1 Introduction

ITER and Wendelstein 7-X are designed to demonstrate steady state operation of fusion experiments. LHD and TORE SUPRA have already shown their long pulse capabilities.

These experiments require strategies to sustain a discharge in case of unexpected events with negative consequences for further operation. These events are elsewhere referred to as exceptions [1] or off-normal [2]. Examples for these events are heat overloads of plasma facing components, the failure of a plasma heating source, or plasma related events (disruptions, magneto-hydrodynamic instabilities). Such events are the result of a missing or degrading resource. A recovery strategy is needed to maintain the discharge in spite of degrading resources in order to maintain the steady state discharge. The spectrum of suitable reactions is wide spread. The number of recovery strategies will grow with the experience gained at the installation. The development of suitable reactions is a topic of actual plasma physics research, e.g. in [3], [4]. For the handling of these events the W7-X Segment Control framework provides means for automated event detection along with options to formulate and initiate a recovery strategy. The details are given in section 2.

Besides handling of failures and degradation there are events that represent an expected plasma physical effect. An example for this kind of event is a transition from Low to High-Confinement mode. These events indicate that a certain plasma state is reached and scientific examination can be altered thus enabling multiple experiments per discharge driven by plasma physics. Within the W7-X Segment Control framework discharges are divided into time slices called segments [5]. Events can be used as a termination condition of a segment. The next segment after the event starts a new experiment scenario. This use case will be discussed in more details in section 3.

2 Resource checking and failure handling

This section deals with the handling of off-normal events.

2.1 Segment based online resource check

The details of the Segment control framework are explained in reference [5]. A discharge is divided into time slices (segments). The behaviour of the CoDaC system is defined by one complex distributed software object called ‘segment description’. A fusion device consists of many components. The control software is modular to reflect the modularity of the device. The piece of hardware controlled by a software module is regarded as a “resource” necessary to carry out experiments.

All modular components check their own resources regularly at run time. It bases this on a comparison between the segment description and the actual capabilities of the component, e.g. set point values are checked against the actual operation range. Similar checks are performed for actual values to stay within proven operational limits. Pattern recognition processes detect exceptional, potentially hazardous plasma or machine states. Data from distributed components are exchanged by means of a dedicated network [6]. The W7-X segment control framework comprises an extendable toolbox of pattern recognition modules and algorithms.

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. Some other subsystems may 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’.

Within the Segment Control framework some dedicated modules combine the state information of all components according to the requisition profile of ‘optional’, ‘mandatory’, ‘unwanted’ and mark the segment as feasible or not.

2.2 Handling the resource check information

The Segment framework comprises a segment scheduler [7], called Segment Sequence Controller. Components can either operate stand alone using their own segment sequence controller or operate subordinated. In subordinated control mode all subordinated components are steered by the central segment controller.

An experiment program consists of a sequence of segments. Unfeasible segments are marked as such and the component causing the unfeasibility is stated. On demand a more detailed analysis of the obstacles can be generated. Using this information the session leader is able to bring the installation into a state with a feasible program.

Although the experiment program has been feasible on start, some segments may become unfeasible due to a degradation of resources. All mandatory resources are continuously monitored by the resource checking framework. The scheduler aborts unfeasible segments immediately (latency ≤ 1 ms). Unfeasible segments are skipped. The experiment program is continued with the next feasible segment that is marked as a possible reentry point if there is any. This feature allows planning of error recovery strategies as a sequence of suitably defined segments. Fig. 1 shows an example discharge carried out at the prototype installation at the WEGA stellarator [7]. A pattern recognition process detects when the plasma is heated but does not ignite after a certain time. The plasma operation segments get unfeasible. The experiment program is continued with the last scenario defining a soft shut down. More elaborate examples have been presented in [7].

