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From Use Cases of the Joint European Torus towards Integrated Commissioning Requirements of the ITER Tokamak

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* See annex of F. Romanelli et al, "Overview of JET Results", (24th IAEA Fusion Energy Conference, San Diego, USA (2012)).

ABSTRACT

The Joint European Torus (JET) is the largest tokamak currently in operation in the world. One of the greatest challenges of JET is the integrated commissioning of all its major plant systems. This is driven, partially, by the size and complexity of its operational infrastructure and also by the fact that, being an international environment, it has to address the issues of integrating, commissioning and maintaining plant systems developed by third parties.

The ITER tokamak, now in construction, is a fusion device twice the size of JET and, being a joint effort between the European Union, China, India, Japan, South Korea, the Russian Federation and the USA, it will share on a wider scale all of the JET challenges regarding integration and integrated commissioning of very large and complex plant systems.

With the scope of leveraging and contributing with some of the history and experience of JET into the ITER project, Fusion for Energy (F4E) has worked together with the Culham Centre for Fusion Energy (CCFE), the host and operator of JET, for the provision of user experiences related to the integrated commissioning of the tokamak. This work presents and discusses the main results and the methods that were used to extract and translate the commissioning experience information into ITER requirements.

1. INTRODUCTION

The integrated commissioning of any large scientific plant is a complex activity that spans many different disciplines. It requires expert knowledge about each of the systems that compose the plant, together with an overall understanding of how these have to be orchestrated. In a tokamak some of these systems (e.g. additional heating) are themselves very complex plants which require intricate commissioning activities. Consequently, the coordination of tokamak integrated commissioning is a complex task that requires deep knowledge of the links and inter-dependencies between the different plants and on how these contribute to the overall operation of the machine.

Culham Centre for Fusion Energy (CCFE) operates the Joint European Torus (JET), which the largest tokamak currently in operation in the world. Fusion for Energy (F4E) and CCFE have worked together in order to try to capture some of the history and experience of the JET integrated commissioning into the ITER project. Since the collection of commissioning experience from a tokamak is a very broad subject, this work has focused mostly on the commissioning of the plant systems' hardware and software and its impact on the Control and Data Acquisition System (CODAS) [1] infrastructure.

F4E has collected, processed and structured details about design choices that have proven successful, technical mistakes and lessons learned, risk assessments, changes to the design, and conflicts between plant system commissioning requirements and how these were addressed. Specifically, F4E was interested in collecting requirements and experiences that had progressively arisen during the history of all JET integrated commissioning activities. The outcome of this work was a comprehensive report whose main results are summarised in this paper.

2. METHOD

CCFE has given F4E the opportunity to interview at least one operations expert and one CODAS interfacing expert for a total of 22 different systems. These systems included diagnostics (e.g. magnetics and bolometry), additional heating (e.g. Neutral Beam Injection and Ion Cyclotron Resonant Heating), plasma control systems (e.g. shape and density controllers) and protection systems (e.g. interlocks). The system experts were required to have managed at least one integrated commissioning activity where the concerned system was involved. F4E provided a questionnaire which had to be completed and delivered together with a short presentation at an interview where the integrated commissioning requirements for the system were discussed.

Using the information collected in these interviews, questionnaires and presentations, F4E has extracted a large number of *user-stories*. These stories typically highlighted a need for a service or a feature that the expert felt was required to commission the system. Based on this collection of stories F4E has produced a set of JET operational requirements which, admittedly, sometimes were not directly concerned to commissioning needs, but that were felt to provide positive ideas for the design of the overall ITER CODAC infrastructure. Each requirement was then linked to at least one supporting user-story as exemplified in Figure 1. Sometimes it was subjective and debatable if a given commission need was driven not by the plant system but by the need to conform to a given specific JET infrastructure constraint. In such cases F4E has either ignored the story or has tried to write the requirement associated to the story in a more agnostic way. In order to try to increase the readability and understanding of the requirements, these were further allocated to at least one of the following categories: data-storage, mimics (live data visualisation), plant configuration, real-time infrastructure, real-time network, real-time framework and CODAS general infrastructure.

