Architecture of central control system for the 10 MW ECRH – plant at W7-X

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Abstract. Electron Cyclotron Resonance Heating (ECRH) is the main heating method for the Wendelstein 7-X stellarator (W7-X) which is presently under construction at IPP Greifswald. The mission of W7-X is to demonstrate the inherent steady state capability of stellarators at reactor relevant plasma parameters. A modular 10 MW ECRH plant at 140 GHz with 1 MW CW-capability power for each module is also under construction to support the scientific objectives. The commissioning of the ECRH plant is well under way; three gyrotrons are operational. The strict modular design allows to operate each gyrotron separately and independent from all others. The ECRH plant consists of many devices such as gyrotrons and high voltage power supplies, superconductive magnets, collector sweep coils, gyrotron cooling systems with many water circuits and last but not least the quasi-optical transmission line for microwaves with remote controlled mirrors and further water cooled circuits. All these devices are essential for a CW operation. A steady state ECRH has specific requirements on the stellarator machine itself, on the microwave sources, transmission elements and in particular on the central control system. The quasi steady state operation (up to 30 min) asks for real time microwave power adjustment during the different segments of one stellarator discharge. Therefore the ECRH plant must operate with a maximum reliability and availability. A capable central control system is an important condition to achieve this goal. The central control system for the 10 MW ECRH – plant at W7-X comprises three main parts. In detail these are the voltage and current regulation of each gyrotron, the interlock system to prevent the gyrotrons from damages and the remote control system based on a hierarchy set of PLC's and computers. The architecture of this central control system is presented.

Author Keywords: Electron Cyclotron Resonance Heating; Central Control System, W7-X

1. Introduction

ECRH is the main heating system for steady-state operation of W7-X (up to 30 min) in the reactor relevant long-mean-free-path transport regime. A heating power of 10MW is required to meet the envisaged plasma parameters [1] at the nominal magnetic field of 2.5 T.

The total ECRH power is generated by 10 gyrotrons operating at 140 GHz with 1 MW output power in CW operation each [2, 3]. Two subgroups of 5 gyrotrons are arranged symmetrically to a central beam duct in the ECRH hall. Each gyrotron is fed by one main-power supply module and one body-modulator/crowbar unit.

The ECRH plant consists of many devices such as gyrotrons and high voltage power supplies, superconductive magnets, collector sweep coils, gyrotron cooling systems with several water circuits and the quasi-optical transmission line for microwaves with remote controlled mirrors and further cooling water circuits.

The quasi steady state operation (up to 30 min) asks for real time microwave power adjustment during the different segments of a steady state stellarator discharge. A flexible central control system is an important tool to achieve this goal.

The architecture of the central control system for the 10 MW ECRH–plant at W7-X is discussed in the following chapters.

2. The Central control system

2.1. Requirements

All devices of the ECRH-plant are remote controlled from one control centre with response times between 1 µs and 100 ms.

A basic design feature of the central control system is a maximum reliability and availability, the hard- and software components must be easy to maintain.

The reliable handling for all devices of the ECRH-plant demands monitoring of all relevant parameters for gyrotron operation. Furthermore the control system has to facilitate error diagnostics for each device of the ECRH-plant.

Other important tasks of the control system are the interaction between W7-X operation control system [4] and the ECRH-plant and the preparation of current gyrotron process values for permanent storage in the central data acquisition system [5].

2.2. General architecture

The central control system for the ECRH-plant is divided in 10 units for gyrotrons and units for the quasi optical wave guide, the vacuum pump system for the magnets, the safety at work with respect to high voltage, the interlock system and the central control for supervision, as seen from Fig. 1.

