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JET Operations and Plasma Control

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ABSTRACT
This paper presents the main lessons that can be learned from two decades of Plasma Control development experience. It will present the general architectural choices and will provide examples from key systems, and, more importantly, will highlight the plasma operation requirements that have driven the developments. The aim is to present a meaningful set of functional and non- functional requirements that were derived from the JET experience and to discuss their potential applicability to future experimental devices, ITER in particular.

1. INTRODUCTION
Development of digital control systems began at JET about 20 years ago, mainly in response to the complex set of requirements raised by the divertor upgrade of the machine. Since then the systems have evolved continuously. A detailed description of JET implementation choices in the field of Operation and Plasma Control could easily fill a long and tedious document, so we provide a summary. Most diagnostics and actuators can now contribute to the plasma control network. A large set of dedicated or general controllers have been installed to allow flexible programming of different control actions.

Fortunately, the most important information can be presented without too many of the system details. It can be found in what has motivated a development, the main functional requirements, but, also more importantly, in what has shaped the particular solution, the non-functional requirements.

The first part of the paper is dedicated to describing the most important JET plasma control functions, those that have been identified to be either necessary for an efficient and safe plasma operation or helpful to creative experiment programming.

The non-functional requirements, the constraints that have determined the technical solutions are the subject of the final section. A large part of the discussion is dedicated to the Real Time Data Network (RTDN [1]) and its systems.

The conclusion will summarize the key characteristic of JET plasma control and discuss their applicability to ITER.

2. PLASMA CONTROL FUNCTIONS
2.1. PLASMA POSITION AND CURRENT CONTROL
At JET the most important set of plasma control functions are performed by the Plasma Position and Current Control (PPCC) [2] system. Its main function is to provide a good control of the Poloidal Field (PF) currents. In a Tokamak the PF coils, the plasma and the main conductive structures form a set of electromagnetically mutually coupled circuits. Proper control of all these currents cannot be performed locally at the PF amplifiers but must be co-ordinated by a multivariable controller. This multivariable current control function covers the operational needs during the plasma-less part of a discharge. Soon after breakdown the control objectives must change: instead of

controlling circuit currents, PPCC must switch to control at least three essential plasma parameters. To support PPCC functions, at JET all the amplifiers are commanded with voltage references. The only actuator diagnostic necessary is a good measurement of the circuit current. A good modeling of the circuit inductance and resistance and detailed information about the power supplies is essential to achieve higher closed loop bandwidth. The delay introduced in the loop chain by the AC-DC thyristor converters, diagnostics and control loop is at JET the main bandwidth limiting factor. The majority of closed loop PF circuit bandwidth (3dB point) ranges between 10 and 30 rad/s; the primary PF circuit being driven by a flywheel generator has an even lower performance of 1 rad/s. Most of these circuits, when controlled with the help of a model-driven feed-forward voltage reference, achieve equivalent bandwidth exceeding 300 rad/s [3]. In fact, when large and rapid current variations are required, amplifier voltage saturation becomes the speed limiting factor.

The plasma current evolution can be controlled by exploiting the transformer action performed by the PF coils set. The natural outward radial expansion of the plasma column can be controlled by providing the right amount of vertical field. Rapid radial field variations are necessary to stabilize the plasma vertical position. Essentially all JET plasmas, having an elongation of about 1.6, are vertically unstable with a growth rate ranging between 100 and $1000s^{-1}$. A special combination of fast controller, fast amplifier and low inductance PF coil are therefore required. For these three functions the required diagnostic is a simple elaboration of the magnetic measurements based on an extension of Ampère's law [4].

2.2. PPCC VERTICAL STABILISATION

Vertical Stabilization (VS [5]) is one of the most difficult topics in plasma control. In JET, similarly with ITER, the VS task is particularly difficult both because of the relatively high growth rate and because of the vertical asymmetry of the machine. A growth rate γ implies that the unstable plasma displacement from the equilibrium point, x_u, naturally grows with the exponential law $x_u(t) = x_u(0)\, e^{\gamma t}$. The longer the delay between the correct measurement of x_u and the consequent application of a stabilizing radial field the larger the required amplifier power: $P \sim x_u^2$[6]. In JET, with a growth rate of $1000\ s^{-1}$, a delay of 500ºs corresponds to almost a factor 3 in the power required. A simple model based on equivalent delay can be used to represent both the errors and delays in the measurement of x_u, and the delay and phase shifts introduced by the controller, the amplifier and the vessel.

