Runtime resource checking at WENDELSTEIN 7-X during plasma operation

**Heike Laqua[a], Jörg Schacht[a] and Anett Spring[a]**
[a]Max-Planck-Institut für Plasmaphysik, EURATOM Association, Teilinstitut Greifswald, Wendelsteinstr. 1, D-17491 Greifswald, Germany
Received 14 July 2006; revised 13 July 2007; accepted 18 July 2007.

Available online 4 September 2007 at:
http://dx.doi.org/10.1016/j.fusengdes.2007.07.017

## Abstract

The super conducting stellarator WENDELSTEIN 7-X (W7-X) is designed as a steady-state device which will run pulses of 30 min or more. During discharges W7-X will be controlled by a dedicated "segment control system" addressed in this article.

Due to the innovative nature of a fusion device and its subsystems a failure of a subsystem during a discharge cannot be ruled out. Safety critical failures are handled by the safety system. In many cases a failure leads only to a degradation of the plasma quality and not to a safety critical situation. Because of the long pulses the segment control has to detect the situation and steer the discharge into another state in which preferably the discharge can continue without the failed subsystem or the discharge is gracefully brought to an end.

After a short summary of the main aspects of the "segment control system" this paper deals with the online resource check required for fault detection and recovery. It explains how the online resource check is integrated in the control system and how the control system support recovery strategies.

**Keywords:** Digital control system; WENDELSTEIN 7-X; Real time system; Plasma control; Steady state fusion plasma

## Article Outline

## 1. Introduction

The super conducting stellarator WENDELSTEIN 7-X (W7-X) will run pulses of up to 30 min duration with full heating power. Pulses might even be longer with reduced heating power since the duration is limited by the consumption of cooling water only. All discharge scenarios compatible with these capabilities will be supported by the control system: short pulses with arbitrary intervals, steady-state discharges and arbitrary sequences of phases with different characteristics in one discharge. The latter scenario includes short and long pulses. Long discharges with phases of different characteristics are understood as series of short discharge sections called “segments”. Thus, the heart of the control system is the “segment control system”. It relies on a hierarchical control system described in Section 2. The concept of “segment control” will be explained in Section 3.

Due to the innovative nature of all fusion systems, and the nonlinear complex behaviour of the plasma, a failure of a subsystem or an unexpected outcome of an experiment during a discharge cannot be ruled out. Safety critical failures are handled by the safety system [1] leading to an immediate break-up of the discharge. In many cases the failure leads only to a degradation of the plasma quality and not to a safety critical situation. In short pulse experiments immediate shutdown of the discharge was the consequence. This is not an option for long pulse experiments since the maintenance of a steady-state discharge is an important objective of these plasma devices. Redesigns of control systems of short pulse plasma devices take online checking and recovery from failures into account, too [2]. Therefore, failures and undesired plasma states have to be detected online by the control system performing a resource check as described in more detail in Section 4. Sometimes the discharge can continue without the failed subsystem, the failed system can be substituted, or the undesired plasma behaviour can decay when control parameters are varied. If the discharge cannot continue it is gracefully brought to an end instead of an abruption by the safety system. An example in Section 5 will illustrate the benefits of the concept. Section 6 summarises the state of realisation.

## 2. Hierarchical control structure

The control system of W7-X has a hierarchical architecture [1], conf. Fig. 1. The top of the system is the “*Project*” which stands for an ensemble of control *Groups* which can operate in a coordinated manner to control a whole plasma device as W7-X. A project consists of an aggregation of “*Groups*”, i.e. the control systems of technical subsystems or diagnostics. A *Group* is controlled by one or more “*Control Stations*”, which are computers either running a real time operating system and the W7XSegmentControl software (*Fast Control Station*) [3] for fast control or a platform independent Java application called “*CoDa-Station*” [4] for data acquisition. A *Control Station* consists of “*Modules*” at the base of the hierarchy. Some of them are the software counterparts of installed hardware devices. Others are monitoring modules comparing actual values with physical or technical constraints. A survey on different modules not described here can be found in [3].

