EUROFUSION WPS1-CP(16) 15779

H Laqua et al.

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Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Experiences with the Segment Control system at Wendelstein 7-X operation

Heike Laqua, Torsten Bluhm, Michael Grahl, Martin Grün, Christine Hennig, Andreas Holtz, Jon Krom, Georg Kühner, Marc Lewerentz, Heike Riemann, Jörg Schacht, Anett Spring, Andreas Werner, the W-X Team[a]

[a]*Max Planck-Instiutut für Plasmaphysik, Teilinstitut Greifswald, Greifswald, Germany*

Wendelstein 7-X (W7-X) is a superconducting stellarator having undergone the first experimental campaign after its construction. It is capable of steady state magnetic field operation. After an upgrade to cope with permanent heat loads of several Megawatts, W7-X will be able to run steady state discharges, too. The W7-X control system demonstrated to support all types of experiments compatible with steady state magnetic field operation, i.e. short plasma discharges and sequences of discharges with arbitrary time intervals. The contribution describes the basic concepts of the W7-X control system. Application examples are presented and discussed. Further planned extensions to the control systems are presented.

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Keywords: Wendelstein 7-X; Plasma control; data acquisition; Continuous; Steady state.

1 Introduction

Wendelstein 7-X (W7-X) is the world's largest superconducting stellarator. It has undergone its first experimental campaign called Operational Phase 1.1 (OP1.1) between December 2015 and March 2016.

A major goal of W7-X is to demonstrate the essential stellarator property, viz. continuous operation. Therefore W7-X is capable of steady state magnetic field operation from the beginning. After an upgrade to cope with permanent heat loads of several Megawatts, W7-X will be able to run steady state discharges, too. Discharges will be limited by the cooling capabilities and can last for hours.

Discharges lasting longer than some seconds lead to special requirements on the control and data acquisition (CoDaC) system [1]. Data have to be monitored, archived, and fed back into control systems during the discharge. Traditionally, plasma related data are available after a discharge. Local clocks are not synchronized but for certain points in times by a trigger. As discharges get longer the samples get de-correlated.

Although only pulses up to a length of 10s have been executed during the first operation phase the control and data acquisition system is prepared for steady state operation right from the beginning. The data acquisition systems archive data related to plasma operation as well as data from the supporting systems. The supporting systems, e. g. the vacuum system, run and generate data all around the clock.

The steady state magnetic field inhibits glow discharges. Repetitive discharges powered by Electron Cyclotron Resonance Heating (ECRH) are a means for wall conditioning for this case [4] and have to be supported by the W7-X control system.

author's email: heike.laqua@ipp.mpg.de

2 Segment Control

2.1 Basic concepts

Time is the key quantity to properly correlate data from distributed acquisition systems. The continuous operation mode requires every acquired data to be addressable by an absolute timestamp. To make these timestamps comparable between different data acquisition systems they have to be synchronized to a central timing system [7]. All data are continuously archived in small portions tagged with their timestamps. The timestamps represent the primary index to the data in the archive [7].

During a long discharge many plasma physical experiments can be run. The long-time discharge is subdivided into short phases with different characteristics. The definition of the desired characteristics for the phases of a discharge includes all the technical and scientific components involved in the course of the experiment. These individual phases of the subdivided discharge are called *segments*. An experiment program is a sequence of segments. A control scenario based on segments is the most complex and versatile experiment program including short pulses with pauses and homogenous steady-state discharges. The segmentation determines the name of the Control, Data Acquisition, and Communication (CoDaC) system: **Segment Control** system.

Segment Control has a hierarchical structure reflecting the component structure of W7-X. The CoDaC work is done by software applications called Control Station. The characteristics of the Segment Control system are defined by *Properties*[9]. *Properties* are sets of key-value pairs that define the attributes of a specific control. A *Station State* is an aggregation of *Properties*. It is used to define the overall state of a Control Station at a given point in time and holds for the active segment. The Segment Control system alters the behavior of a Control Station over time by executing a sequence of *Station States* and observing the returned state information. By grouping of Control Stations and synchronizing the state switching for all group members either the whole system (W7-X) or subsystems can be controlled.

2.2 Control Station Software

Two software applications implement Segment Control. *CoDaStation* [9] is a JAVA application running on top of a general purpose control system (Windows and Linux). It focuses on data acquisition and integration of a multitude of digitizers, e.g. analog-to-digital converters and cameras. *Fast Control Station* [10] runs on top of the real time operating system VxWorks. Its key aspect is feedback and feed forward control of actuators for plasma control.

2.3 Support of legacy diagnostics

W7-X has a lot of contributed diagnostics developed and tested at existing pulsed plasma experiments [11]. Most of the have been operating under MDSplus [12]. These "legacy" diagnostics require triggers instead of *Station State switches* for synchronization. These diagnostics are supported by a Standard trigger system based on the hardware of the central timing system [7]. It distributes seven different Standard Trigger signals. All triggers are pre-planned. The trigger requests are propagated to the hardware prior to the planned trigger time to compensate hardware and transport delays. The signals are distributed via a fiber optic. Additionally a software version of the trigger is distributed as a multicast packet over the local area network using the User Datagram Protocol (UDP).