The size of the required installed power P is ultimately linked to $x_u(0)$, the initial perturbation. In JET the worst case initial perturbations are linked to the occurrence of ELMs where, because of the machine's vertical asymmetry, the β drops cause not just a radial movement but also a vertical one.

The design of VS needs to take in account these factors. Because of the impact to the required installed power, the VS closed loop delay is the most important factor in designing the VS control function. For instance, the 50μs delay associated with the JET VS controller would waste 10% of the required power in the worst case growth rate scenario. Detailed information on JET VS control function and its enhancement (plasma control upgrade PCU) is provided by [5] and [6].

2.3. PPCC PLASMA SHAPE CONTROL

Once plasma current and plasma centroid position are properly controlled, by using appropriate current references for the remaining PF circuits it would be possible to program a successful plasma discharge. Unfortunately, the actual current references to be used cannot be evaluated unless one knows in advance the evolution of the plasma internal pressure and current profile parameters β and l_i. By trial and error, and a bit of experience, these waveforms can be produced, but this is inefficient and not very reliable.

To control directly the plasma shape is, in fact, a better approach, one where less experimental time is required and one where the results are less sensitive to changes in the machine conditions. At JET the full boundary plasma boundary control function is provided by the XSC controller [7]. The magnetic diagnostic data is elaborated using the XLOC/FELIX code [8, 9] to produce plasma wall distances (gaps) in 32 locations. XSC uses a model of the gap sensitivity to the PF currents to calculate in real-time the current waveforms necessary to maintain the shape whatever the evolution in the plasma internal parameters.

The XSC full boundary approach is not sufficient to cater for all the experiment needs. In many circumstances, maintaining a very rigid plasma shape is either not necessary or actual detrimental to the experiment. For instance maintaining the plasma minor radius during the plasma termination where the l_i is growing causes the plasma vertical instability to significantly worsen. In addition the full boundary control not only imposes heavy requirements to the PF actuator currents, but requires controller parameters tailored to each plasma configuration.

In JET most discharges can be accomplished by using a reduced plasma shape control approach. In this scenario PPCC controls only the distance to the outer wall at the mid-plane, the distance to the top, and the position of the two strike points in the divertor area. Pre-programmed current waveforms are used for the remaining 4 PF circuits.

3.4. PLASMA CONTROL PROTECTION FUNCTIONS

In JET there are accessible operational regions, where some elements of the machine mechanical or electrical integrity can be put at risk. For instance certain combination of PF and TF currents generate too large static forces on the coils. Disruption in certain plasma conditions can generate forces too large for the vessel ancillaries (ports) to cope with. Certain in-vessel components systems can sustain a large power load for only a limited time before overheating. Moreover, even remaining within nominal operational regions, faults can develop on some Tokamak elements that, if not handled properly, could lead to severe damage to the machine.

In order to minimize the impact of these abnormal conditions, many Tokamak systems are supplemented with a machine protection system. These very simple but reliable systems act by taking the most ruthless and rapid action that minimizes the damage to the Tokamak. Their effect is typically fatal to the plasma discharge and lead to a disruption and sometimes to a lengthy plasma recovering process, but reduces the risk of mechanical damage.

Triggering a machine protection action is therefore not desirable and to avoid this Plasma Control provides several limit avoidance functions. For instance PPCC monitors the actuator currents and tries to maintain a 5% (typical) margin to their absolute limit; a system called Plasma Protection monitors several plasma parameters trying to identify conditions that could eventually lead to disruptions.

Once a potentially fatal condition is detected by a system, the function of coordinating the Plasma Control response is performed by the Pulse Termination Network (PTN [11]). Actuators and controllers have a small set of triggerable plasma termination scenarios. Fault detection functions provide a set of dangerous condition triggers. The termination network acts as a programmable interconnection matrix making sure that every trigger initiates the appropriate pulse termination action.