3. JET CODAS ARCHITECTURE

The JET CODAS is designed as a three-level hierarchical and modular distributed control system. The Level-1 central supervisory level provides a standard human machine interface, data storage and analysis, central timing, networking, experiment management, cross-subsystem control and management of the real-time control.

The Level-2 is the subsystem level, providing conventional control, data acquisition, timing and interlocks. Each of the major plant systems (e.g. toroidal field (TF), poloidal field and vacuum) correspond to a different subsystem. There are 22 subsystems in total, including 11 that load-level approximately 90 diagnostics. The subsystems are designed to be autonomous in order to allow commissioning or asynchronous operation independently from the rest of JET.

The Level-3 is the component level and consists of individual components of subsystems (e.g. vacuum pumps, power supplies and lasers). Components may be software applications, in particular real-time control and protection applications, as well as hardware devices.

The three level architecture is an ideal, whereas in reality the actual structure is often less clear cut. The trend at JET is for all systems, components, sub-components to be set up and monitored

using the same tool (pulse schedule editor) of the Level-1 software [2, 3]. This facilitates the implementation of the Level-1 live parameters database and hence the implementation of the Level-1, cross-subsystem, control. Level-1 has introduced the concept of commissioning status for systems or functions of systems. In particular, it can be used to monitor the commissioning status of Integrated Operation Protection Systems (IOPS) systems.

4. MAIN RESULTS

A total of 97 requirements were captured from an universe of 213 *user-stories*. Some of the main ideas that were common to many of the plant systems are shown in Figure 2.

From this exercise it was clear that commissioning is taken very seriously at JET and that it is supported by a series of management procedures (e.g. IOPS) and design choices (e.g. three levels hierarchical breakdown of CODAS). Some of the design solutions, such as the high degree of modularity and the network-level interfaces, were not explicitly driven by commissioning needs but have naturally supported them. An example is the real-time network, which allows functions that are distributed in different systems to be safely commissioned in a staggered fashion in distinct time periods. This interface also enables the injection of synthetic commissioning data from external plant systems, a feature that has proved to be of great importance in minimising the number of dependencies and conflicts during the concurrent commissioning of many plant systems. It should be noticed that having this interface at the network level implies that no software or hardware changes are required in order to inject synthetic data. Consequently, there is no risk of posteriorly driving the system to an uncommissioned state (e.g. by having to recompile code or by unlinking *commissioning libraries*).

One of the most important features that is generally available in the JET plant systems is the possibility to safely perform commission activities in parallel to the machine operation. This is found to be key in minimising competing needs (human, services and hardware) and in allowing the development of a commissioning schedule that supports the gradual increase of the operational space of the machine (e.g. commissioning of additional heating systems in parallel to other plasma experiments).

The traceability and identification of all the data required to compute a function, possibly allocated over several plant systems, is key to the development of robust commissioning procedures, with proper allocation of responsibility and boundaries, and to an agile identification of complex faults. As an example, the plasma shape computation is a composite function, distributed over different plant systems, that involves several possible sources of error, such as the real-time computation of the integrals of many magnetic probe voltages and the execution of plasma equilibrium codes.

JET also has a very strong fail-safe culture in the operation of plant systems, where the failure of any protection relevant system is announced by the inability to produce a given pattern (e.g. pulse train or ATM packet). As a corollary, the greater the number of plant system components involved in the generation of this pattern, the more robust the fail-safe mechanism will be. In fact, most plants

force the involvement of both hardware and real-time software processes in the production of the pattern so that even if a fault is developed in the software processing chain (e.g. an infinite loop in the control software or a crash of the operating system) the protection pattern is still inhibited.

The Level-1 pulse-scheduler holds a global overview of the JET plant configuration and is a crucial element in promoting the concept of commissioning modes. These guarantee that the configuration values of a given plant are consistent with its expected operational state (e.g. commissioning without plasma, commissioning with no current in TF coils, . . .) and ensures that all the environmental (e.g. status and values of other plants) and regulating rules (e.g. people with the required level of expertise assigned to the correct operational role) are being implemented. This delegation of function and responsibility from the plant system to the Level-1 infrastructure ensures a greater level of transparency of the commissioning exercise and enables to link and cross-reference the configurations of many plant systems. It also improves repeatability and reduces the required commissioning time, hence making the machine more available. Finally, this centralisation also enables to safely and responsibly unlock specific features of plant systems (e.g. a novel plasma shape control method) as they are progressively commissioned in parallel to the operation of the machine (e.g. at the tail of a plasma a pulse the risk of endangering the machine is usually lower).

