Title:
Stellarator WEGA as a test-bed for the WENDELSTEIN 7-X control system concepts

Authors:
Jörg Schacht, Dieter Aßmus, Torsten Bluhm, Andreas Dinklage, Stefan Heinrich, Christine Hennig, Uwe Herbst, Ralf König, Heike Laqua, Marc Lewerentz, Ina Müller, Matthias Otte, Steffen Pingel, Jürgen Sachtleben, Anett Spring, Andreas Werner, Andreas Wölk

Affiliation:
Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Wendelsteinstrasse 1, 17491 Greifswald, Germany

Abstract:
The concepts for the control of the fusion experiment WENDELSTEIN 7- X (W7-X) consider all requirements regarding safety, steady state operation, flexibility, availability, performance and scalability.
The early demonstration of the steady-state control concepts with all interacting parties is necessary to minimize development costs since integrated tests of components are scheduled for a later stage of the W7-X project planning.
Therefore the implementation of an integrated test bed for the control concepts of W7-X is very important to minimize project risks. Main objectives of the test bed project are an integrated test of control, data acquisition, diagnostics operation and data processing in a W7-X like environment (steady-state segmented operation, real-time control, interplay of the central slow control system with components control systems, on-line data analysis tools), a demonstration of the W7-X safety concept and the education of engineers and session leaders for a W7-X like machine operation.
The contribution describes the use of the small in-house stellarator experiment WEGA as test bed for the W7-X control concepts.

Keywords:
Control system; Fusion experiment; WENDELSTEIN 7-X; Real Time Control; Segment Processing; Slow Control; Safety System

Main text:

1. Introduction

The development and installation of the system control for the fusion device is part of the research project WENDELSTEIN 7-X (W7-X) [1]. The W7-X device is based on the stellarator principle. The magnetic field for the particle confinement will be produced by 50 non planar and 20 planar superconducting coils. A very important property of the W7-X device is its capability for steady state operation. The duration of discharges is mainly limited by the cooling capacity. Pulses with a steady state operation of up to 30 minutes with full heating power or even more with lower power are realizable. The main goal of W7-X is to demonstrate the conceptual reactor capability of stellarators including the steady state operation. In order to realize the physics goal of W7-X a new concept for the control system of this experimental device was developed.
The W7-X control system consists of technical and diagnostic components, which are necessary for the different activities for commissioning, tests, preparation and processing of experiments. Every component has its own control system for operation in an autonomous control mode. The behavior of the components can be controlled by numerous parameters. The components' settings produce the plasma as required. Further settings are necessary for a proper measurement of the plasma and control parameters. To process predefined experiment programs necessary components are subordinated to the central control system. To operate widely automatically the segment control system translates the experiment programs into a sequence of commands and actions under consideration of the actual machine state. A detailed description of W7-X control system is given in [2] [4] [5] [6] [7].

The possibility of steady state operation allows three different types of experiment scenarios: short pulses with arbitrary intervals, steady state long discharges and arbitrary sequences of short phases with different characteristics in one discharge. The experiment flow can be divided into different time intervals, so called segments (see Fig. 1). A segment description completely defines the behavior of all components, which are involved in the experiment during this segment. All segment descriptions, needed to run an experiment, have to get prepared as database objects by using a special editor [3]. Thus the planned plasma discharge consists of a chain of predefined segments to be carried out in real time. The so called segment processing is the basic concept, which guarantees flexible planning and processing of experiment programs.
Due to the long design and assembly phase of the W7-X device the commissioning and the test phases of control components have to be realized as fast as possible to detect possibly without hidden risks. Tests with prototypes are a very helpful and proven method to evaluate software and hardware projects. The Work Breakdown Structure (WBS) of the W7-X control project takes care of such tests. Each W7-X control component has to be tested individually in a stand alone mode. These tests comprise the functions of the slow control system, the segment control system, and the safety system. After these tests have been finished successfully the full integration of the component subordinated under the central operational management and the central segment control system will follow as next step.