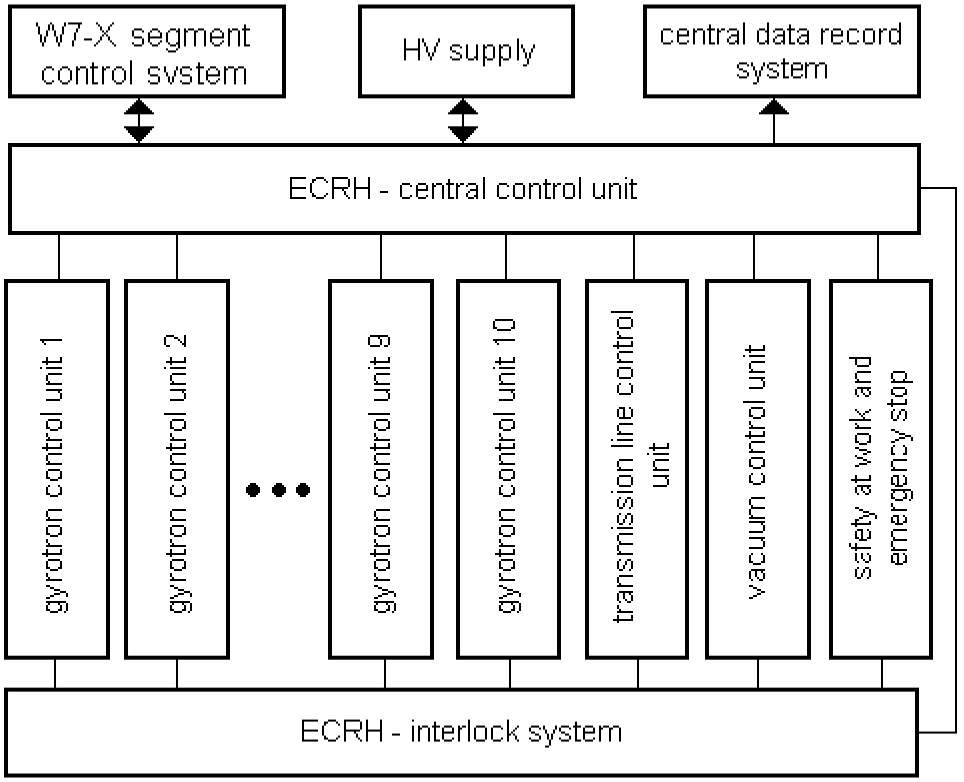

Fig. 1 Control system schema

Central control system for the ECRH-plant interacts with the following devices of W7-X:

- W7-X segment control system
- High voltage supply
- Central data acquisition system.

The W7-X segment control system operates in real time and sends set points for gyrotron power, polarisation, launch angle and modulation to the ECRH-control system during a segmented plasma discharge. By means of the segment control a discharge is split into time-slices with all hierarchically ordered components operating simultaneously and in real time according to a given scenario [6].

The high voltage supply receives voltage set points, On- / Off- and shutdown commands and sends status information's about the ten high voltage pulse power modules.

A prototype installation of the central data acquisition system [5] is currently under construction. The most essential signals are stored in a provisional data storage system until the completion of the central data acquisition system.

2.3. ECRH – central control unit

Graphic user interface, based on Siemens WinCC software, represents the kernel of the ECRH central control unit (Fig. 2). All essential values of the ECRH-plant are displayed. The graphic software works on one server with the operating system ‘Windows 2003 Server’. The operator works on one of the client PCs with connection to the WinCC server.

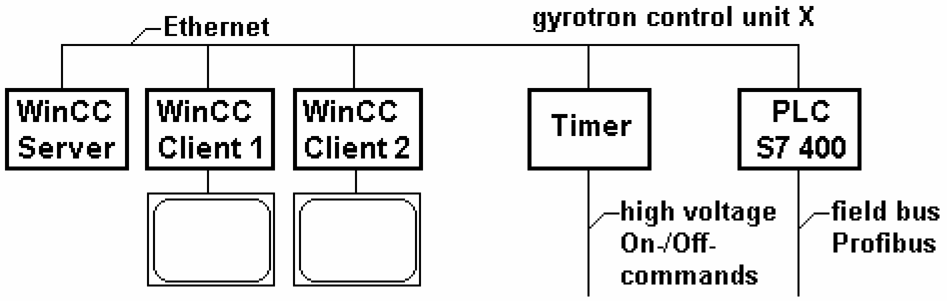

Fig 2 Central control unit with one gyrotron control unit

Four operators are necessary to prepare the ten gyrotrons for a plasma discharge at W7-X and therefore two WinCC client PCs will be added upon completion the ECRH-plant.