The possibility of being able to run local pulses at subsystem level has shown to be a very powerful concept. It allows the demonstration and testing of a large number of the interfaces with CODAS (e.g. state-machines, mimics monitoring and data collection) and it enables several plants to be independently commissioned at the same time. It also supports the traced storage of the plant system configuration and of the data acquired during the commissioning activity.

There were also some commissioning features that plant system responsible officers would like to have and that are not currently available. An example is the need for a greater uniformity of tools and data formats during all the operational states of the JET plant (from shutdown, through restart and terminating in operation). These often call for concepts related to continuous operation, data acquisition and monitoring which are still difficult to justify in a minute-scale pulse based experiment. The need to share crucial resources, such as the central timing and triggering system, has proved to be a challenge and has an impact on the pace at which commissioning can be performed. The same type of problem was also highlighted when plant systems belonging to different Level-2 subsystems had to be orchestrated together in integrated commissioning exercises. The cost-benefit relation of increasing the level of service and features that would allow for a more expedite integrated commissioning is not always obvious. In particular, some of the most complex integrated commissioning activities are related to the operation of JET and actually require a real experiment with plasma (e.g. additional heating conditioning) and consequently the possibility of doing very complex offline integrated commissioning would not address all the issues.

In our opinion this work has allowed to capture and transfer valuable knowledge and experience from the larger and most international tokamak in operation in the world.

