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HV-system for CW-gyrotrons at W7-X and the relevance for ITER

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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 under construction at IPP-Greifswald.

A 10 MW ECRH plant with CW-capability at 140 GHz is under construction to meet the scientific objectives. The microwave power is generated by 10 gyrotrons with 1 MW each, two gyrotrons are operational at IPP in Greifswald. The tubes are equipped with a single-stage depressed collector for energy recovery and operate with an output power modulation between 0.3 and 1 MW with a sinusoidal frequency of up to 10 kHz, which is achieved by modulating the depression voltage and is an interesting feature for NTM control at ITER. The general features of the ECRH-plant such as frequency, power, cw-capability, flexibility and the experimental experience are of high relevance for the ITER system.

Each gyrotron is fed by two high-voltage sources. A high-power supply for driving the electron beam and a precision low-power supply for beam acceleration. The high-power facility consists of modular solid state HV-supplies (-65 kV, 50/100 A) providing fast power control and high flexibility. The low-power high-voltage source for beam acceleration is realized by a feed back controlled high-voltage servo-amplifier driving the depression voltage. A protection system with a thyratron crowbar for fast power removal in case of gyrotron failure by arcing is installed. Both the high power and low-power high-voltage sources have the capability to supply a 2 MW ITER gyrotron without any modification. Analogue electronic devices control the fast functions of the high-voltage system for each gyrotron and a hierarchy of industrial standard PLCs and computers supervise the whole ECRH-plant.

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 equipped with its own water/oil cooling module and is fed by one main-power supply module and one body-modulator/crowbar unit. The individual modules of the main power supply are located in a separate building and are connected with the ECRH hall via triaxial HV lines having an approximate length of between 60 and 100 m. The body-modulator/crowbar units are located in the in close vicinity of each gyrotron in the ECRH hall. All devices of the ECRH plant are remotely controlled. Design of the HV plant and its relevance for ITER – ECRH is discussed in the following chapters.

2. CW gyrotron for W7-X and ITER (under development) – Basics

Currently two kinds of gyrotrons for ITER are under development. One candidate is a gyrotron with a coaxial cavity [4]. The other candidate is based on the same principle design (cylindrical cavity) as the gyrotrons for W7-X and is under construction at different laboratories [5, 6]. Both types of gyrotron generate a Gaussian output beam with a frequency of 170 GHz. The output power aims at about 2 MW in CW operation.

The basics, which are responsible for the electrical properties and requirements, are comparable to all types of gyrotrons, which are used at W7-X and used in future at ITER. The electron beam of the gyrotron is accelerated between electron gun and resonator body and decelerated between resonator and collector. A negligible fraction of the electron beam is collected by the resonator body. The microwave output power depends sensitively on the acceleration voltage. Therefore the voltage ripple of the high-power supply for the beam current has no influence on the stability of the gyrotron output power as long as means for generation of a highly stable voltage for beam acceleration are used [7].

3. Comparison of electrical requirements

The electrical requirements of the CW-gyrotrons from W7-X and ITER are comparable except for the beam currents, as seen from table 1. The ITER gyrotron requires approximately twice the beam current as compared to the W7-X gyrotron.

	CW- gyrotron at W7X [3]	CW-gyrotron at ITER (coaxial cavity gyrotron) [4]
acceleration voltage	79 – 81 kV	85 – 90 kV
cathode voltage	58 – 62 kV	< 60 kV
depression voltage	< 25 kV	< 30 kV
beam current	40 – 45 A	80 A
frequency	140 GHz	170 GHz
RF output power	1 MW	2 MW

Table 1: Basic parameters for the W7-X and the ITER gyrotron.

4. The high voltage power supply system for gyrotrons at W7-X in Greifswald

The scheme for feeding the 1 MW gyrotron for W7-X is illustrated in Fig. 1. The high voltage power supply system is divided into three basic components (main high voltage power supply (PSM), body power supply and crowbar / filament unit).