2.4. Types of signals at gyrotron service

Three well defined types of signals are processed in the gyrotron control unit.

- Signals with low sampling rate (50 to 100 ms)

Signals with low sampling rate are managed by programmable logic controllers (PLC).

The majority of signals at gyrotron service are signals with low sampling rate (50 to 100 ms). The character of this signal may be both digital and analogue. All On-/Off-commands to pumps, auxiliary power supplies and to locking mechanism as well as return information about the state of several devices are digital signals.

Cooling water pressures and flow rates, voltage and current set point values are analogue signals with low sampling rate.

- Analogue signals with high sampling rate (up to 1 µs)

Analogue and digital signals with a high sampling rate are generated and processed by fast electronic devices. These signals are transmitted between different devices via optical fibres, which have a higher electromagnetic compatibility (EMC).The gyrotron values such as beam current, cathode voltage, body current and body voltage contain important information about the gyrotron behaviour during the operation. The transmission of these analogue values with high sampling rate (up to 1 µs) is an essential part for successful gyrotron operation. These signals are monitored on oscilloscopes and will be stored by the central data acquisition system in the future [5].

- Digital signals with very short delay (0,5 to 1 µs)

Start, stop and interrupt of gyrotron operation require fast digital signals. Start and stop of gyrotron operation are triggered by commands with short delay (0.5 to 1 µs) to switch high voltage power supplies (main high voltage and body voltage) on and off [7, 8]. These commands are generated through the timer, as shown in Fig. 2. The fast ECRH-interlock system triggers the interrupt signal, which causes the transmission of shut down commands to the high voltage power supplies and the crowbar firing.

2.5. Gyrotron control unit

The structure of the control unit for one gyrotron module is shown in Fig. 3. The data interchange between the ten gyrotron control units and the ECRH-central control unit is realized via Ethernet.