3 Experiences during OP1.1

The Segment Control system satisfied all requirements regarding the experiment program setup: technical tests, plasma studies, wall conditioning. Even programs up to 10 minutes with up to 20 sequential discharges have been run reliably. 940 experiment programs have been executed during the experimental campaign.

3.1 Running pulsed plasma discharges

Arbitrary set point trajectories can be defined and executed as shown in Fig. 1 and Fig. 2. The measured values follow the set points as expected for feed forward control according to the delay of the actuators. For most set points the update rate is 1 kHz as for the gas flow shown in Fig. 1 and Fig. 2. Most set point trajectories are defined as a set of vertices. For ECRH set points the update rate is 10 kHz allowing the definition of an ECRH power modulation with up to 1 kHz modulation frequency. It is possible to select between different modulation types (sine, triangle) and define one or more modulation phases in one segment. As obvious from Fig. 1 the synchronization between the distributed actuator controllers, e.g. gas injection and ECRH has no relevant jitter between set points and actual values.

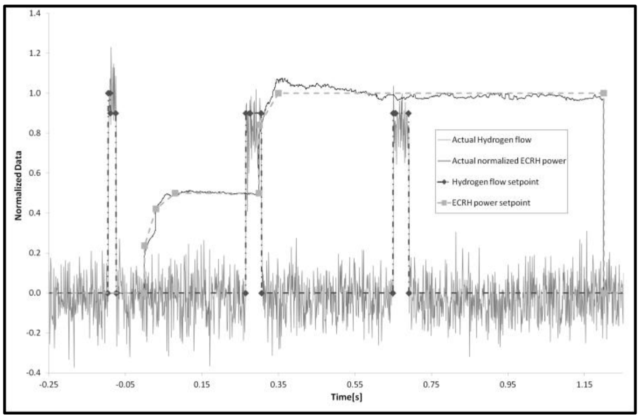

Fig. 1 Set point trajectories and corresponding measured actual values of a high performance discharge

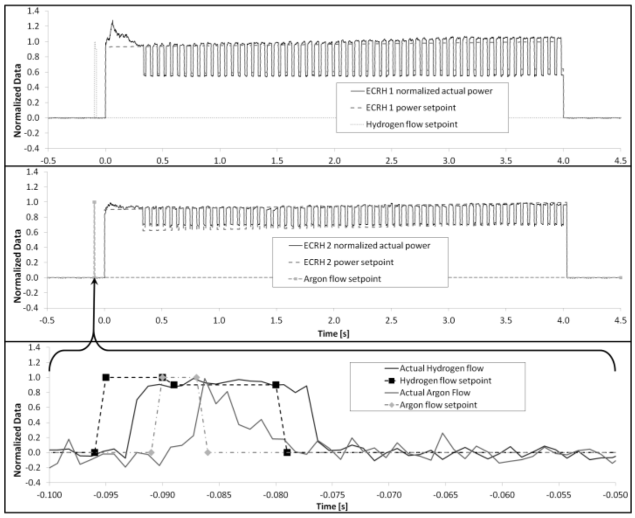

Fig. 2 Set point trajectories and corresponding measured actual values of a discharge with modulated signals. The delay of the gas flow actuators is ca. 3 ms as obvious from the zoomed in third graph.

3.2 Discharge sequences in one experiment program

Long discharges making use of the fact that the magnetic field is stationary in W7-X have been conducted. The aim of these discharges is wall conditioning. It is a repetition of short plasma pulses with pauses to pump the particles released during the discharge as shown in Fig. 3. The necessity for those kinds of experiment programs came up during OP1.1 and was not anticipated by the Segment Control developers. Nevertheless, due to its segmentation features the control system supports this type of experiment programs naturally. An experiment program is not limited to a single discharge as in the shot oriented plasma control systems. This demonstrates the flexibility of the segment control concept.