The voltage noise generated by this switch-mode operation of the main power supply is suppressed by a low-pass filter. The triaxial cables of about 60 - 100m length connect the main power station with the gyrotrons. Snubber circuits assist in handling the stored energy in the long HV cable in case of a breakdown. The thyratron is a fast switching protector, which produce a short circuit in case of an arc in the gyrotron. The snubber between thyratron and gyrotron assist the active thyratron ignition. The central ground point is the gyrotron collector. [8]

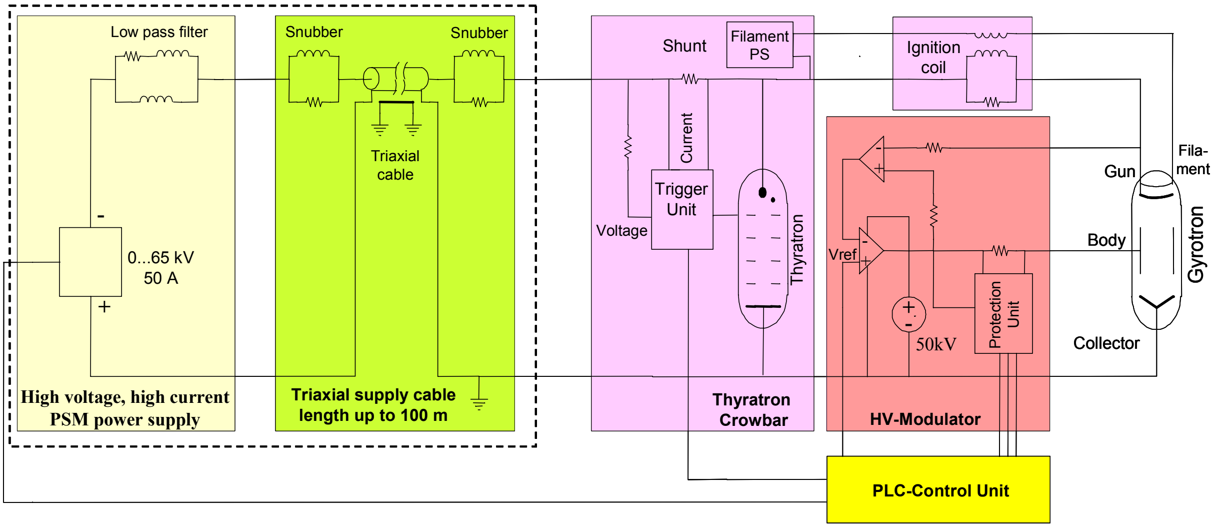

Fig. 1: Principle sketch of the HV-supply for the 1 MW CW, 140 GHz gyrotron

4.1. The main high voltage power supply for W7-X

This power supply is based on the PSM principle (Pulse Step Modulation) using semiconductor components. Programming of the output voltage is made by switching individual sources on and off at a specific time sequence. The voltage noise generated by this switch-mode operation is suppressed by a low-pass filter.

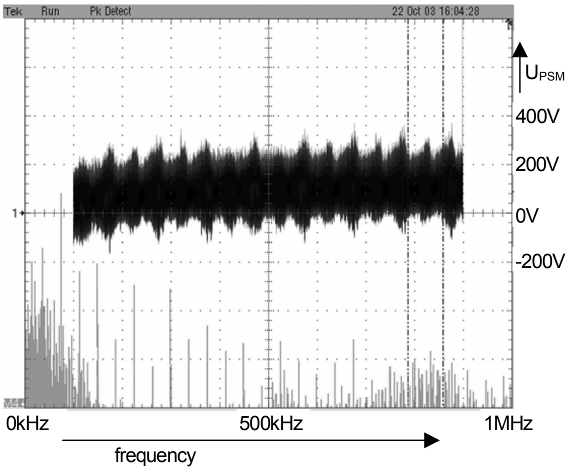

Fig. 2: PSM-voltage, AC-part and noise frequency distribution

The characteristics (frequency and amplitudes) of the voltage noise after the low pass filter of the main high voltage power supply are shown in Fig. 2. The upper track is the AC – amplitude of the voltage and the lower one shows the frequency distribution in the range up to 1 Mhz.