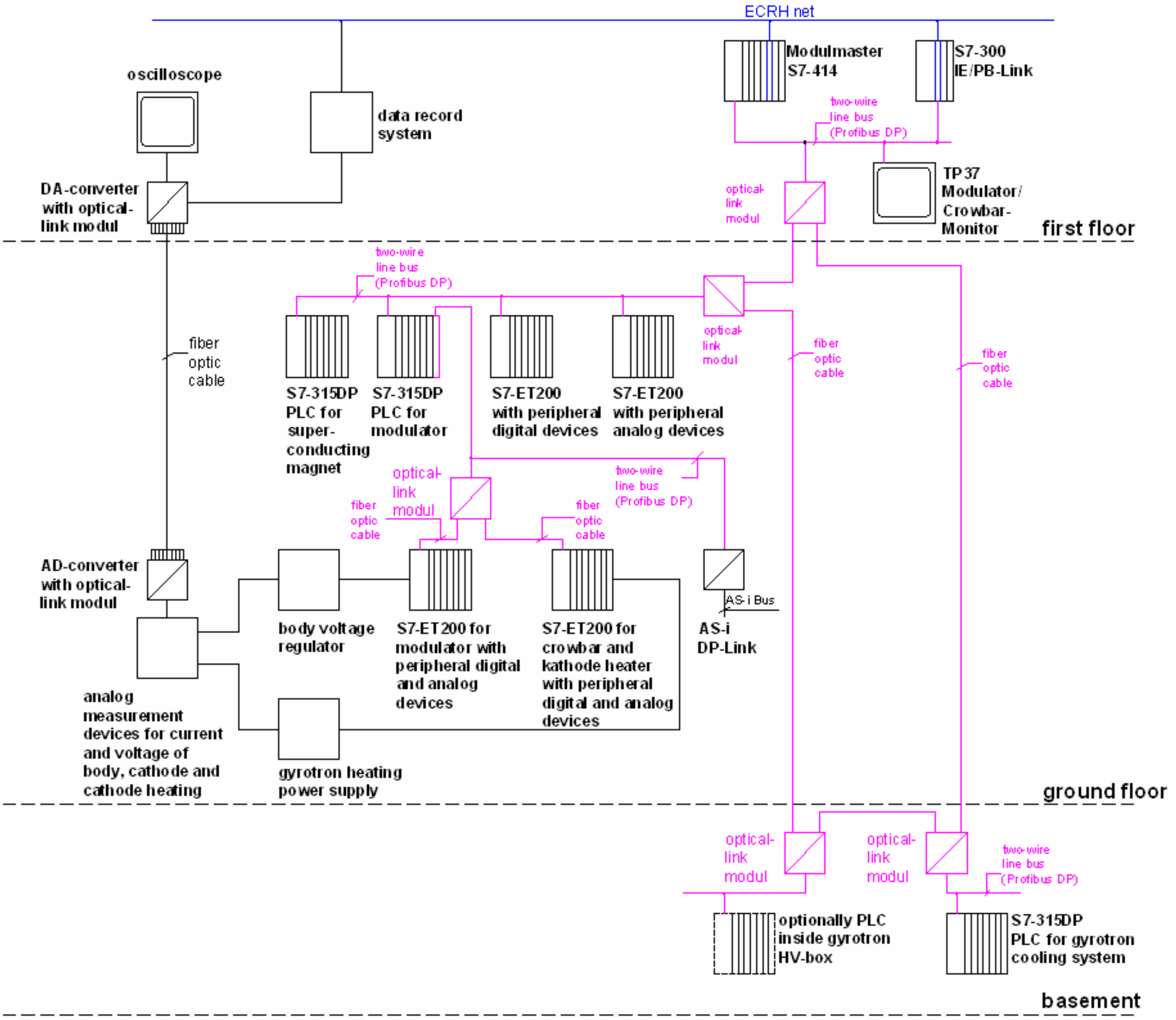

Fig. 3 Structure of one gyrotron control unit

Each gyrotron control unit is equipped with four PLCs.

- Master PLC
- HV-Modulator / Crowbar PLC
- Superconductive magnet PLC
- Gyrotron cooling system PLC

The data transmission between PLCs is based on a field bus system (Profibus) with both, hard wire and optical fibre guides. The connection across several floors is carried out as a redundant closed loop of optical waveguide (see Fig. 3). All safety relevant and machine protection commands are transmitted via field bus. The Ethernet connection does not guarantee a save and stable flux of data and therefore it is only use for the transmission of set points and monitoring of actual valves with low sample rates. All set points are checked by each process-oriented PLC.

Fast analogue monitoring signals are transmitted via optical fibres [9].

Each gyrotron control unit is equipped with a head end, which consist of one PLC Siemens S7 400 (Master PLC), receiver for fast analogue data, transmitter for fast On-/Off- commands and one touch panel for operator control and monitoring. The 'Master PLC' interacts via the field bus system (Profibus) with the other three PLCs, called as 'Slave'. Each slave PLC has the capability to transfer his part of the ECRH-plant in a save mode in case of a lost connection to the 'Master PLC'.

2.6. Transmission line control unit

The transmission line control unit (Fig. 4) is equipped with PLCs for mirror alignment, mirror cooling system and load cooling system. The data transmission between the ECRH-central control unit and mirror control PLCs is performed by Ethernet connection via optical fibre guide and by the field bus system. The cooling system PLCs are connected by the field bus system (Profibus).