2.5. PLASMA PROTECTION SYSTEMS

WALLS [12] performs several monitoring functions that try to evaluate the thermal stress to the first wall tiles. Doing that requires implementing a very sophisticated and extensive algorithm which requires a large set of diagnostic inputs. Such complexity hardly fits with the guaranteed high reliability and availability requirements of a machine protection. On the other hand, the consequence of a single violation to these protection limits has no immediate fatal consequence but only contributes to the lifetime of the components. It is under this last condition that this high level protection action becomes acceptable.

Some of the auxiliary heating systems should only operate when there is sufficient plasma current and density. This protection function is performed at JET by PEWS (Plant Enable Window System) which maintains a set of enable signals to each of the managed plant systems. Should any of the relevant plasma parameters go outside the allowed range (window), the enable signal is removed and the systems turn off. This protection function is supplementary to each additional heating primary machine protection as it can implement checks making use of sophisticated diagnostics that would not be classified for low level protection.

2.6. GAS INTRODUCTION AND DENSITY FEEDBACK

Successful formation of a plasma requires the right magnetic conditions together with the timely injection of an appropriate gas. This is the one of the functions of JET gas introduction system (GIS). Once the plasma is formed maintaining a sufficient density requires some level of gas fuelling. The Plasma Density Feedback [13] control function commands the opening of gas valves to achieve the prescribed density. The performance is sufficient for initial and final phases of a discharge and in general during L mode operation [L-H ref]. In H mode discharges the density is instead primarily linked to the plasma ELMy behavior which in turn depends on the gas fuelling. In these circumstances an increase in fuelling might in fact reduce the density.

GIS does, in fact, serve a larger set of experimental purposes. JET is complemented with several injectors, each of which can have a different gas species or a different pressure. Moreover the injectors are located in different part of the machine, mainly the divertor, the mid-plane and the top. This flexibility is used by directly programming specific waveforms for each valve, and by specifying the desired gas species.

2.7. EXPERIMENTAL FUNCTIONS, CENTRAL CONTROLLER AND HIERARCHY OF CONTROL FUNCTIONS

Tokamaks are presently experimental machines. This not only means that it is not yet known how certain problems will be solved but it also indicates that some unexpected challenges may arise during the experimental exploitation.

If one limits the plasma control architecture to include only established systems, such as PPCC, then it would not be possible to rapidly meet the aforementioned challenges. Development of a proper system, not just involves a long and expensive development cycle, but also requires a manageable set of well specified requirements.

When tackling a novel control problem, the experimenters initial strategy is twofold, on the one hand they need to learn how to properly measure the relevant physic parameters and on the other they must establish with what available actuator they might be able to effectively control it. In the ideal world these two activities would lead to the development of a good set of models with which one could develop a set of diagnostic and control systems. In practice, such models are very difficult to produce and in fact a working control system can be built even with less information, as one can design closed control loops (PID or bang-bang controllers) to be robust against model errors. For this reason, after having produced a simplified model based on an experimental sensitivity analysis, the experimenter wants to try closing the loop.

In JET these experimental requirements are supported through the co-operation of several diagnostics, actuator and control system which communicate thanks to the RTDN [1] network. In particular a real time central controller (RTCC [14]) has been introduced to allow rapid implementation of generic control laws among the set of available diagnostics and actuators. The main difference from the core control systems is that the development cycle of a new control law often is significantly shorter (days rather than months) and because of the low consequence of failure allows rapid prototyping Some of these functions (radiation control, impurity control, ≤ control…) have now become of routine application and will eventually form the base for the development of fully fledged control systems.

Another important concept is the layering of control functions. RTCC provides references not just to actuator but in some cases to existing controllers. This results in a simpler control law that can rely on the safety and performance of the other control functions to achieve the desired goals. This approach, allowing a progressive development of the control functions, should be taken in consideration by the designers of future machine like ITER since it will allow distinguishing and integrating control functions that are well understood with those that, today, can only be speculated about.