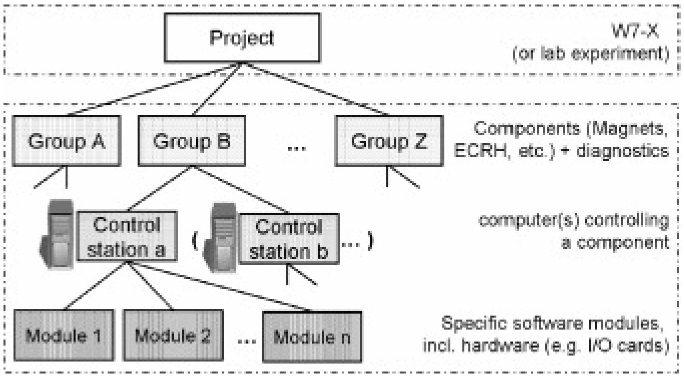


Fig. 1. Hierarchical structure of the experiment control system.

## 3. The concept of segment control

Segment control is realised as software control by computers [3]. The behaviour of all controlled subsystems is determined by software objects. They contain parameters and algorithms to define their dynamic behaviour. Corresponding to the hierarchical structure of the control hardware the software objects are modular and structured hierarchically. The description of each discharge segment is realised by one complex distributed software object called '*segment description*'. Breaks are described by means of 'Idle' segments. Segment descriptions are generated and stored in the database by means of a special editor [5]. On request of the session leader all computers involved in the segment control create the segment descriptions required in the near future. On command of a central sequence control all partial objects of each segment description are activated synchronously in all computers.

Fig. 2 shows the segmentation of a long discharge. Physics scenarios are described by an ordered chain of one or more segments, which cannot be separated at run time. A scenario always has to begin with a transition segment providing a blending between the last scenario and the new one. Transitions have to be carefully defined taking technical and plasma physical aspects into account. In many cases a transition segment can be formulated without knowing the past, e.g. a set point may ramp from an arbitrary end value of the last scenario to the starting value needed for the next scenario. If this simple assumption does not hold the two scenarios are linked and should be combined to one. A discharge program consists of one or more scenarios.

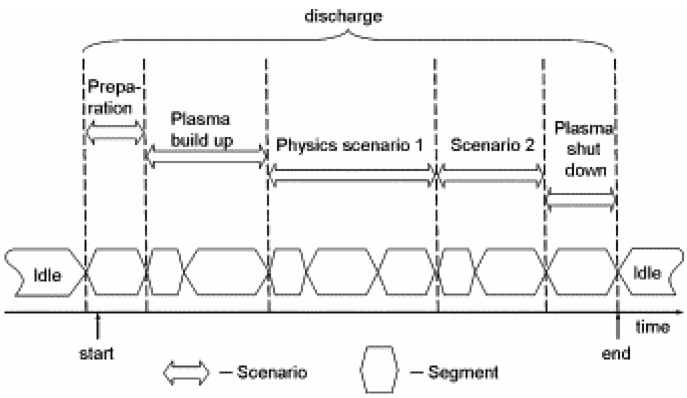


Fig. 2. A discharge is broken down into scenarios which in turn consist of segments.

## 4. Segment based online resource check

### 4.1. General concept

Online resource checking is essential because in fusion experiments, highly complex integrated subsystems are used in a very demanding way. That is why they can be subject to failure. Furthermore, the segment control system controls an experiment with sometimes unexpected and unpredictable outcome. Thus, the planned and the actual behaviour of the plasma device W7-X must be checked on a timescale relevant for plasma parameter changes. For the inherently stable stellarator W7-X with a confinement time of 400 ms this time constant is in the order of a millisecond.

Since the planned behaviour with all set points is stored in the segment description it is manifest that a resource check has to base on a comparison between the segment description and the actual capabilities of a subsystem. Besides set points actual values must be taken into account, too. In addition the rules of the resource check depend on the planned plasma characteristics given in the segment description. On one hand not all installed subsystems, e.g. not all diagnostic systems, need to be active during a discharge; a failure of these '*optional*' subsystems can safely be ignored. On the other hand some subsystems might be '*unwanted*' since they interfere with the main program. Subsystems which must be active and capable of performing the required actions in the active segment program are called '*mandatory*'.