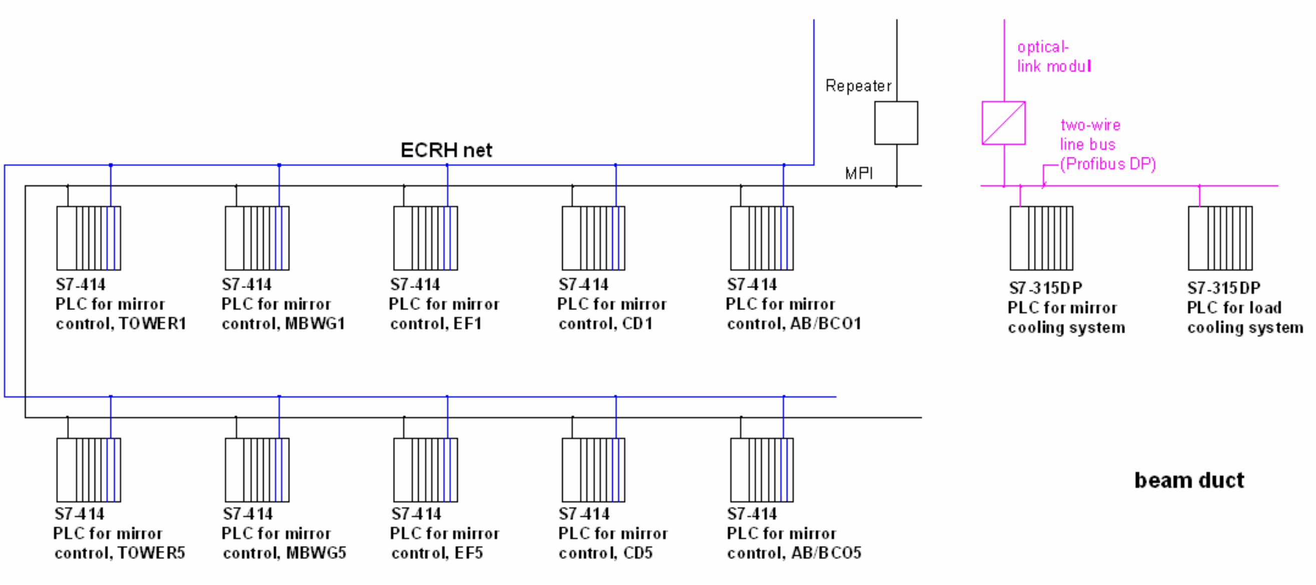

Fig. 4 Structure of transmission line control unit

Mirrors and polarisers (126 pieces upon completion the ECRH-plant) are position controlled by servo-motors around two axes except for the polarisers around one axis. A commerciality available standard control system for servo-motors is integrated in the main ECRH-control system. Each position controlled mirror and polariser is equipped with an analog angle feedback. The mirrors motion occurs in micrometer range with a very slow speed, except for the front steering mirrors. They are moveable with a motion speed of about 10 degrees/s in real time during the pulse. Especially each polariser acts in connection with his associated launcher mirror to provide the optical polarisation for any launcher position (oblique to perpendicular). The launcher mirror array covers a wide poloidal and toroidal steering range to meet the requirements for optimum current drive (typically at 15° toroidal angle), O-X-B launch [10] (at 35° toroidal angle) and off-axis heating [1].

2.7. Vacuum control unit

The vacuum control unit monitors the thermal insulation vacuum in each of the 10 superconductive magnets and controls the vacuum pump system, which consists of vacuum pumps and gate valves. Furthermore this unit monitors the liquid helium and liquid nitrogen levels of the magnets and controls the automatic liquid nitrogen refill system. The liquid helium refill is performed manually. The vacuum system is structured in two normally independent pumping stations; each operates at five magnets and consists of a turbo vacuum pump in combination with a rotary vane vacuum pump.

The quench detection is performed by the magnet power supplies, which are controlled by a PLC as a part of the gyrotron control unit.