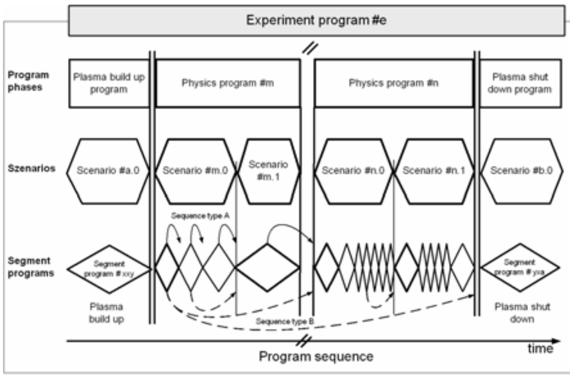

Fig. 1: Segmentation of experiment programs

Integral test scenarios should be conducted in an early stage of the W7-X project. This kind of tests allows a practical verification of control system properties in an adequate environment.
The proposal to employ the in-house fusion experiment WEGA as an advanced test-bed for the device control was also pointed out as a result of the Design Review on control, data, and software for W7-X (March 2005).

2. WEGA as demonstration prototype

WEGA is a former hybrid tokamak and stellarator experiment and was used in Grenoble (France) in the 70's and 80's for lower hybrid heating scenarios. Set up as a classical stellarator at IPP Greifswald (Germany) was made in 2000/2001. The first plasma operation started on 13th July 2001. Until now about 22.000 discharges were processed.
A comparison of the fusion devices W7-X and WEGA confirms the suitability of WEGA as a demonstration prototype for W7-X control system. All important types of technical and diagnostic components of W7-X do exist at WEGA, too. In addition prototypes of W7-X diagnostics can be installed at WEGA. The principle of plasma operation at WEGA is very similar to the one at W7-X. From a technical point of view WEGA has excellent properties for utilization as a demonstration test-bed for W7-X.
In the mid of 2006 the W7-X board decided to establish the project "Prototype W7-X control system". The main project aims are the following:

- Integrated test of the concepts for control, data acquisition and data processing in a W7-X like environment
- Test of the concepts for the W7-X safety system as a part of the prototype
- Education of personnel for design and installation of W7-X like control components and the operation of fusion experiments
- Test and evaluation of user interfaces and tools for preparation and processing of experiment programs
- Design, realization and test of diagnostic prototypes for the W7-X.

The whole prototype project is divided into two phases - phase I: Implementation of the W7-X like control system and phase II: Commissioning, test, and operation. In the first phase seven technical control (e.g. safety system, supply for the magnetic system, cooling system) and four diagnostic components (e.g. interferometer, video diagnostic) will be built up or reconstructed.
The first project phase has started in September 2006 and will be finished in December 2007. All components modified in phase I have to be tested intensively in autonomous mode. Afterwards integral tests of the segment control system can be made.
The duration of the second phase, following the first phase immediately, depends on the test results from the first phase. At best WEGA will operate with the new control system until the start of W7-X operation. This allows using the WEGA experiment as a permanent test-bed for miscellaneous tests. Main activities in phase II are intensive testing of the segment control system and extending the control components of WEGA with W7-X diagnostic prototypes, e.g. magnetics, spectroscopy, and bolometry.

3. Implementation of W7-X like control system

After the organization of the project was completed, design and implementation of the new control system at WEGA had to be decided.
Important conditions for the design of the new WEGA control system was the given project budget, the planned project duration and also the available personnel. The reconstruction should only have a small impact on the current work program of the WEGA team. To fulfill this requirement WEGA can be controlled using either the old or the new system.

3.1 Structure of the prototype control system

The prototype control system at WEGA will have the same structure as the W7-X control system. As shown in Fig. 2 the control system has a hierarchical structure, consisting of the central control system at the top and a large number of local control components at the bottom as well as the main interfaces between central and local control components, and the standardized structure of a control component too. The local control components are designed to fulfill special tasks, e.g. plasma heating, cooling or diagnostics. Table 1 summarizes all local control components of project phase I. The safety system of WEGA shall be used as a prototype for the design of the W7-X safety system. Therefore the W7-X safety concept is applied to WEGA. The safety control system is realized using the same technical components planned for W7-X.

