-conformities will lead to a redesign of the PCS function or a change to operation limits.

5.4. PCS integrated commissioning with plasma discharges

The truly integrated deployment of the PCS starts with PO. The main complication in the planning of PCS commissioning with PO is the fact that PCS is needed to execute plasma discharges, while the execution of these discharges themselves is needed to commission the PCS. Dedicate plasma operation scenarios may need to be developed to show that such tests can actually be carried out, preferably risk-free. For example, what plasma operation can be used to fully test FWHL control functions, without risk to overheating the FW itself? Or in the terms of the analogy of the aeroplane: what type of risk-free flights can be practically carried out to test the plane, without immediately flying at maximum altitude?

All PCS functions that require commissioning in the presence of plasma, follow the generic procedure shown in Figure 5.4b. For each PCS function the following basic points need to be carried out: the validation of the plant and especially plasma models related to these control functions (category E) and the validation of the control performance (category D). The validation of the plant or plasma model and control performance will confirm that the design assumptions were correct. The model validation tests also provide a detailed response which could allow one to tune and optimize the controller. The model validation allows extrapolation to higher performance operation (activity categorized as F), thus starting a loop that validates the plasma model, optimizes the control performance and allows the expansion of the ITER operation range. This is also done with input from the commissioning of other systems such as the ITER protection system (CIS) but in this case also the actual performance of auxiliary heating and fuelling system or the important validation of the ITER DMS that follow parallel commissioning tracks. This will also lead to the optimization of ITER operation scenarios themselves as well. The entire IRP, but especially the early stages of it, can be viewed as ITER tokamak commissioning and validation of models or assumptions, leading to a step-wise expansion of its operation range towards its full performance operation at Q=10. Thus the loop shown in Figure 5.4b will be repeated several times for different operation scenarios if needed. Note that in both procedures in Figure 5.4, PCSSP again aids the reconfiguration of control functions if the tests result in an improved knowledge of the plant behaviour, i.e. actuator and diagnostic models, or plasma models.

Importantly, during PO the procedures (as shown in Figure 5.4b) for each PCS function are rarely expected to be carried out without interruption. The individual activities that make up the procedure can be carried out combined with similar ones for other PCS functions, while others require specific plasma operation scenarios, hence depend on the general progress of ITER plasma operation itself. These procedures do not necessarily show a plan for the PCS commissioning during PO. This should be recognised by not only developing these procedures for each PCS function but also indicating what types of pulse or plasma discharges are needed to complete the activities. Hence, the PCS commissioning can be ordered per functional procedure, or as separate activities for a given operation scenario (specific dry-pulse, plasma discharges). This then allows easy integration of these activities into the planning of future ITER plasma operations, likely to be carried out by actors who differ from the people who carried out the function design and described the respective commissioning activities.

5.5. Linking PCS commissioning activities to design artefacts.

The systematic approach in developing the procedures to commission PCS functions focuses in the first place on ensuring that all commissioning test categories are covered. Next, each activity aims to verify or validate a specific part of the design of that function. Figure 5.1 shows the relationship between the commissioning and design and especially the design assessment. Each of the activities in the procedures focuses on the verification and validation of specific artefacts in the PCSDB that make up the PCS design, as illustrated in Figure 5.4. Tests focus on verifying FB, input and output ports, validating models assumed during the design or redoing tests used to assess the design.

Thus the procedures for the PCS commissioning are built up in the PCSDB by following the generic procedures and linking specific artefacts for the design of this function, to each activity. Thus, if the activity indicates models need to be validated, the procedure in PCSDB allows tracing the exact set of models, for this activity for the respective PCS function. An example of this view is shown in Figure 5.5. As noted above, the commissioning procedure outlines generically what needs to be done, and the PCSDB artefacts and commissioning use-cases help to specify details on what exactly needs to be tested and how this is to be done, respectively. Not only does the PCSDB help to specify the commissioning procedures, it also allows one to quickly trace all aspects of the function design, such as its specifications, design justifications and assumed models, if issues or questions arise during the execution of the procedure.

Such detailed procedures are developed for all steps in the PCS commissioning process (SC, IC, PO), and for all functions. The key is to ensure that the PCS commissioning plan is systematically prepared, all aspects are covered, and that the work can be done efficiently (e.g. avoiding doing tests double, or doing tests in the wrong order). Thus overall plan consists of many dozens of such commissioning procedures.