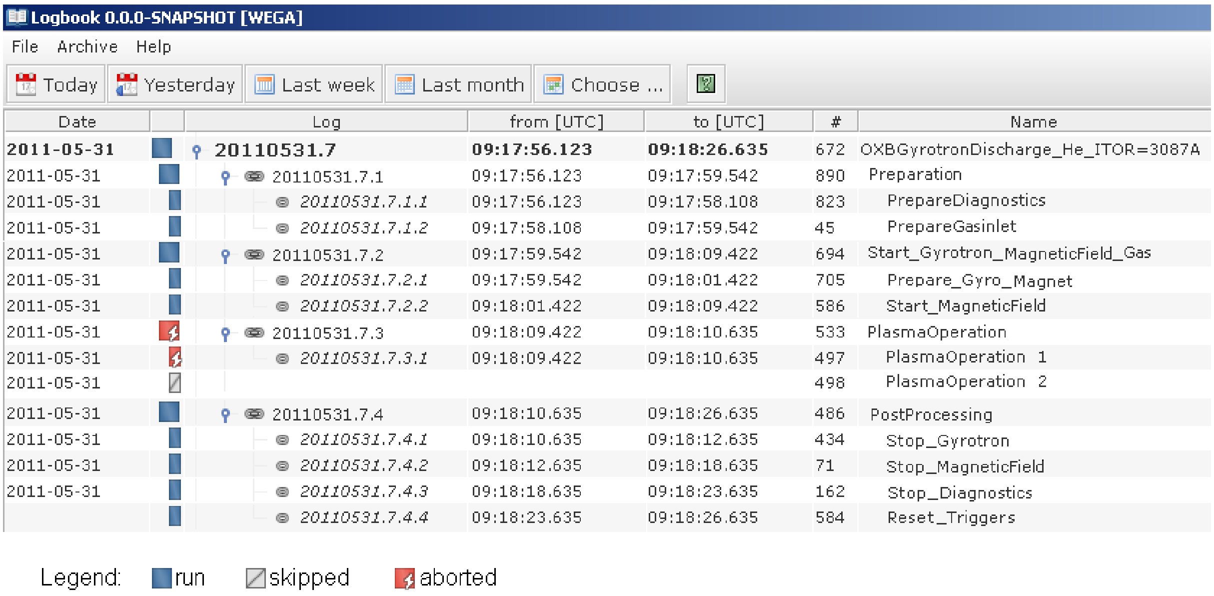


Figure 1: Logbook representation of a failed discharge

Other event handling approaches are followed with controlled fusion devices. The colleagues from TORE SUPRA realized an expert system to handle off-normal events [9]. The expert system overrules the values planned in the discharge program in case of off-normal events. In this aspect this approach differs completely from ours for W7-X. Within the W7-X event handling framework the error strategies are part of the experiment program and under control of the physics experts. The **P**lasma **C**ontrol **S**ystem developed at DIII-D follows an approach similar to the W7-X one. In contrast to our approach DIII-D uses a finite state machine architecture [2] with a fixed number of error handling states whereas the W7-X approach allows to define the error handling in a more flexible way within the discharge program.

3 Program scheduling driven by physics

Pattern recognition modules can be configured to generate events when the pattern is recognized. The W7-X segment control software includes a set of signal processing modules. The toolbox will extended when new algorithms are required. Advanced pattern recognition processes developed at other installation e.g. at the Joint European Torus JET [10], can either be ported to the used programming languages Java and C++ or installed as a Web Service [11].

The generated event can be used as a termination condition of a segment. Figure 2 illustrates the usage of this feature for event driven physics at WEGA. The first segment is planned to produce a plasma transition as described in [12]. The transition is characterized by a steep decrease of the sniffer probe signal in coincidence with a density increase above a threshold value. A pattern recognition process using modules from the signal processing toolbox has been set up. In this example a combination of signal conditioning, step detection, and threshold detection modules is used to detect the transition at run time. An extra heating system is needed to induce the transition. After the transition the additional heating has to be switched off as soon as possible by a switch to the next segment. In the example it takes 30 ms from event detection to the reaction. The update period of the

Heating controller is 10 ms. Roughly, one cycle is needed for the event recognition, one for the propagation, and one for the synchronized reaction. This event handling feature is now routinely used at WEGA.