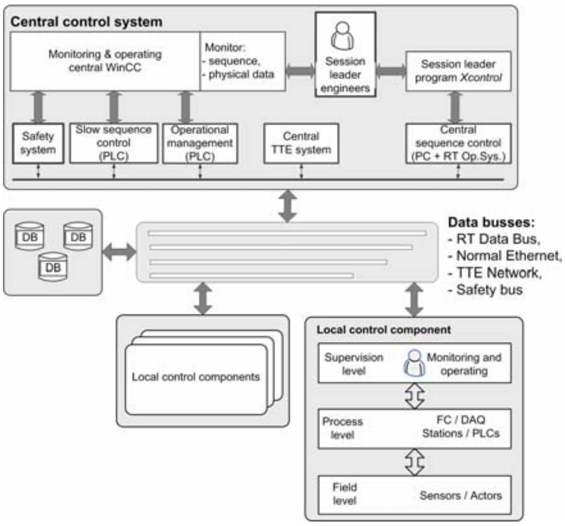

Fig. 2: Structure of the W7-X control system

Table 1: Control components for phase I

component	type	segment controllable
Central control system	technical component	yes
Safety system	technical component	no
Power supply for the magnetic system	technical component	yes
Cooling system	technical component	no
Micro wave plasma heating system	technical component	yes
Gas inlet system	technical component	no
Vacuum system	technical component	no
Machine instrumentation	diagnostic for machine operation	no
Interferometer	diagnostic for machine operation	yes
Video diagnostics	diagnostic for machine operation	no
Spectroscopy	scientific diagnostic	yes

3.2. Distribution of field level signals

The old LabView based WEGA control system must be operable during the implementation of the new control system. Therefore a signal multiplexer unit was developed. Depending on the chosen control system the process level signals are connected to the components' field level (see Fig. 3). The signal multiplexer ensures that only one control system is able to control the WEGA control components. The selection can only made manually (key-operated switch) by an authorized operator for safety reasons. Field Point modules from National Instruments are used in both control system to read sensor signals and actor states. The components' PLCs (Programmable Logic Controller) of the new control system can receive data packages from field point modules via an OPC server (OPC: Open process communication) as shown in Fig. 4. The effort for a highly time-consuming re-cabling can be minimized by use of the signal multiplexer and reuse of Field Point modules.