3. PLASMA CONTROL NON FUNCTIONAL REQUIREMENTS

3.1. DISTRIBUTED AND SEPARATED FUNCTIONS

When JET plasma control was being implemented, one of the clearest requirements that emerged is that its functions had to be physically distributed over the plant. Soon afterwards it came clear that, in fact, these functions were best performed by separate systems.

A distributed control system (DCS) is one where the necessary I/O and processing functions are implemented by co-operation of different hardware systems. In JET these systems are the various diagnostics, diagnostic elaborations (see BetaLi[15] and QProfile[16]), actuators local managers, controllers and plasma protection systems that contribute to the plasma control function. These elements are not only physically distributed over a wide area (100m - 200m apart) but each has large and disparate I/O requirements. Implementing a single system would mean dealing with of the order of several 1000s analogue I/O channels, some with very high sample rate (>20kHz) and some with significant signal isolation problems, and at the same coping with a large processing load and a very complex system.

When robustness and maintainability requirements are taken into account, the function separation allowed by a distributed system also becomes an advantage. Failure of some plasma control functions could lead to scenarios where the machine integrity can be compromised. For instance disruptions, that are easy consequence of a faulty plasma shape control or vertical stabilization systems, can cause an air leak in the vessel.

Separating these functions into different systems serves two purposes. First the resulting smaller systems are more easily managed: re-commissioning effort after an upgrade is proportional to the system size. Secondly a hardware/software failure impacts only the function performed by one system. This last aspect, combined with smart plasma termination strategies or with redundant supply of services can be used to achieve some fault tolerance. For instance, the Shape Controller deals with the possible failure of the main magnetic diagnostics provider by acquiring magnetic information from a second source which it then uses to implement a safe plasma termination scenario. In fact, JET plasma control implements very little redundancy. Since JET pulses are relative short (30s – 60s) compared to the inter-pulse time (>20m), a controller hardware failure during the experiment is very unlikely. Since software faults in complex systems are more likely, robustness is obtained by thorough commissioning.

A further advantage of separation, when coupled with an extendable and secure interconnection infrastructure, is that it allows the addition of a new function by adding a new system without the need to re-commission the whole network. This aspect has been the key to JET ability to progressively grow a modern plasma control system, without the need to invest too much experimental time.

3.2. THE COMMUNICATION INFRASTRUCTURE

A communication infrastructure is the necessary backbone of for a distributed system. It implements a number of concurrent point to multi-point signal communications characterized by a certain (maximum) latency and update frequency. In the case of JET, the requirements, in terms of main performance numbers, are relatively small: ~1000 32 bit signals, <200ºs latency for a 400 byte packet, 1kHz data rate.

The most important of these parameters is in fact the latency. While the number quoted is good enough for most JET applications (VS is the exception), the smaller the delay the larger the stability range for any control system. For this reason, and considering that the closed loop latency is the sum of all processing and communication ones, it is advisable to strive towards solutions that minimize latency.

Probably the most important constraint comes from the need to guarantee the performance parameters and the integrity of established data flows while still allowing for the rapid introduction of new and experimental systems. The main risk is that a new system, whether because of bad design or not having been fully commissioned, suddenly starts to interfere with some of the essential data flows. This scenario would be possible at JET especially because systems are developed by different teams and some are contributed as part of external collaborations. This risk became clear at JET when trialing different solutions and it was one of the main drivers behind the choice of ATM [17].

One of the most important features of the ATM network is the implementation of a Permanent Virtual Circuit (PVC [17]). This is a mechanism, implemented by the switch, which guarantees that a certain stream of information coming just from a pre-determined source is communicated exclusively to a chosen list of destinations. In JET the map of PVCs connections is set on the switch and cannot be changed by any node. The resulting interconnection fabric is functionally equivalent to a set of analogue (hard wired) connections. However much a particular plasma control system misbehaves, the switch will not allow it to interfere with others.

ATM provides an asynchronous transport mechanism where packets are sent as soon each source is ready. Sources produce data at different rates, each synchronized to a fraction of the JET central clock frequency. The delay between the raw data acquisition and the packet production is set by the required computational time. The result is a set of synchronous data streams each with the minimum possible latency.