The online resource check of a certain segment is passed successfully when all mandatory control elements are ready for this segment and all unwanted elements are inactive. Otherwise the resource check fails. If the segment under test is the running segment the segment sequence controller will terminate this segment and start a substitute. In case the segment under test is the next segment immediately before a segment switch the segment sequence controller will not start this segment and will select a substitute. The substitute has to be a successfully checked transition segment or the 'Idle segment' thus ending the discharge. Different selection strategies are envisioned, e.g. take the next segment fulfilling the above mentioned conditions in the discharge program or the 'Idle segment' if no one can be found. The outcome of the resource check for all checked segments can be observed [6].

### 4.2. Resource checking in the hierarchy of the control system

According to the hierarchical architecture of the segment control system depicted in Fig. 1 runtime resource checking is accomplished hierarchically, too. This means that the answer to the question "Can the specified segment description be carried out immediately?" is delegated from the highest level to the lower ones. The highest level is either the *Group* level when a subsystem operates autonomously for commissioning and tests or the *Project* level when a subsystem operates subordinated as part of the *Project* [1]. The answer to this question might either be 'Yes, feasible', 'Never ', if a resource is missing or has a long term failure, or 'Not now' if all resources are available but in an inappropriate state to carry out immediately the demands of the segment in question. The information is gathered on the next higher level, evaluated according to whether the individual lower level control elements are mandatory, unwanted or optional. The condensed information is passed up in hierarchy.

A hierarchical checking procedure delegates the decision about whether a segment description is feasible to the periphery having more information about the detailed actual state of the controlled process. Especially hardware failures can only be detected at the front ends and are valuated where they are detected.

For online resource checking each module has to implement a method checking itself. This method is specific for the module, e.g. taking into account driver feedback in case of a hardware encapsulating module or checking continuity in case of a waveform generator. On the ‘control station’ level a ‘Segment Manager’ module polls all mandatory modules for their feasibility status on a process timescale relevant for the process control by this station. On this level ‘unwanted modules’ do not exist since it is assumed that the control station is designed to fulfil exactly the needs of the controlled process. However, auxiliary modules can be declared ‘optional’. The result of the check is communicated to a dedicated module, usually implemented in another control station, collecting and valuating the result for the whole *Group*, the so called *Group Sanity Checker*. The *Group Sanity Checker* computes a summarised result depending on the requisition profile, i.e. which stations are mandatory, unwanted, or optional. A segment is feasible when the segment is feasible for all mandatory *Control Stations* and when all unwanted *Control Stations* are inactive. The latter is the case when the station is either inactivated by the *Group's* operational management [1] or the segment is marked as feasible, i.e. the part of the segment description for this station equals its idle segment and the station is capable of running this segment. This allows carrying out an experiment if the control system of a *Group* is functional while the *Group's* data acquisition system is not available. Unwanted activities, e.g. the calibration of a diagnostic during a discharge, can be avoided. On this level a *Group* may be operated autonomously or can pass the resource check to the *Project* level when being operated subordinated. In subordinated mode the condensed check result is passed to a *Project Sanity Checker*. This module implements the same logic for computing the summarised check result as the *Group Sanity Checker* depending on the requisition profile for the *Groups* of the *Project*. The requisition profile for *Control Stations*, *Groups*, and *Projects* may vary from segment to segment.

## 5. Example: ECRH in a W7-X scenario

A typical example of a demanding subsystem is the electron cyclotron resonance heating (ECRH) system. The ECRH system is used to illustrate the features and benefits of online resource checking during a W7-X plasma discharge. The cutting edge gyrotrons might suddenly fail and are therefore monitored [7].