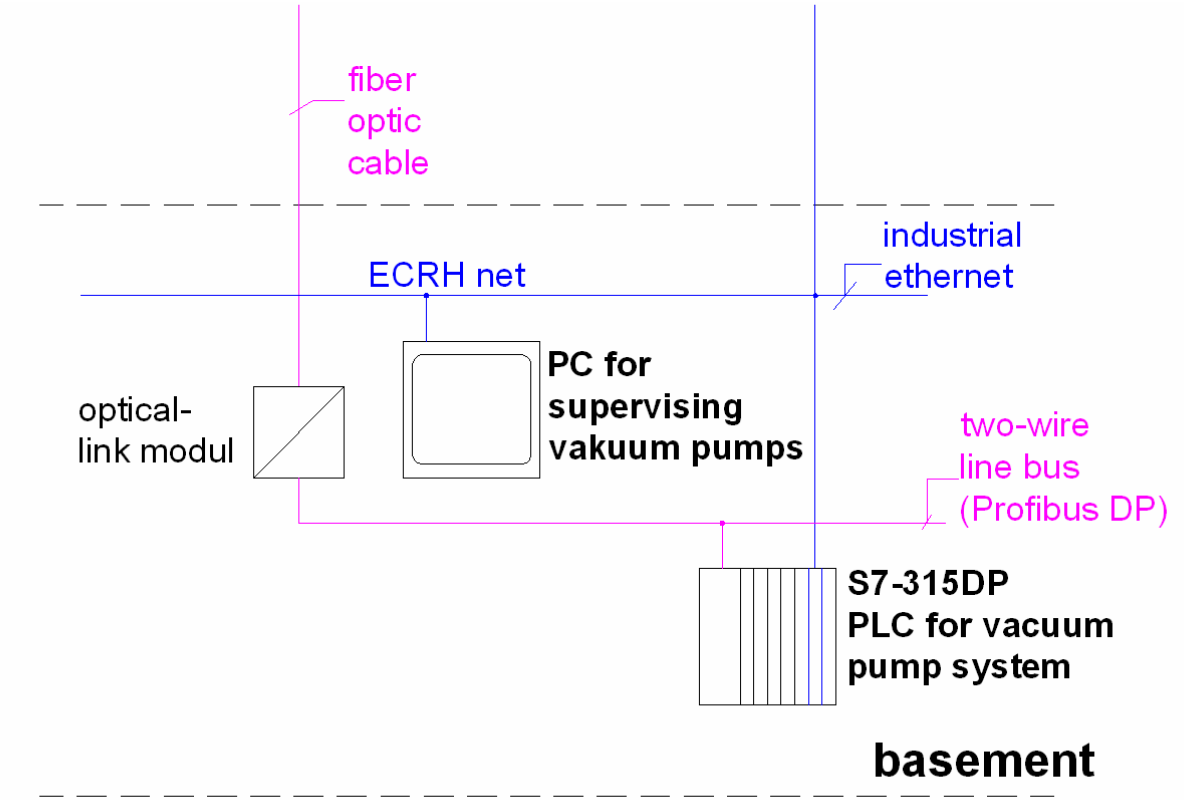

Fig. 5 Structure of vacuum control unit

The vacuum control unit has two connections to the ECRH-central control unit, field bus and Ethernet. Both of them are based on optical fibre guides. The vacuum control unit is based on one PLC Siemens S7 315, as shown in Fig. 5. The limit of signal modules for digital and analogue inputs/outputs (up to 32 in case of S7 315) is achieved at this PLC installation.

2.8. Safety at work and emergency stop

The ‘Safety at Work’ – system meets the requirements of category 4 in accordance with EN 954-1 (European Standard). The system protects persons against electric shock. It consists of ground switches in combination with door lock devices and is controlled by AS-Interface lines.

AS-Interface is a low level field bus norm for simple actuators and sensors with communication capability [11]. An AS-Interface network can be configured as bus, star or tree. A maximum of 31 slaves can be connected to a standard AS-Interface system (62 to an expanded AS-Interface system). The AS-Interface network is linked to the higher level field bus by a gateway (DP/AS-Interface Link module).