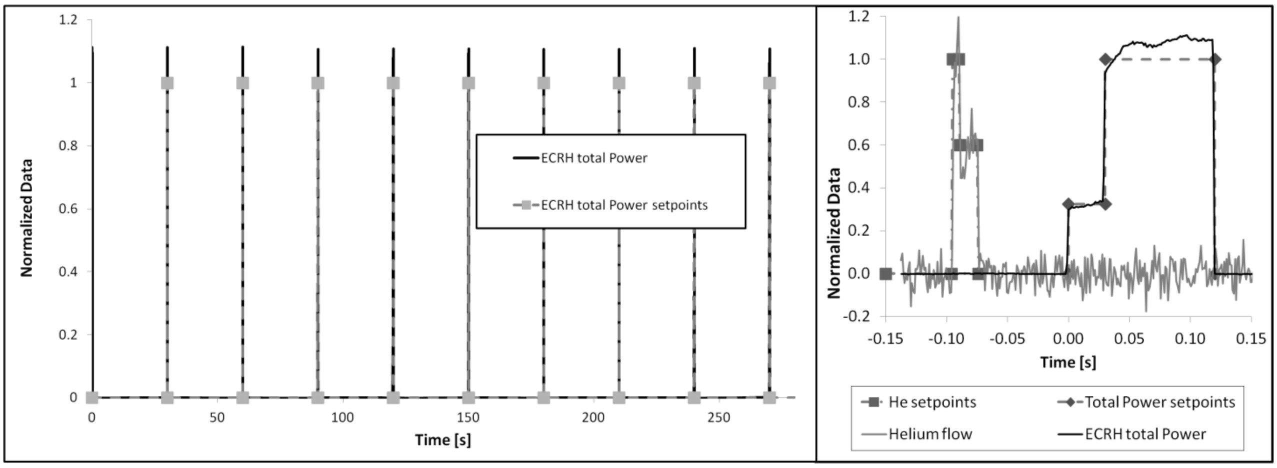

Fig. 3: Set point trajectories and corresponding measured actual values of a discharge sequence. The detail plot on the right hand side shows a single discharge which is repeated 10 times.

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3.3 Segment controlled diagnostics

In OP1.1 six diagnostics have been operated segment controlled using the *CoDaStation* software acquiring ADC data with sample rates up to 50 MHz and high resolution camera images with frame rates up to 1 kHz. Next to these diagnostics, another group of *CoDaStations* collected data 24 hours a day from the actuator and Programmable Logic Controller based systems.

Initial problems with overflow of internal data buffers resulting in wrong time stamping could be resolved during OP1.1. New features, e.g. more data channels or channels with higher resolution, were added to the Control Stations and commissioned in OP1.1.

The peak data rate of all data acquired by *CoDaStations* was 1.2 GByte/s. The acquired data per experiment day increased from ca. 170 GByte per day at the start of OP1.1 to 350 GByte per day in the last week of the campaign.

3.4 In-discharge monitoring

Control Stations provide monitoring signals which are displayed at experiment time in an oscilloscope like way [13]. They are computed from the raw ADC data as moving averaged data streams. Since they are stored in the archive as well they can later be used for overview plots. Simple computations with monitor signals from different sources could be realized ad hoc during OP1.1 by configuring a *Fast Control Station* to compute the total ECRH power from separate ECRH power generators (gyrotrons).

Control Stations distribute status information to be displayed by the user control interface [14].

Monitor and status signals have shown to be very useful to detect problems and to start as soon as possible after the problems have been solved.

3.5 Data archive

The data archive operated reliably during OP1.1. A total amount of ten TByte of data was acquired during OP1.1. Within five month after OP1.1 the data volume increased to 18 TByte because contributors had uploaded their data and analysis data had been stored.

3.6 Reliability of Standard Triggers

Fig. 4 shows the statistics over all hardware triggers generated during OP1.1 – except for one day when we experienced hardware failures while receiving the trigger signals since those data are not representative. Fig. 4 demonstrates that the time jitter is well below the value of 0.8 ms required by the legacy diagnostics.

The software trigger signals turned out to be not reliable enough to meet the requirements of the diagnostic system. A few trigger packets per day had not been received by the main MDSplus server and hence by none of the MDSplus diagnostics. Although the UDP packet was sent as unicast to the MDSplus server additionally to the multicast the reliability could not be substantially improved. The UDP protocol does not guarantee delivery of every packet. Network stacks are allowed to discard UDP packets.

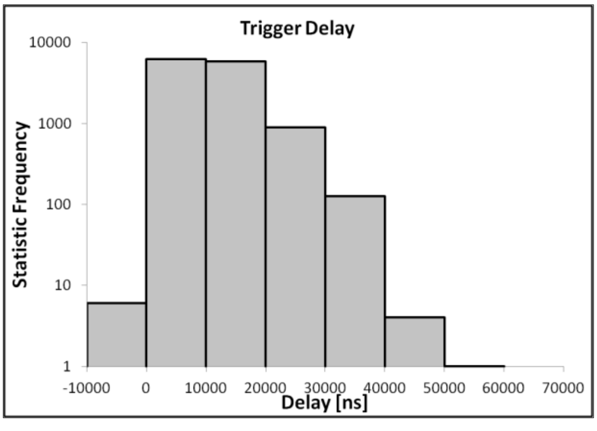

Fig. 4 Trigger delay measured as roundtrip between sender and receiver. Delay may be negative because triggers are requested in advance to compensate for delays.

4 Future work

In OP1.1 there had been only feed forward control of plasma parameters. For the next experimental phase we foresee the introduction of feedback flow control of the fast gas injection valves. Additionally, a feedback controller for the electron density will be added and tested. New actor systems, e.g. a pellet injector, will be integrated.

New multi channel, high speed data acquisition systems will be commissioned using AdvancedTCA [15] and MicroTCA [16] technology. Camera systems will be supported using the GigE [17] and Genicam [18] standards. The archive will be prepared to store an expected amount of 1 PByte during the next campaign and to cope with peak upload rates of 25 GByte/s.

The drawback of the unreliable UDP protocol for the Standard triggers will be removed by establishing a hardware connection between Segment Control and MDSplus server, since there had been no failure of the hardware variant of the Standard triggers observed.

Acknowledgments

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