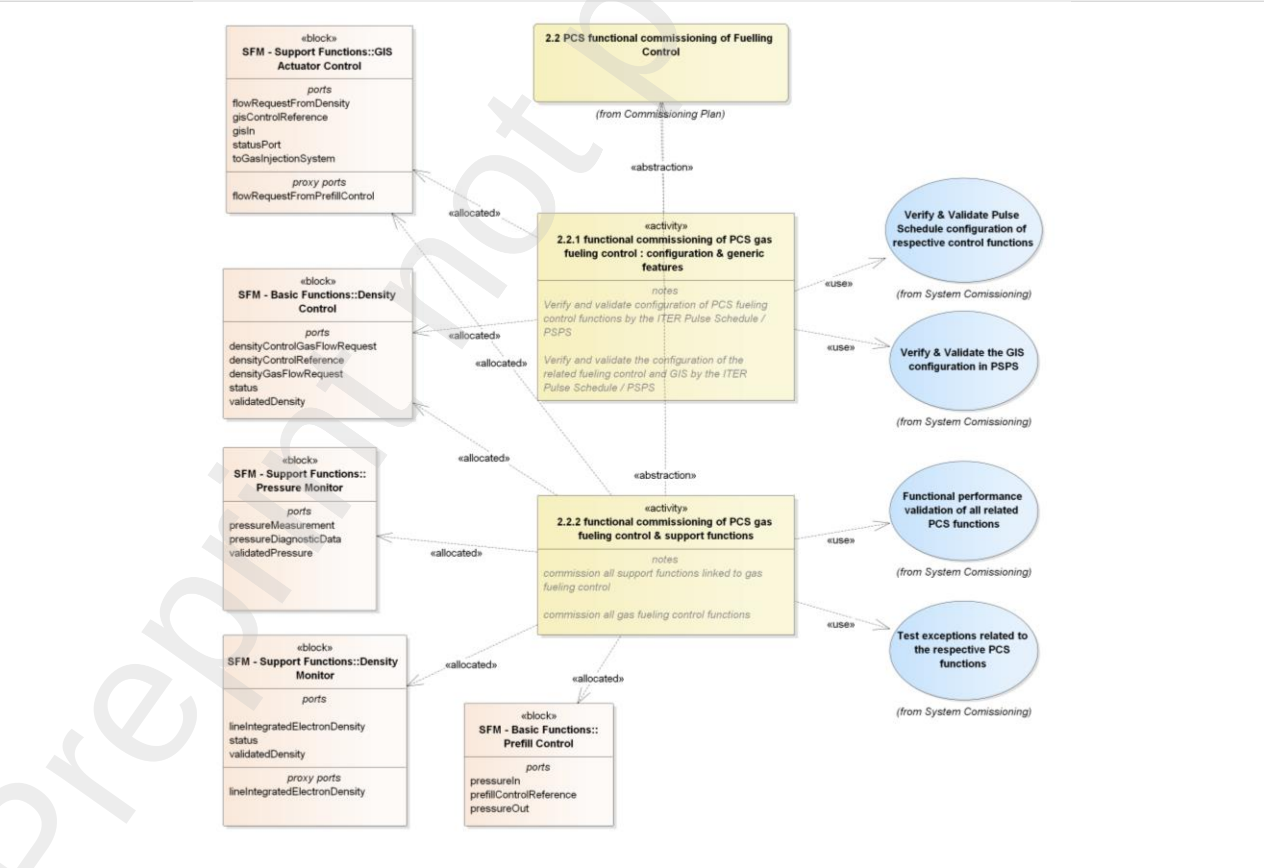


Figure 5.5: a) An example of a procedure for one PCS System Commissioning (SC) activity, as developed in the PCSDB, broken down in different steps (central blocks) following the generic system commissioning procedure (see Figure 5.4a). Each of these are linked to different design artefacts that identify more precisely what needs to be tested (here, the FB shown on the left, that again can be traced to design artefacts that further specify the commissioning use-case, such as models to be validated, performance requirements test cases to be repeated, etc. as shown in Figure 4.3). The use-cases (ovals on the right) indicate how this is to be done.