The arrival of a message at a destination carries more information than just the payload itself. The fact that arrival is promptly signaled by an interrupt to the processor can be used as a watchdog for the source system. In RTDN each packet has a header containing the JET time of the original raw data acquisition. The comparison between this time and the arrival time is a measurement of the circuit latency. Safety relevant systems like PPCC and WALLS, reject the data source whenever a too large latency is detected. Whenever a too long sequence of consecutive rejections has occurred an emergency plasma termination is initiated. The mechanism has proven very effective in detecting faults in some diagnostic sources.

3.3. CODAS[18] (CONTROL AND DATA ACQUISITION SYSTEMS)

All plasma control systems are necessarily elements of the CODAS three-level hierarchical and modular architecture [18]. Time and triggering information, experiment parameters and countdown events are all required elements for their correct operation. In addition they require post pulse data collection services in order to support fault finding and performance optimization.

In JET plasma control systems are managed as components in the three-level hierarchy (Level3), and as such are individually mapped into a specific CODAS sub system (Level2). The mapping choice is typically driven by the necessity to facilitate integrated testing between plasma control facilities and their related diagnostic or actuator.

A system on its own cannot take into account the status or the configuration of the JET machine in its entirety. In general its parameters need to be obtained by specifically processing the user inputs together with plant information: the machine status, the applicable limits obtained by evaluating operating instructions, the programming of other plant or plasma control systems. This important elaboration, at JET, is performed by the top level of the hierarchy (Level1) [19].

At JET, large part of the Level1 pulse setup parameters is relative to the plasma control system (in particular Shape Controller). The main reason is that modern data driven digital real time control systems easily satisfy the user requirements for flexibility by allowing extensive programmability of references and control strategies. The Shape Controller allows the experimenter to divide a discharge into 25 time slices; in each a completely different control strategy can be chosen. XSC [3], a special control mode of Shape Controller, allows detailed programming of the control algorithm by choosing diagnostics, actuators and, to some degree, the algorithm.

Recent developments, WALLS [12], and PCU [6] have further increased the demand to Level1. These systems, rather than implementing a sequence of operations determined at compilation time, execute a sequence of complex operations specified in the parameters received from CODAS. In these systems not only the computation parameters are fully programmable, but also the choice and the sequence of algorithms. For example, in the new Vertical Stabilization (PCU), one can easily filter any signal (inputs, outputs, or internal) by specifying in the operational sequence a filter module with appropriate parameters.

JET Level1 software has been able to manage this complexity with the introduction of the concept of scenario: a group of parameters which the user can select from an available palette. Some scenarios have a fixed structure, some have a variable one. Some are user editable; some are produced by automatic codes [7]. With the PCU project, they have become nested: scenario elements can be scenarios. In general, scenarios allow PSE to present the user with the necessary level of complexity: for a more routine experiment high level scenarios can be used; when a special function is required each individual parameter can be accessed.

3.4. GENERAL REQUIREMENTS AND DESIGN OF A SYSTEM

The most obvious requirement for a plasma control system is its real time behavior. This means that its computation shall always complete within a given time so that a minimum latency can be guaranteed. A fixed data production rate is also expected.

When designing the algorithm, the most difficult task is to conceive a simple enough implementation that minimizes the risk of a failure and reduce the commissioning demands. The approach used at JET for the larger systems is to shift as much of the computational complexity outside the real time processing loop, into either the parameter pre-processing or into the Level1 user interface. The aim is not for a faster algorithm but for one that is simpler, with less decision branches and in general fewer lines of code.

Recent plasma control developments at JET, the PCU and XSC projects, can claim a particular level of success especially in the ability to deliver working systems without the need for extensive commissioning. The key approach to achieving these results was "model based" design approach.

The idea is that the design of the system is tested at every level against an appropriate model using a simulator. This means that the larger part of the effort had to be concentrated into developing good model of the Tokamak, in this case of its magnetic properties. This was a very heavy and costly activity, but where the resulting saving in experimental time more than compensated for it. In fact without this approach the introduction of new control systems in a machine where the priority is the scientific exploitation would almost be impossible.