The power supply is designed as a multi user supply and meets also the requirements of the other heating systems NBI and ICRH (both with inverse polarity). The main power supply consists of 10 units, 8 of them are capable of 65 kV / 50 A in continuous operation. Each unit generates the voltage with 84 IGBT modules, which are connected in series. Two units are designed for use with ICRH with half the voltage and twice the current (32.5 kV, 100A). Series connection of both supplies is possible for use with two W7-X-gyrotrons. This arrangement allows supplying one ITER gyrotron without any modification. Four units with 65 kV / 50 A have successfully been tested and are operating routinely. The ICRH units are presently under test. [9]

4.2. Body power supply

Both types of gyrotrons (W7-X and ITER) require a second high voltage power supply to achieve an acceleration voltage in the range of 80 to 90 kV. The body power supply has positive polarization and controls the beam acceleration voltage and the RF output power in a range of 30% to 100% of nominal value.

The W7-X low-power HV-supply for the accelerating voltage of the gyrotron electron beam is realized by a HV servo-amplifier in vacuum-tube technology as schematically shown in Fig. 2. This amplifier is fed by a 50 kV, 400mA power supply in switch-mode technology. The output of the amplifier is connected between a tube collector at ground potential and the resonator body which is typically at +25 kV potential with respect to ground. The control of the accelerating voltage between cathode and body is made by sensing this voltage difference for the feed-back loop of the servo-amplifier. The cathode voltage and the body voltage are measured with two separate high voltage dividers with respect to ground, as shown in Fig. 2. The influence of the voltage noise of the main high-power supply on the acceleration voltage is suppressed by feed-back control of the amplifier. Measurement of the actual acceleration voltage is in this set up very difficult. The resonator body collects only a very low fraction of the beam electrons so that the output load of the final stage of the HV servo-amplifier realized in tube technology is mainly capacitive.

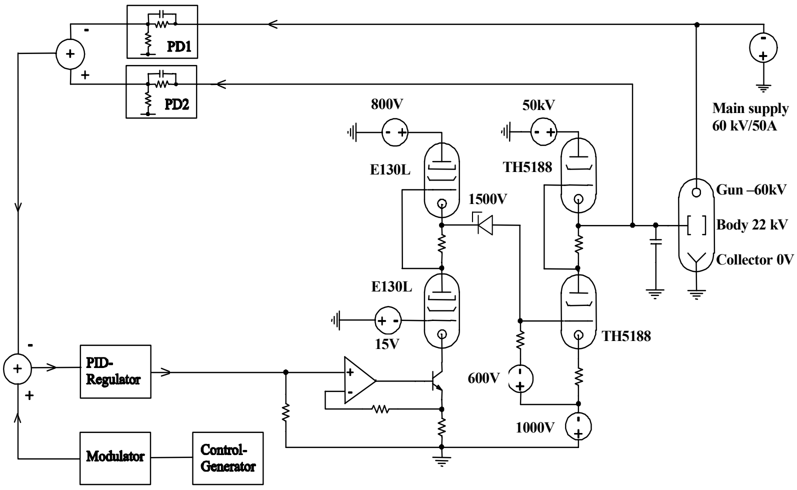

Fig. 3: Circuit of the tube HV power-amplifier.

Fig. 4: Body power supply and crowbar / filament heating unit

This amplifier is designed to drive a capacitive load of 1 nF with a slew-rate of 600 V/μs in the output voltage range from 0 to + 40 kV in continuous operation. This feature allows full modulation of the gyrotron output power by voltage modulation with 15 kV pp at a frequency of up to 10 kHz. The high voltage vacuum tubes are mounted in oil filled cases with active oil cooling. The different modules of the supply are mounted on an air insulated floating deck device to ease maintenance, as shown in Fig. 3.

The capacity part of the load has significant effect on the losses of the high voltage vacuum tubes. Most of the capacity part of the load depends on the length and the quality of the high voltage shielded cable, which connects the body power supply and the gyrotron (typically 60 pF per meter). The influence of the gyrotron capacities is less important, i. e. the distance between body power supply and gyrotron should be as short as possible (10 m for W7-X, maximum 15 m).

4.3. Crowbar / filament heating unit

The low-pass filter of the main power supply as well as the long triaxial cable (up to 100m length) connecting the main power plant with the gyrotron hall provide an energy storage, which should be taken into consideration in case of voltage breakdown by arcing in the gyrotron. The specified maximum of released energy in an arc (<10 J) requires an additional tube protection circuit. This circuit is designed as a fast crowbar by means of a thyratron installed next to the gyrotron. A snubber is installed between thyratron and gyrotron to ensure sufficient voltage at the thyratron terminals for safe trigger of the crowbar in case of voltage breakdown at the gyrotron due to arcing. Trigger events are overshoots of beam current and / or cathode voltage.