All this provides a systematic view of how the PCS commissioning should be carried out, in a uniform manner, for all its functionality. As described before this can then be used to develop later more detailed operation plans that execute these tests, often jointly with the commissioning of other systems. Nevertheless, there remains a risk that all the layering of assessment and commissioning tests, did not cover all eventualities, and thus PCS performance is affected by unforeseen issues. It is important to recognise that this risk is driven by, in the first place, the quality of the design models and the parameter range over which the PCS is assessed, secondly the assumed operation scenarios and use-cases, and finally the choice of tests that are devised. As noted earlier, choices have to be made, and hence, the number of assessment tests will have to decrease with the level of functional integration that is being tested, as shown in Figure 4.7.

The same is true for the PCS commissioning that also adopts a layered approach, slowly integrating functionality and expanding the operation range. Choices have to be made, to ensure that the commissioning remains manageable and especially is done efficiently, thus within a reasonable duration. Constraints in available operation time, often result in skipping over certain tests, which carries risk, of course. On the other hand, it is true, that certain PCS functions carry more weight for PO than others. For example, testing all possible events and exceptions under all conditions will be a very time-consuming affair, hence choices will have to be made. For example, higher priority exceptions linked to disruption avoidance, or with a high RPN, will require a more complete set of tests, than those aimed to help with control optimization in case of rare actuator system faults. To help the future commissioning team with these choices, commissioning use-cases should contain information on success and minimal guarantees. These indicate the result that is achieved by correctly executing this commissioning use-case, but also the effect or risk one takes when it is not done, respectively. Hence, providing important input when future detailed operation and commissioning plans are being planned.

6. Summary

The ITER PCS has the task of executing an ITER tokamak pulse, during which it has to carry out a large number of control functions to achieve the goals of the pulse and respond to a multitude of events that require it to adjust its targets without any human interference. The analogy is made between executing a tokamak pulse and the flight of an aeroplane. Though both the ITER PCS and the control system of an aeroplane might be comparably complex, a difference is that the PCS has to execute the tokamak pulse fully autonomously, hence without any human interference. Another important difference is, that ITER aims to operate in a range that exceeds that of any of the current tokamak experiments, and the absence of a well-known operation reference (i.e. accurate control-oriented plant models) which complicates the design of many of its functions. Discussions on ITER control generally focus on what specific control functions have to be achieved or how new control schemes could improve some of its control functions. This paper does not focus on such details, but on how the ITER PCS in its entirety is to be developed, i.e. to design and deploy it. Thus how to carry out the design and prepare for the deployment for all its required functionality.

The design of PCS functions is aided by showing the deployment of similar functions on existing tokamaks. However, showing a certain control function works on a current device is not identical to the design of an ITER PCS function. The latter means one can prove that a viable design exists that meets all requirements, the function can execute its duties fully autonomously in the required operation range and a clear deployment and commissioning strategy exists for that function. The development of the ITER PCS is a complex process that should manage several issues. Firstly, this process may span over many years, and the actors that commission the PCS functions may not be the same as those who designed them. Secondly, it consists of many different functions, that on the one hand, require them to be designed by teams with distinct expertise, while on the other hand, system integration (i.e. the joint operation of all these functions) should be considered in the design as well. Although many of the planned ITER control functions have been shown to be viable by testing them in current tokamak experiments, ITER will be the first device that will have to deploy all these functions simultaneously, in an integrated manner. Thirdly, an inefficient deployment should be avoided, for example mixing empirical testing and design. Such an ad-hoc approach is prone to introduce errors. Furthermore, such designs may only meet the requirements of current operations but not anticipate any future operation scenarios or use cases.

A system engineering formalism is applied to systematically design and deploy the ITER PCS for each operation stage. This means that each of its functions is described in a uniform way by defining the same set of artefacts, such as functional requirements, specifications, functional breakdown, function relationships, input and output ports, functional performance requirements, assumed models, simulation test cases, commissioning use-cases and procedures. All these are linked and stored in a system engineering database (PCSDB) that allows the various design teams and future PCS actors involved with the implementation or commissioning, to easily trace and justify all these design aspects. It is often stated that determining a clear set of requirements is often seen as a significant part of the design. However, the system engineering approach doesn't imply a rigid treatment of all function requirements. As indicated in Figure 4.2, the system engineering design process is more agile and includes iterative optimization of the specifications in the process. The approach forces one to follow a specific pattern (or model), thereby guaranteeing a comprehensive design description. The system design is deemed complete if all requirements are covered by an appropriate design implementation and that for this design implementation all design artefacts (i.e. requirements, models, simulation tests, commissioning use-cases, etc.) have been determined.