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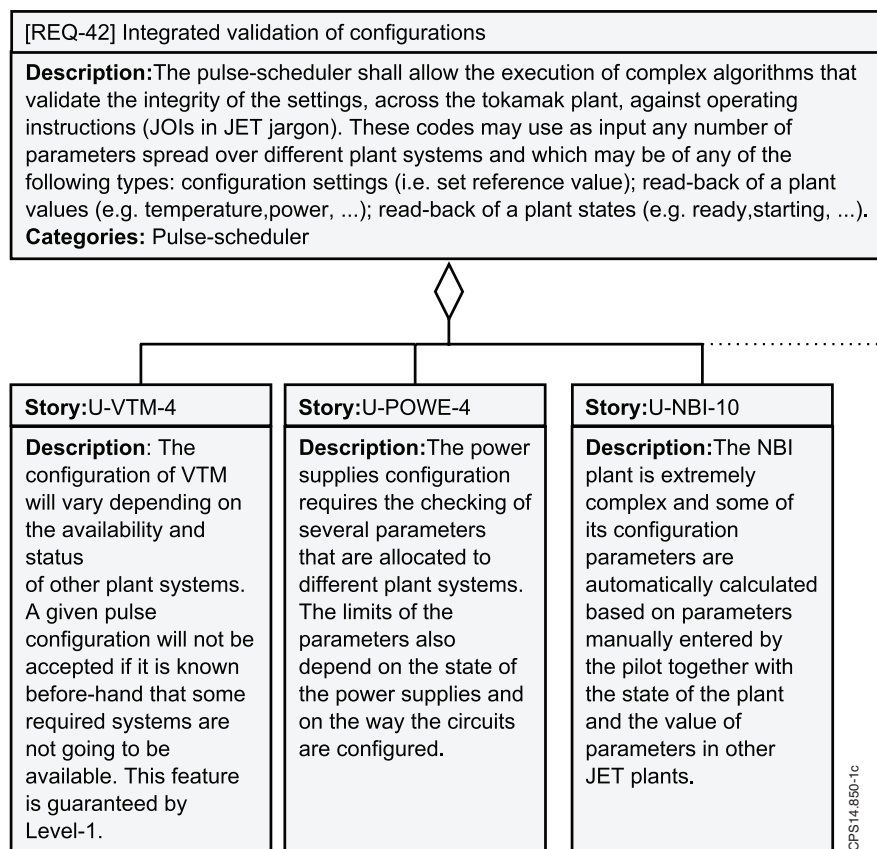
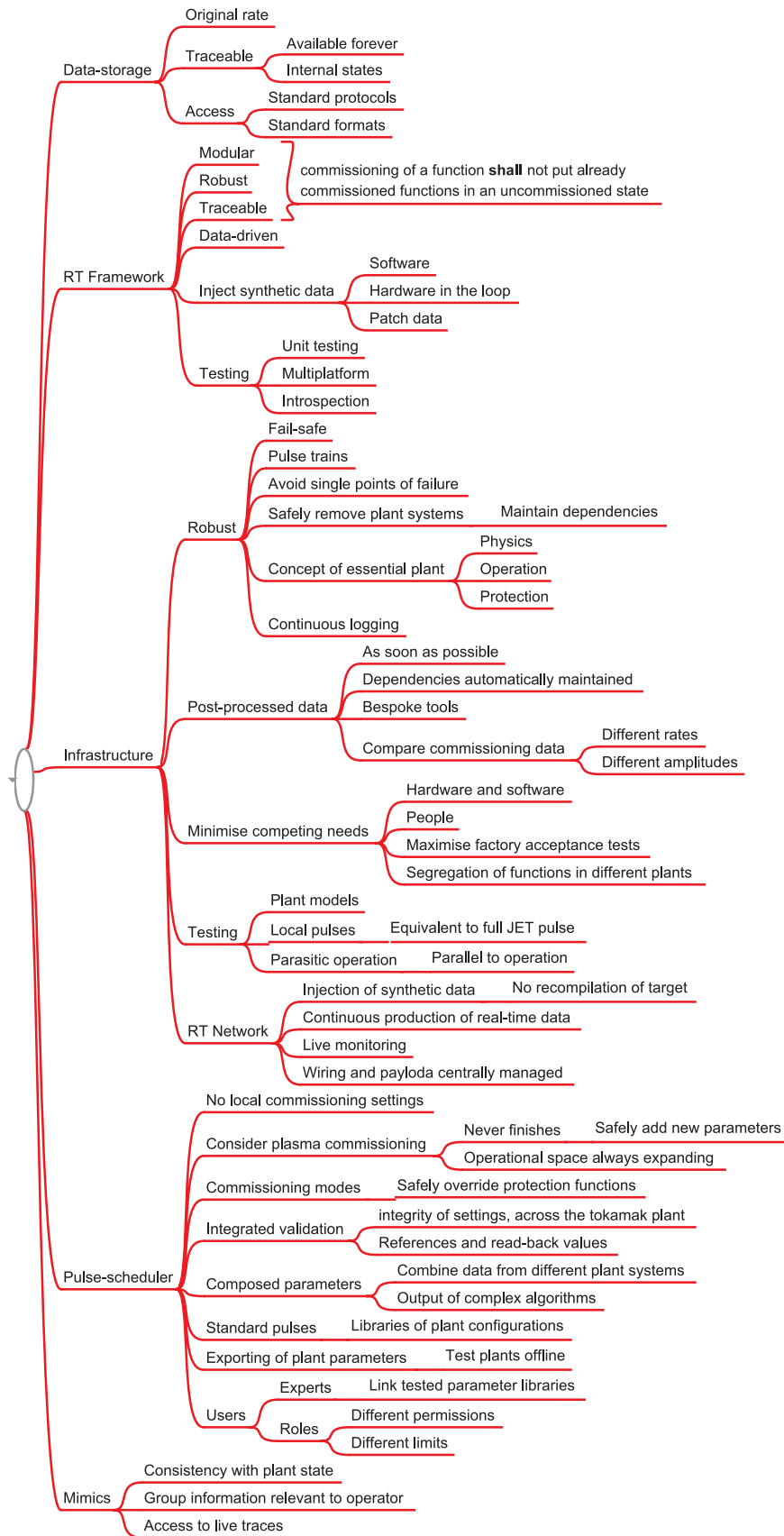


Figure 1: Each requirement was developed from at least one user-story. In this example the need to have a central and integrated validation of the plant configuration was highlighted by many system responsible officers, such as the Vessel Thermal Map (VTM), the power supplies (POWE) and the Neutral Beam Injector (NBI).



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Figure 2: Some of the main ideas that were captured during the collection of the user-stories. It is clear that the pulse-scheduler and the real-time infrastructure (frameworks and network) play a key role in the integrated commissioning of the JET plant.