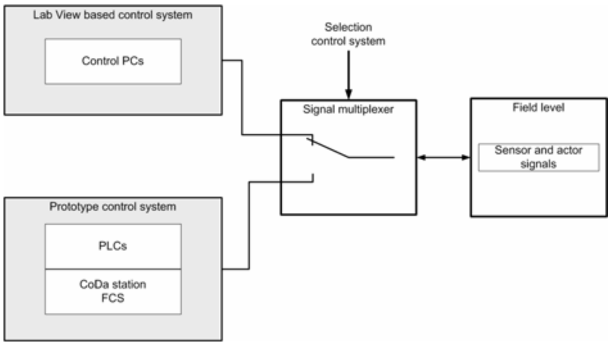

Fig. 3: Signal multiplexer unit

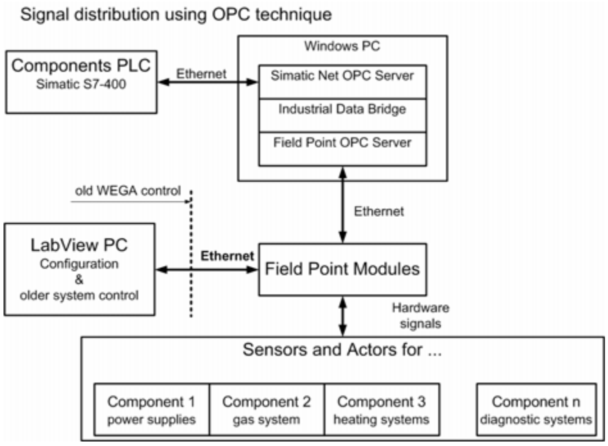

Fig. 4: Interconnection of field level signals with the components' PLCs

3.3 Component "Power supply for magnet system"

The component consists of four separate power supplies: one for the helical, one for the vertical, one for the toroidal, and one for the compensation field coils respectively. The power supplies for the helical and the toroidal field coils are thyristor convertors which can be used in Y or in delta connection. The maximum current of these supplies can be up to 7.5 kA. The devices for the vertical and compensation field coils are standard power supplies with a maximum current of 40 A for the vertical field and 1 kA for the compensation field. Fig. 5 gives an overview of control devices and interfaces of the individual supplies for the magnet system. The PLC generates set points for the output currents of the power supplies on field level, cf. Fig.2. The set points are updated at a rate of 100Hz and converted to analog signals. Actual state variables and commands are distributed between the PLC on process level and field level via OPC server. Further on the PLC is responsible for operational management and the communication with the supervision level, i.e. the human machine interface (HMI). As a standard the HMI is realized with WinCC (Window Control Center, Siemens). Also on process level the Fast Control Station (FCS) is in charge of the segment control system of the component, e.g. the FCS produces set points for the power supplies based on the segment description and sends them as data packet to the PLC.
The component control system can operate in an autonomous and a subordinated mode. If the component is subordinated under the central control experiment programs for the whole machine can be processed coordinated with other active components. For test purposes it is possible to process segment programs, which have been defined only for this component.

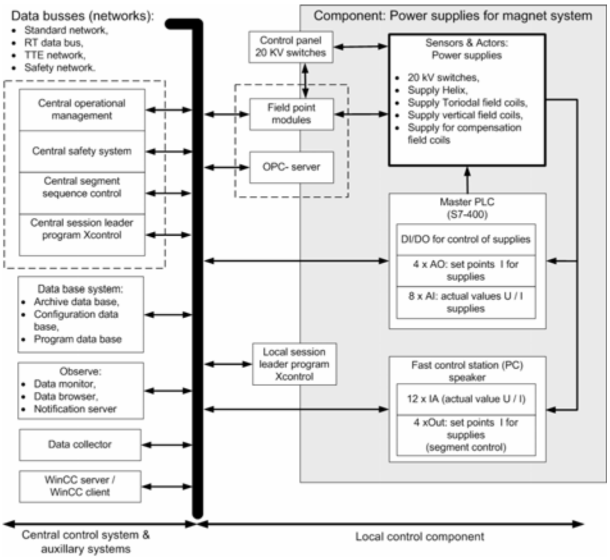

Fig. 5: Control system structure of component supply for magnet system

3.4 Component "Cooling system"

The cooling system provides cooling water for the magnetic coil system and other WEGA components. Main components are the primary water circuit with a heat exchanger device and the secondary water circuit in the experiment area of WEGA. A circulating pump with a power of 45 kW is the main actor of the secondary circuit. The power of this pump is controllable by a frequency converter. Control parameters are the outgoing pressure, the maximum of incoming pressure and the outgoing water temperature. For monitoring purposes additional temperature and mass flow sensors are installed in the secondary water circuit. These field level values are distributed via OPC server. Fig. 10 shows the control system structure of the component cooling system.