The filament heating power supply is mounted inside the air insulated floating deck crowbar device. (Fig 3) This arrangement allows a hard wired connection between the heater power supply and the cathode and a reliable heating power control. Two types of heater power supplies are necessary, DC heating supply for gyrotrons from Thales Electron Devices (TED) and AC heating for gyrotrons from Communications & Power Industries (CPI). Both supplies are completely remote controllable. This feature allows the regulation of heating power during long pulse operations in a feed-back loop.

Simulation of the whole circuit including the PSM-supply by PSpice was used for optimization of the decoupling elements in the tube protection circuit.

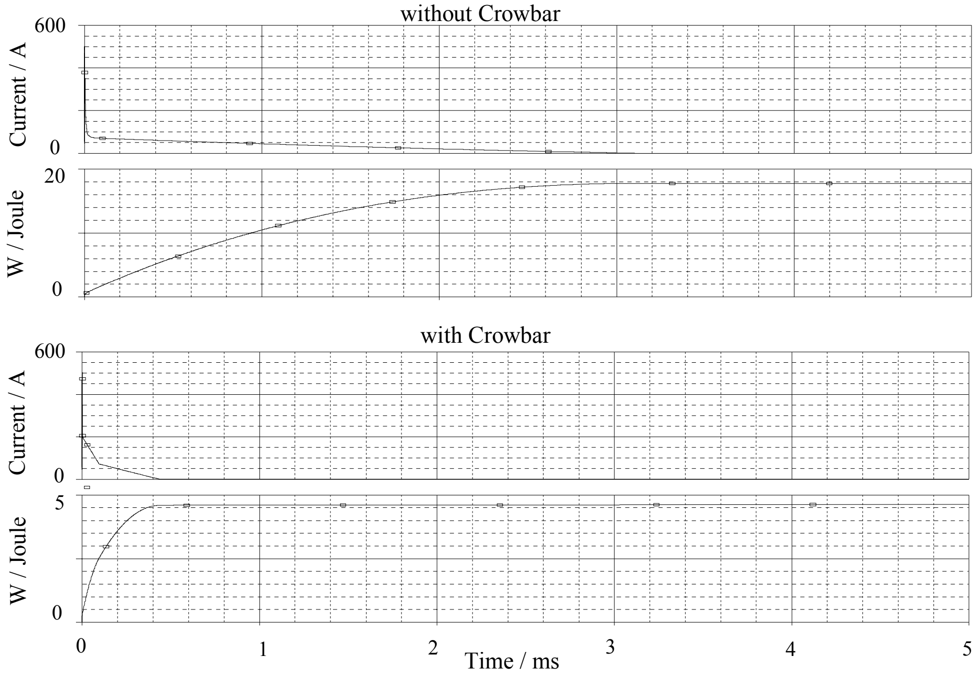

Fig. 5: Gyrotron current and released energy after HV breakdown by arcing w/o (upper traces) and with crowbar (lower traces).

An example of such a simulation is shown in Fig. 3 where the current and the cumulative dissipated energy into an internal gyrotron flashover with a voltage drop of 170 V are traced as functions of time. The upper traces show current and dissipated energy in a circuit without crowbar, where only an over current protection by fast switch-off of the main power supply is considered. The released energy overrides the specified maximum energy of 15 J due to the dissipation of the electrical and magnetic stored energy. An additional fast crowbar switch limits the energy to a safe value below 5 J as shown in the lower traces. [8] The PSM – high voltage supply needs 5 μs shut down time. The simulation results for different arc voltages are listed in table 2.

assumed arc voltage [V]	released energy w/o crowbar [J]	released energy with crowbar [J]
100	11,0	12,1
120	12,3	6,6
170	17,9	4,8
370	20,8	6,3
1000	26,1	8,0

Table 2: Released energy after HV breakdown by arcing depending on arc voltage.

The actual gyrotron inside arc voltage in case of a flashover vary in the range form 100 V up to 1000 V. The released energy doesn't override the specified maximum energy with a crowbar, as well the simulations show.