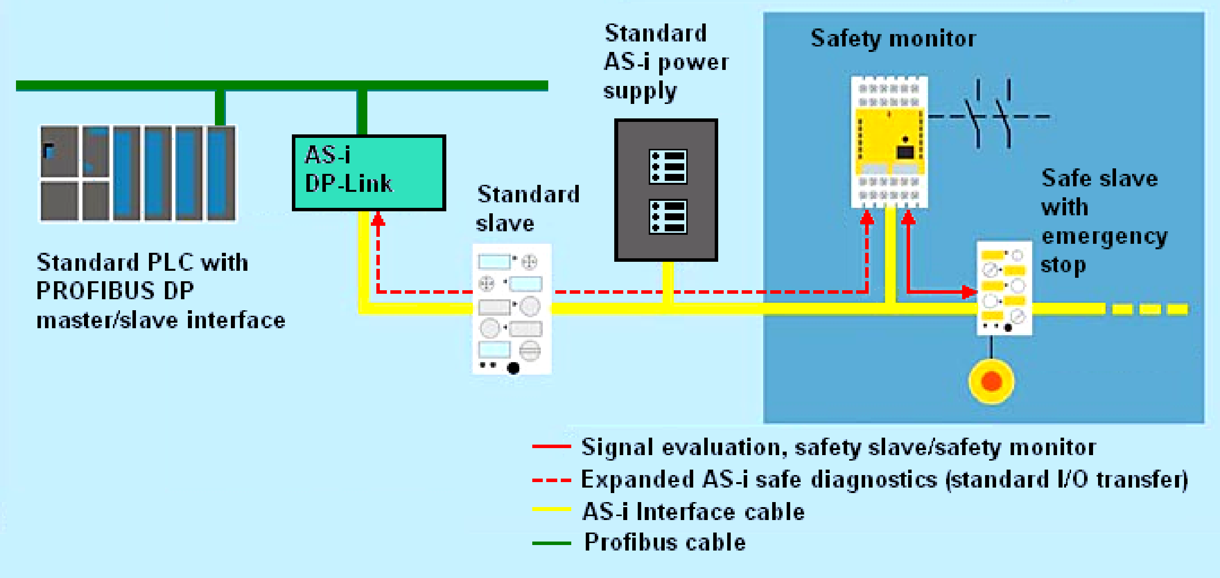

Fig. 6 structure of AS-Interface network lines with emergency stop

Within the AS-Interface field bus system safety-related components are available, which can be used in applications up to category 4 (acc. to EN 954-1). The safety monitor evaluates all of the safety inputs and ensures a safe shutdown. The safety monitor operates as an actor for controlling of contactors, magnet valves, electromagnetic locks etc. The safety slave is a sensor for detecting the states of emergency stop switches, protective door contacts or safety light grids.

Each gyrotron control unit is equipped with one AS-Interface network to perform the task of safety at work.

Three AS-Interface network lines provide exclusive emergency stop switches at the high voltage application areas of the ECRH-plant (see Fig.6). Another AS-Interface network controls the door locking mechanism and the emergency stop switches within the beam duct.

The high number of AS-Interface lines is a consequence of the strict modularity and the large dimension of the ECRH-plant.

3. Fast ECRH - interlock system

A versatile and flexible interlock system was developed to shut down a particular component quickly under certain conditions [12]. The central ECRH-interlock system has a modular design consisting of an arbitrary number of identical distributed modules, which are connected to a dedicated interlock bus. The interlock modules of the ECRH-plant for W7-X are located near each gyrotron, at the optical transmission system and near the launchers, too.

Each module monitors ten analogue signals with programmable threshold windows and triggers one or several programmable fast interlock signals, as seen from Fig. 7. The configuration of these modules is defined via software, which makes the system fast and flexible at the same time. The risk of a malfunction is minimized by redundancy and self-surveillance of the interlock bus. The fast functionality is realized by a field-programmable gate array (FPGA).