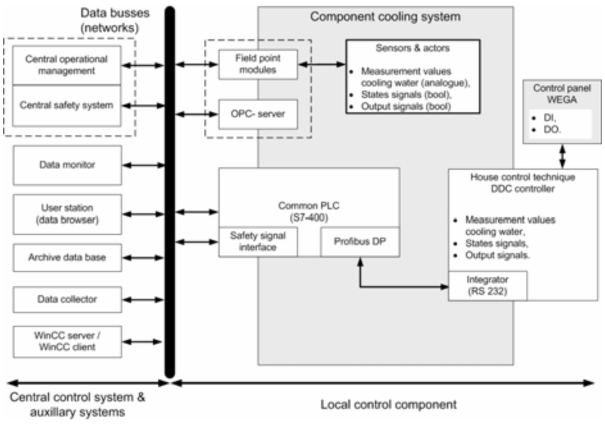

Fig. 6: Structure of the component cooling system

This component is part of the infrastructure and therefore not segment controlled. The process level is build of a PLC only. To save resources, a so called common PLC is used. In this case several control components share a common hardware. The local operational management of the cooling system is connected via Ethernet with the central operational management of WEGA. The PLC provides all communication with the supervision level.
The cooling system has a hardwired interface to the central safety system to exchange safety relevant information, e.g. emergency stop, enable signals and states.
Important data of the component are archived permanently. Hence the PLC periodically sends actual data to a data collector. The data collector writes the received PLC data packets to the archive data base.

3.5 "Machine Instrumentation"

The component is an example for a dedicated diagnostic for machine operation. To prevent coils and internals from overheating, WEGA is equipped with about 300 flow and temperature sensors. Due to non-criticality of performing sudden magnet system shutdowns in case of cooling system dysfunction, and thanks to robustness of installations, gauge handling is quite simple at present: Each individual fault will result in cutting off current supplies and heatings, and subsequently operators have full flexibility to disable several measurement and monitoring circuits in order to continue operation in reduced configuration.

Considering the needs of W7-X, WEGA instrumentation will be reengineered to incorporate two significant aspects: Accidental shutdowns have to be avoided by exploiting sensor redundancy relationships, and system safety has to be ensured by restricting operator interference to deactivation of fundamental controls only. For this purpose, expert knowledge on redundancies as well as safety analysis results will be incorporated in the control system resulting in tiered data interpretation. Balanced fault handling will increase operational availability of the system, and preprogrammed configuration scenarios will speed up and support operator interventions. Defining the tolerance and safety rules to be implemented in software, first estimations of required high time and manpower effort are made caused by extended requirements on flexibility in large scientific equipments' set-up.

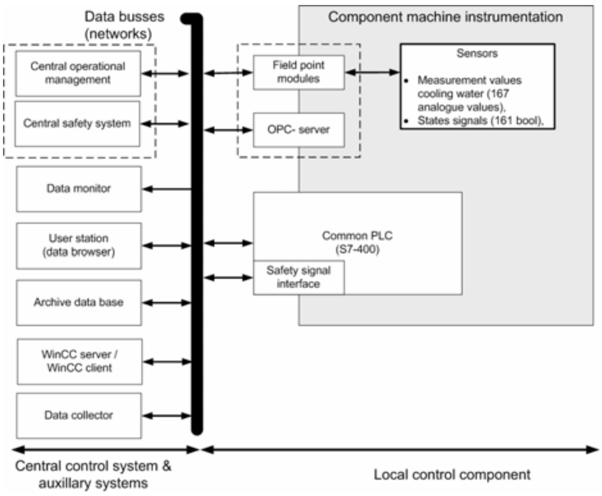

Fig. 7: Structure of the component Machine Instrumentation

4. Project status and outlook

At the moment the emphasis of the project is on the installation of the technical components. For example the components' cooling system, supply for the magnet system, the vacuum system, and the microwave heating system are in different states of assembly. The machine instrumentation (MI) is the first diagnostic component being designed.
The installation of the main infrastructure components is finished. The new WEGA control room is equipped with working places for the session leader, experiment engineers and responsible officers for the components.
The central control system with subcomponents central operational management, central segment sequence control and safety system are in their realization phase.
The first technical components will be ready for first tests of their local operational management and local segment control system in July 2007. Step by step all planned components for project phase I have to be integrated in the WEGA control system. A detailed planning of project phase II is to be performed with respect to the test results of phase I end of 2007.

5. Acknowledgement:
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