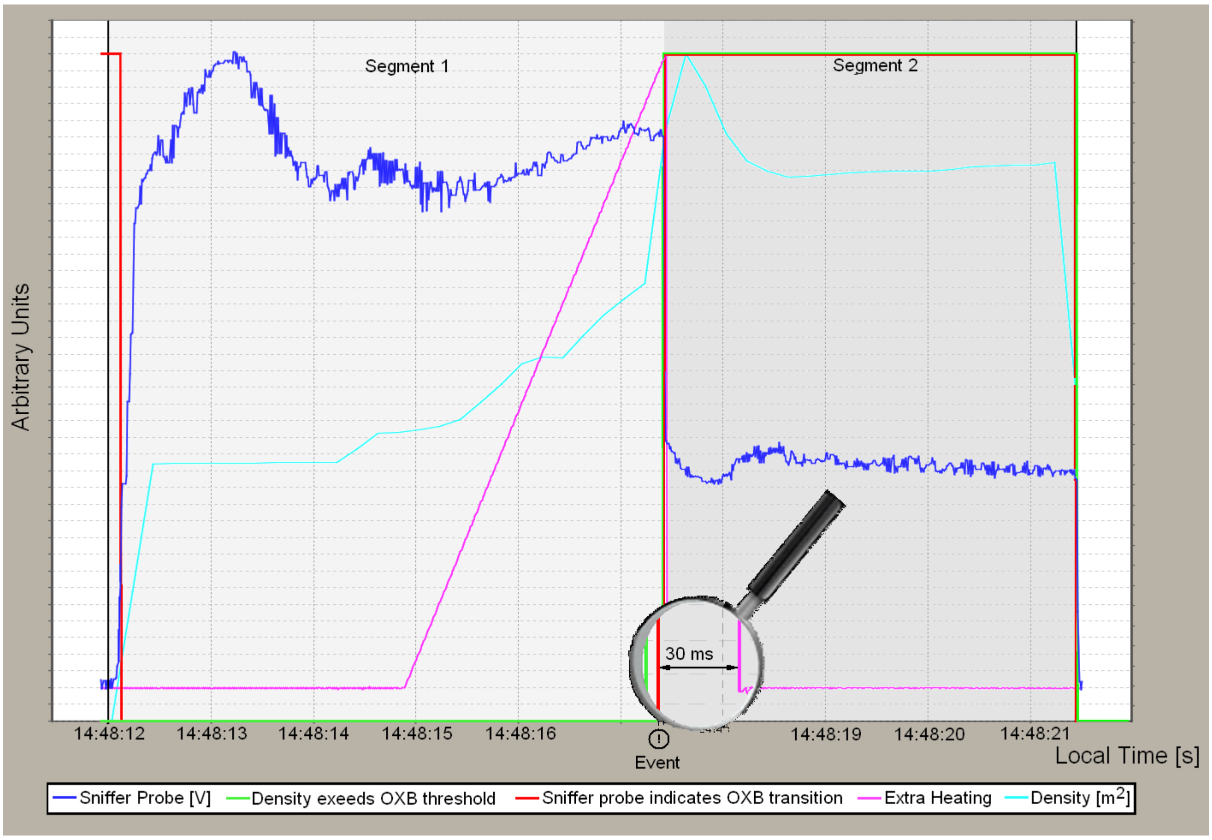


Figure 2: Example of control driven by plasma physics

4 Conclusion

Event handling capabilities are an important factor to achieve the maximum physics output of long discharges. The Segment control system developed for W7-X provides two event handling strategies. One is intended to handle events indicating a negative or even hazardous impact on the running discharge by continuing the program at the next feasible entry point. The other one handles detected events indicating an experimental success optimizing the scientific exploitation of a fusion device by stopping the actual segment after an event and starting a new physics scenario with the next segment.