In order to support this approach, plasma control systems implementations need to provide for extensive test capabilities. The JET approach has been to develop multi-platform code so that the systems could be directly used as part of the simulations with the plant model. Extensive modularization and configurability of the code structure [20] have been used to allow rapid implementation of different test schemes that could also be executed on the real target.

3.5. REAL TIME DIAGNOSTICS REQUIREMENTS

Compared to traditional diagnostics design, the real time requirement imposes further constraints. The most important is the fact that the important plasma information needs to be available with a certain small latency. This might be very difficult since the interpretation of certain diagnostic data might require calibration information that can only be easily obtained at the end of the shot. The low latency requirement can also translate into large computational requirements or imply an effective reduction of the diagnostic precision.

Availability is also a difficult challenge to diagnostic engineers. Even allowing for a faultless implementation, the availability of the diagnostic information is typically contingent to certain plasma condition. A real time information feed with conditional availability can be still used as part of a control function, but this must be complemented by the presence of alternate control strategies, less precise but covering the whole operation space.

CONCLUSIONS & ITER RELEVANCE

The first part of the paper critically discusses the basic functional requirements of JET plasma control system. Rather than looking into the most advanced and scientifically interesting new control functions the paper shows what are the basic functions that need to be provided. The most important message is that a flexible mix of functions is the only way to properly satisfy operation requirements.

In fact, JET experience has been that the more sophisticated control functions, while potentially delivering advanced functionalities, suffered from having limited applicability. The problem is that advanced control laws tend to be less robust compared to simpler ones as they critically depend on the validity of the model they were based upon. Future designers should keep this consideration in mind when designing a plasma control system that is able to effectively and robustly satisfy the user needs.

Flexibility has also been the most important non-functional requirement. The ability to rapidly match the varying demands from the experimenters has been essential to provide a good service. At the same time, safe and effective exploitation of the heightened machine flexibility called for tools that minimized the human error and the risks associated with the experiment unpredictability.

JET machine operation time is a scarce resource, to be allocated primarily to experiments rather than technical and commissioning activities. Plasma control architecture needed to manage complexity and reliability without requiring much testing time on the tokamak.

Flexible, safe and manageable have been the strongest requirements behind JET plasma control development. JET size, its international and collaborative nature have determined how these requirements were best met. Rather than a centralized plasma control system, a distributed expandable and collaborative network of systems has been the most adequate solution.

JET real time network (RTDN) is, probably, the most important element behind JET Plasma Control manageable and safe flexibility. Its strongest feature is the permanent virtual circuit, the network switch managed mechanism that provides guaranteed data flows among collaborating systems. JET RTDN network effectively implements a set of synchronous real time networks, each with the smallest possible delay. Using ATM asynchronous delivery mechanism RTDN does not enforces synchronism but verifies it.

Can JET experience translate into ITER requirements? The author thinks so. The two machines have a comparable set of features and functions, at least from the point of view of the plasma control. Flexibility will be the keyword for ITER too. Plasma control requirements will vary over the many years of exploitation: H, D and DT phases will all pose different plasma control requirements. Remarkably similar is also the distributed and collaborative nature of both machines: ITER systems will be contributed by different domestic agencies.

Not only ITER experiment will last close to one hour, but current plans of its exploitation consider 24 hour operation. This means that the probability of
a hardware fault occurring during a plasma experiment is markedly higher compared to JET. Commissioning alone will not guarantee the necessary reliability.
The necessary complexity and flexibility of ITER systems will probably require a higher level of redundancy.

Long pulses also means that JET simple approach to limit avoidance, terminate the pulse, will not satisfy ITER requirements. This opens the door into a very difficult control problem, real time decision of the correct strategy. Given the number of possible combination of fault scenarios, it may not be possible to simply prescribe a recipe for each. Development on the same direction will be necessary to properly handle emergency plasma termination during JET Beryllium wall exploitation phase.

In conclusion, the author thinks that ITER plasma control system will have to cater for the same basic requirements that JET had to satisfy over the years. Manageable and safe flexibility will be important for ITER given the enormous challenges in both reliability and functionality it will face.

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