### 5.1. Example A

For simplicity let us assume that the discharge begins with a preparation scenario followed by a physics scenario and ends with a shutdown. A certain gyrotron is selected as the main heating source for the physics scenario. In this simple example a scenario consists of one segment only. A critical failure in this gyrotron in a segment with ECRH shall stop that scenario but not the discharge. Therefore, a substitute scenario with the same physics parameters but another gyrotron is prepared. The substitute scenario is placed directly behind the main scenario in the discharge. In the main scenario the module monitoring the main gyrotron is a mandatory module of the *Fast Control Station*, the one monitoring the second one is optional. In the substitute scenario both monitoring modules are mandatory but the logic of the module monitoring the main gyrotron is reversed, i.e. the substitute scenario is only feasible when the main gyrotron is *not* ready. The station is mandatory for the Group “ECRH” and the ECRH-Group in turn is a mandatory part of the Project ‘W7-X’. Example A in Fig. 3 illustrates this set up and the different possible realisations. If the main gyrotron fails during the execution of the main scenario, the segment control system switches to the substitute thus activating the second gyrotron which will also be monitored. In case the second gyrotron fails, too, the segment sequence control will search the remaining valid program for another feasible scenario or stop the discharge if none can be found. If all goes well the substitute scenario will never become feasible since a malfunction of main gyrotron is mandatory for this scenario. It is skipped automatically by the segment sequence control.

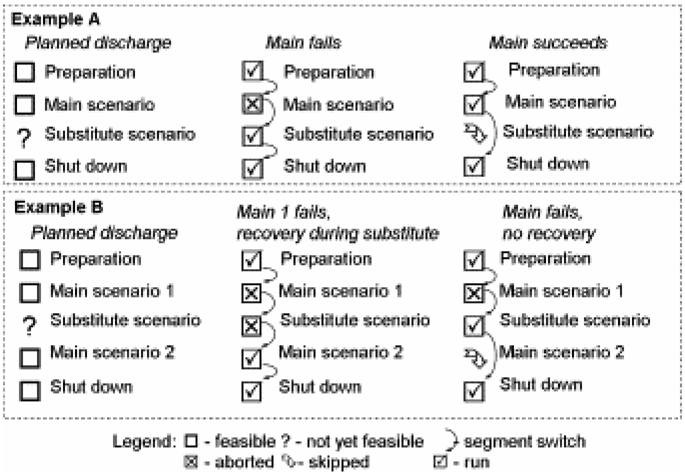


Fig. 3. Operational diagram for Examples A and B with different outcomes of a discharge depending on the resource check.

### 5.2. Example B

In another scenario (scenario main 2 in Fig. 3; example B) the planned density is close to the cut-off density of the second harmonic extraordinary mode (X2) which is the standard ECRH heating scheme for W7-X. Above this density the X2 mode cannot any longer penetrate into the plasma. In case of lost density control the actual density may exceed the cut-off. A discharge abort might damage parts in the plasma vessel by uncontrolled reflected microwave power. A substitute scenario during which the main gyrotron emits microwaves with ordinary polarisation (O2 mode) is defined. The cut-off density in O2 mode is twice the one of X2. When density control is regained a switch to a third scenario (main 2 in Fig. 3 example B) with standard X2 heating shall be triggered; i.e. the substitute shall only be feasible when the actual density exceeds a threshold slightly below the X2 cut-off. If the density limit is reached in the first scenario it will be stopped and the substitute scenario will be started. When the density falls again below the threshold defined in the substitute it gets unfeasible and the main scenario 2 is activated by the error recovery system of the segment sequence controller.

### 5.3. Example C

The two use cases can also be combined. Two main scenario using the main gyrotron in X2 mode are prepared along with three substitutes: (1) main gyrotron in O2 mode, (2) provision gyrotron in X2 mode, (3) provision gyrotron in O2 mode and chained as depicted in Fig. 4. When the main scenario fails because the main gyrotron fails the substitute scenario 2 is activated. When after the gyrotron failure the density increases the substitute 3 is started. If the failures occur reversed the substitutes 1 and 3 are used. In case of density control loss only the chain of activated scenarios is as shown in the right most column in Fig. 4. If all goes well only the two main scenarios are realised. In this case all substitute scenarios are unfeasible and will be skipped.