Acknowledgement

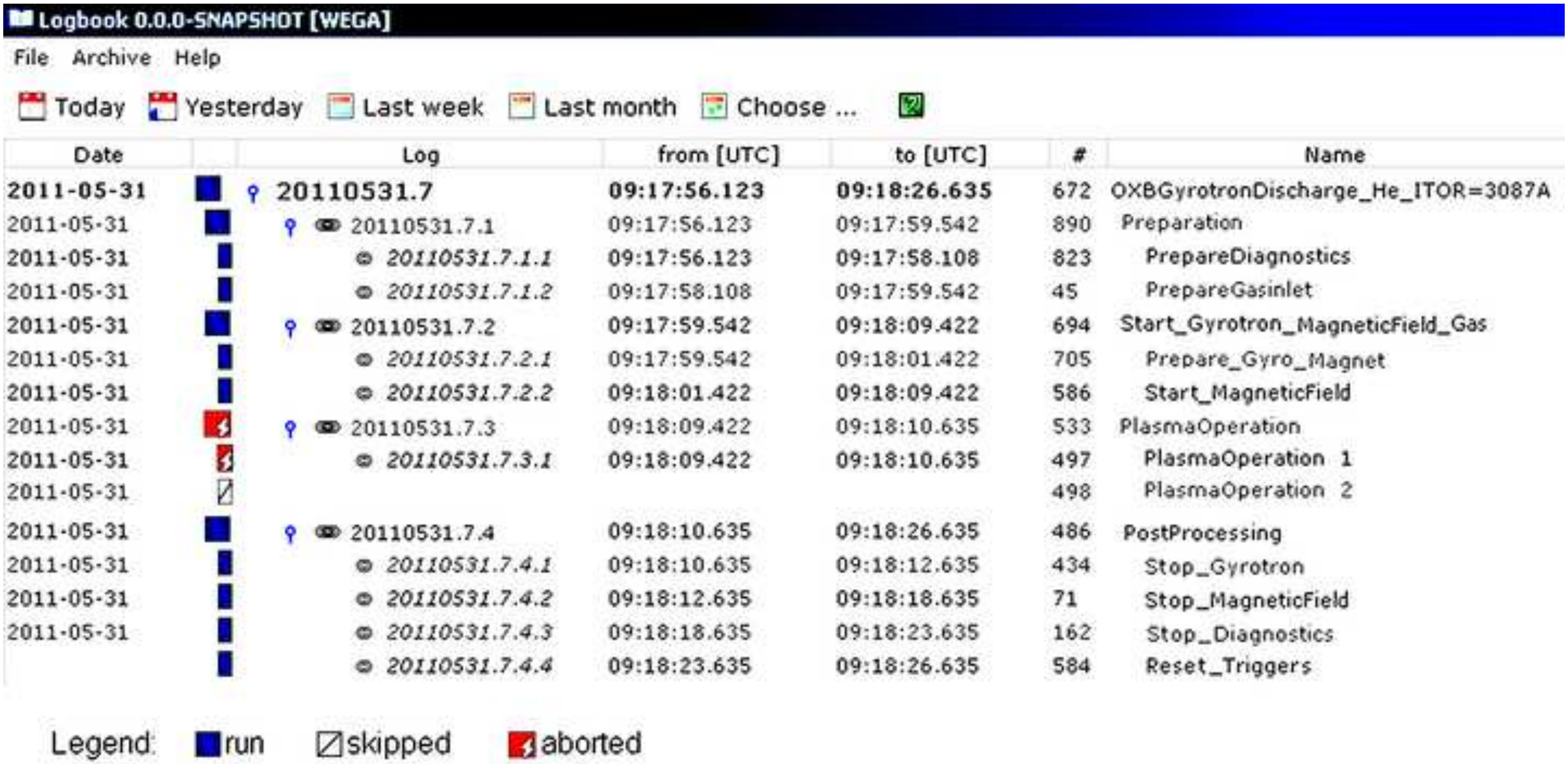
The developers would like to thank the WEGA team for the close co-operation, intense testing and many fruitful discussions.

References

[1] A. Winter, et al., Status of the ITER Plasma Control System Conceptual Design, *Proceedings of ICALEPCS 2009,* *http://accelconf.web.cern.ch/accelconf/icalepcs2009/papers/tup110.pdf*