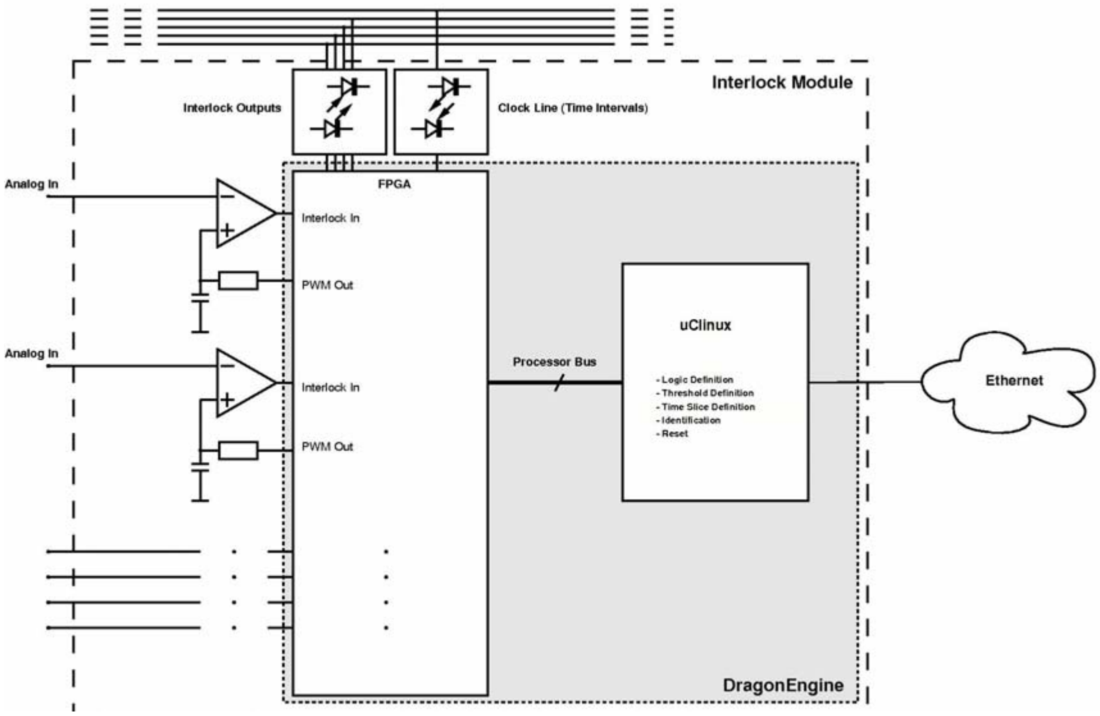

Fig. 7: Principle sketch of the fast interlock modules and bus system

The central ECRH-interlock system monitors all devices, which could enter a dangerous state. The detection of fast events such as arcs near the diamond windows, in the transmission line, launcher, and gyrotron failures is safeguarded by the interlock system. The arc detectors located at many positions, e.g. mirror surfaces, gyrotron and torus windows, loads etc. Furthermore the interlock system displays and stores the first event, because one event often triggers other sequential events. This function is essential to locate errors in the ECRH-plant. It will be impossible to restart a gyrotron pulse after a fast event within the running plasma discharge.

4. Summary and conclusions

The ECRH-plant at W7-X is a large and complex installation. The central control system enables a safe and reliable gyrotron operation from the graphic user interface. The great numbers of PLCs (54 in total upon completion the ECRH-plant) is at first a consequence of the strict modular ECRH-plant concept and second a consequence of the principle of distributed and process-oriented intelligence. The benefits of these principles exceed the handicaps of a more difficult software development. Furthermore the distributed and process-oriented intelligence decreases the complexity of sensor and actor wiring compared to a few single PLCs with a lot of periphery modules.

An excellent interaction of all devices from the ECRH-plant was achieved with adapted types of data transmission lines such as Ethernet, field bus (Profibus, AS-Interface) and fast optical fibre guides.

The central control system for the ECRH-plant at W7-X operates successful at full performance with pulse duration of about 30 minutes [1, 9].

The interlock system is capable of detecting all dangerous states with a switched off delay of 5 µs. The interlock system is daily tested during each gyrotron conditioning campaign because all dangerous states are possible when gyrotron operates in a test phase. An example is the test of the arc detectors with a flashlight.

All supporting systems for one gyrotron have been successful tested together. The parallel operation of two gyrotrons will be the next step of the ECRH-control system development.

Reliability and availability of ECRH at W7-X depends not only on high power CW-gyrotrons, but also on many other devices in the gyrotron environment. Approximately 30% of the gyrotron pulse interrupts are caused by blackouts of periphery devices, because gyrotron operates in a test phase, where all parameters are pushed to the limits. In particular measurement instruments for pressure and flow rate as well as a couple of Ethernet switches failed sometimes. The further enhancement of reliability and availability of the ECRH-plant requires the careful replacement of all instruments and network devices with insufficient reliability. Some devices have to replace with a device of the same type and some devices have to replace completed, because the used type is not EMC-save. Routine gyrotron operation proceeds subsequently with a significantly higher reliability.

The interfaces to the central data acquisition system and to the W7-X segment control system are currently under development.

CW operations of the gyrotrons at W7-X are not only a question of well done physics, but they are also dependent on a well designed control system.

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Figure legends

Fig. 1 Control system schema

Fig. 2 Central control unit with one gyrotron control unit

Fig. 3 Structure of one gyrotron control unit

Fig. 4 Structure of transmission line control unit

Fig. 5 Structure of vacuum control unit

Fig. 6 structure of AS-Interface network lines with emergency stop

Fig. 7 Principle sketch of the fast interlock modules and bus system