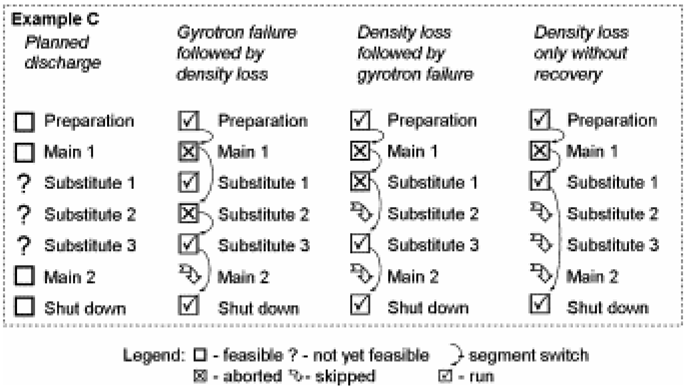


Fig. 4. Operational diagram for Example C with different outcomes of a discharge depending on the resource check.

## 6. Status of realisation

The generic online checking algorithms for *Project*, *Group* and *Control Station* have been implemented as part of the real time W7XSegmentControl software package. The checking methods for individual modules are on the way. The simple error recovery strategy mentioned in the example is finished, too. The user interface Xcontrol [6] monitors continuously the result of the online resource check.

The online resource check has also been implemented for the Java based CoDa-Stations for the *Control station* and *Group* level by the XDV data acquisition group.


## Acknowledgement

The authors would like to thank the XDV data acquisition group for their support and the fruitful discussions and proposals.


## References


[1] J. Schacht, H. Niedermeyer, H. Laqua, A. Spring, I. Müller, St. Pingel and A. Wölk, Tasks and structure of the WENDELSTEIN7-X control system, *Fusion Eng. Des.* **81** (15–17) (2006), pp. 1799–1806. SummaryPlus | **Full Text + Links** | PDF (377 K) | View Record in Scopus | Cited By in Scopus (5)

[2] V. Mertens, J. Hobirk, A. Kallenbach, P. Lang, A. Mück, G. Pautasso, G. Raupp, A. Sips, J. Stober, H. Zohm and ASDEX Upgrade Team, Development of active control systems on ASDEX upgrade in view of ITER discharge scenarios, *Fusion Eng. Des.* **66–68** (2003), pp. 119–127. SummaryPlus | **Full Text + Links** | PDF (1113 K) | View Record in Scopus | Cited By in Scopus (3)

[3] H. Laqua, H. Niedermeyer, J. Schacht and A. Spring, Real-time software for the fusion experiment WENDELSTEIN 7-X, *Fusion Eng. Des.* **81** (15–17) (2006), pp. 1807–1811.

SummaryPlus | **Full Text + Links** | PDF (117 K) | View Record in Scopus | Cited By in Scopus (5)

[4] P. Heimann and the XDV Team, Status report on the development of the data acquisition system of Wendelstein 7-X, *Fusion Eng. Des.* **71** (1–4) (2004), pp. 219–224. SummaryPlus | **Full Text + Links** | PDF (120 K) | View Record in Scopus | Cited By in Scopus (7)

[5] H. Kühntopf, H. Kroiss, T. Bluhm, P. Heimann, Ch. Hennig, G. Kühner, J. Maier, M. Zilker and W7-X control group, Specialized editor for processing objects in a database to prepare discharges for WENDELSTEIN 7-X, *Fusion Eng Des* **81** (15–17) (2006), pp. 1741–1745. SummaryPlus | **Full Text + Links** | PDF (327 K) | View Record in Scopus | Cited By in Scopus (2)

[6] A. Spring, H. Laqua and J. Schacht, User control interface for W7-X plasma operation, *Fusion Eng. Des.* **82** (2007), pp. 1002–1007. SummaryPlus | **Full Text + Links** | PDF (454 K)

[7] G. Michel, A fast and versatile interlock system, *Fusion Eng. Des.* **74** (1–4) (2005), pp. 611–615. SummaryPlus | **Full Text + Links** | PDF (239 K) | View Record in Scopus | Cited By in Scopus (1)