[2] B.S. Sammuli, et al., "Approaches to tokamak off-normal event detection and response at DIII-D, KSTAR, and EAST, Fusion Engineering and Design, Volume 85, Issues 3-4, Proceedings of the 7th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research, July 2010, Pages 456-460, ISSN 0920-3796, doi: 10.1016/j.fusengdes.2010.05.002.
[3] J. Bucalossi et al., J. Nucl. Mater. (2011), doi:10.1016/j.jnucmat.2011.01.045
[4] P.T. Lang *et al* 2004 *Nucl. Fusion* **44** 665 doi: 10.1088/0029-5515/44/5/010
[5] H. Laqua, H. Niedermeyer, J. Schacht and A. Spring, Real-time software for the fusion experiment WENDELSTEIN 7-X, Fusion Engineering and Design, Volume 81, Issues 15–17, 2007, Pages 1807–1811, doi:10.1016/j.fusengdes.2006.04.005.
[6] H. Laqua, H. Niedermeyer and I. Willmann, Ethernet based real time control data bus, IEEE Trans. Nucl. Sci. 49 (2002), pp. 478–482.
[7] H. Laqua, J. Schacht, A. Spring, Runtime resource checking at WENDELSTEIN 7-X during plasma operation, Fusion Engineering and Design, Volume 82, Issues 5-14, 2007, Pages 982-987 doi:10.1016/j.fusengdes.2007.07.017.
[8] J. Schacht, , et al., Stellarator WEGA as a test-bed for the WENDELSTEIN 7-X control system concepts, Fusion Engineering and Design, Volume 83, Issues 2-3, Proceedings of the 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research, April 2008, Pages 228-235, ISSN 0920-3796, DOI: 10.1016/j.fusengdes.2007.09.016.
[9] Ph. Moreau, et al.,Failure mode and Recovery Strategies for the Operation of the TORE SUPRA Tokamak, Proceedings of ICALEPCS 2009, http://accelconf.web.cern.ch/Accelconf/icalepcs2009/papers/wep098.pdf
[10] M. Ruiz, et al., Test-bed of a real time detection system for L/H and H/L transitions implemented with the ITMS platform, Fusion Engineering and Design, Volume 85, Issues 3–4, July 2010, Pages 360-366, doi:10.1016/j.fusengdes.2010.04.069.
[11] A. Werner, et al., A service based interface for scientific data retrieval, Fusion Engineering and Design, Volume 85, Issues 3–4, July 2010, Pages 579-582, doi:10.1016/j.fusengdes.2010.03.052.
[12] H.P. Laqua, E. Chlechowitz, M. Glaubitz, S. Marsen, T. Stange, M. Otte, D. Zhang, J. Preinhaelter, J. Urban : 28 GHz EBW Heating, Current Drive and Emission Experiments at the WEGA Stellarator, In Proc. of 16th Int. Workshop on ECE and ECRH EC-16, Sanya, China, 2010

Figure
Click here to download high resolution image



Date		Log	from [UTC]	to [UTC]	#	Name
2011-05-31	run	**20110531.7**	**09:17:56.123**	**09:18:26.635**	672	OXBGyrotronDischarge_He_ITOR=3087A
2011-05-31	run	20110531.7.1	09:17:56.123	09:17:59.542	890	Preparation
2011-05-31	run	*20110531.7.1.1*	09:17:56.123	09:17:58.108	823	PrepareDiagnostics
2011-05-31	run	*20110531.7.1.2*	09:17:58.108	09:17:59.542	45	PrepareGasinlet
2011-05-31	run	20110531.7.2	09:17:59.542	09:18:09.422	694	Start_Gyrotron_MagneticField_Gas
2011-05-31	run	*20110531.7.2.1*	09:17:59.542	09:18:01.422	705	Prepare_Gyro_Magnet
2011-05-31	run	*20110531.7.2.2*	09:18:01.422	09:18:09.422	586	Start_MagneticField
2011-05-31	aborted	20110531.7.3	09:18:09.422	09:18:10.635	533	PlasmaOperation
2011-05-31	aborted	*20110531.7.3.1*	09:18:09.422	09:18:10.635	497	PlasmaOperation 1
2011-05-31	skipped				498	PlasmaOperation 2
2011-05-31	run	20110531.7.4	09:18:10.635	09:18:26.635	486	PostProcessing
2011-05-31	run	*20110531.7.4.1*	09:18:10.635	09:18:12.635	434	Stop_Gyrotron
2011-05-31	run	*20110531.7.4.2*	09:18:12.635	09:18:18.635	71	Stop_MagneticField
2011-05-31	run	*20110531.7.4.3*	09:18:18.635	09:18:23.635	162	Stop_Diagnostics
	run	*20110531.7.4.4*	09:18:23.635	09:18:26.635	584	Reset_Triggers

Figure

Click here to download high resolution image