Being a functional system, the capability to simulate each function plays a central role in the PCS design. Hence, the design is implemented on a test platform, PCSSP that allows simulation of the functional behaviour and to assess if this behaviour meets the proposed requirements. For the ITER PCS this is done systematically for all PCS functions, hence the need to develop control-oriented models for all proposed functions. The quality of the control function design depends in part on the fidelity of the available control-oriented models. Moreover, the availability of good models is critical to the design of the PCS and model development is known to take up a big part of the overall design effort. Obtaining good control-oriented models for the ITER PCS design is not straightforward, and scientific studies on currently running tokamaks could assist, by developing and validating such models. Good models may be available to design, for example, ITER magnetic control, but little is available for ELM, FWHL or detachment control. The same counts for synthetic diagnostic models, which, in contrast to actuator models that are available in great detail, are often not considered in earnest during tokamak control design.

It should be repeated that models that are considered here can vary in complexity, from detailed magnetic models, including magnets, power supplies, the influence of passive conductors, etc., to simple ones, indicating characteristic time-scales or diagnostic models that are mere parameter conversions or filters than complex algorithms determining the obtained measurement from plasma data. The model should teach the design team, about the plant system behaviour. The choice of the model depends on the need, and should also include an understanding of the range of validity. The latter should be taken into account, when assessing the control function, or when progressing with assessments of integrated functions. The design should also base the need for configurability or redundancy in the design on the quality or accuracy of the available model. The unavailability of suitable control-oriented models to design specific PCS functions mandates additional research and development to support the design.

Simulating the proposed design, also requires one to look ahead on how not to operate, but to deploy the system. Thus, not only determine if the function is capable to meet the requirements for ITER full-performance operation, but also how these functions perform and are being tested during early operations. As noted above, it is often more difficult to fly an aeroplane at a lower altitude than at its planned cruising level, moreover, how can the capabilities of the aeroplane be properly tested at these lower altitudes? The design should consider therefore a variety of operation scenarios and use-cases, to prove the functionality meets its requirements and the system can be deployed, i.e. commissioning tests are viable and an effective and efficient plan can be developed.

The proposed method includes multiple layers of testing. Assessing the design by simulation, simulating the performance of the implemented system itself, followed by step-by-step commissioning. An effective PCS commissioning plan is to be based on verifying and validating design artefacts, e.g. model validation. But the work to carry out the design and the deployment should be decoupled. ITER operation could be used to optimize the control performance. But it should not be used to fill in gaps in the design. In many cases, ITER PCS functions should be capable of a certain performance, right from the start of operation, e.g. ELM control should be able to avoid too large ELMs impacting on the divertor from the start of H-mode operation, and thus the ELM control functionality cannot be designed after first operating with uncontrolled ELMs. This ad-hoc method to control design is also prone to error, as it may short-cut the time spend to assess and implement i.e. code on the RTF) and system commission the new function.

The strategy proposed here ensures an easier and more systematic way of communication between the design teams that work on the various functions, teams that implement and those that eventually deploy the functions. It ensures design flaws are detected early by assessment via simulation of the required functional performance. It also makes the design process more efficient, especially if certain repetitive tasks (e.g. assessment) can be automized. However, this approach does not completely eliminate the potential for design errors; instead, it helps reduce the risks associated with such errors, ensuring that the system functions as intended. It is important to recognise that the risks are predominantly due to the choice of the use-cases and operation scenarios and the quality of the assumed control-oriented models, utilized for the function design assessments. Any non-conformities can hence be efficiently resolved by tracing the basis of these design choices in the PCSDB and allowing straightforward re-testing of functions in PCSSP, in cases models are altered in the future.

As a final remark, the strategy that is outlined here has been applied to the design of the first version of the PCS, planned for ITER First Plasma operation [Snipes2021], and the same strategy is now being used as part of the project to design the functions for subsequent ITER operations. However, during the PCS development, the tactics being deployed as part of the strategy, for example, what artefacts to consider, how to link them, PCSDB views and output documentation or generic commissioning procedures) are often modified to continuously improve the overall process.

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