5. Fast analogue monitoring and interlock signals

The internal feed back control loop of the body power supply is designed with conventional analogue integrated circuits, which is fast, reliable and easy to maintain.

Because electromagnetic compatibility (EMC) is critical in high voltage environments where each device has a different potential, all signals are transmitted via optical fibres. In particular, fast monitoring signals such as beam current, cathode voltage, body current and body voltage are transmitted optically. That applies to the fast interlock signals, such as HV on/off and shut down, too. These fast interlock signals are monitored in a common interlock unit inside the body power supply. The interlock unit generates a collective interlock signal, which is transmitted via fibre optic cable to the central ECRH interlock system and triggers the shutdown process within < 2μs.

6. Central ECRH interlock system

It is a common requirement in large fusion experiments to shut down a component quickly under certain conditions. Therefore a versatile and flexible interlock system was developed [10]. 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. 4. 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 hardware (FPGA).

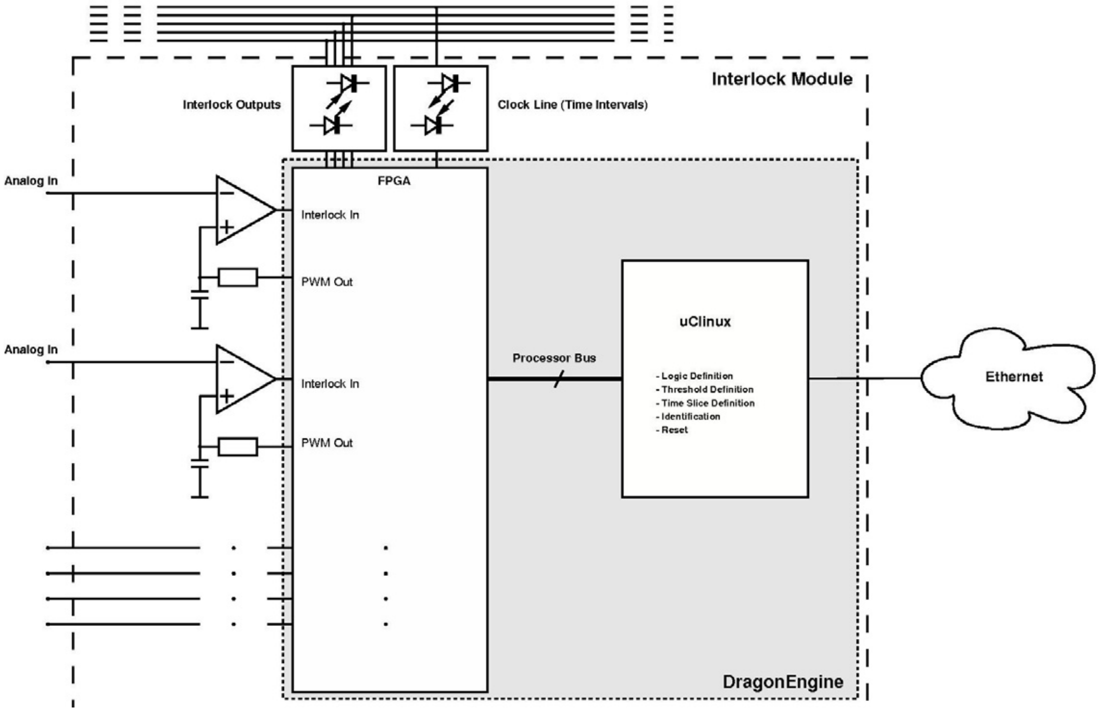

Fig. 6: Principle sketch of the fast interlock modules and bus system

The central ECRH interlock system monitors all devices, which are could achieve 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. 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.

7. Central PLC system for the ECRH plant

The ECRH plant consists of a large number of supporting devices such as superconductive magnet, collector sweep coil, gyrotron cooling system with many water circuits and last but not least the quasi-optical transmission line for microwaves with remote controlled mirrors and further water cooling circuits. Reliable handling of all devices is achieved by a remote control system, which includes all subsystems of the whole ECRH plant. A hierarchy of industrial standard PLCs (SIEMENS S7 system) and computers control the ECR heating plant. The data transmission between PLCs is shown in Fig. 5 and is based on a field bus system (profibus) with both, hard wire and optical fibre guides.

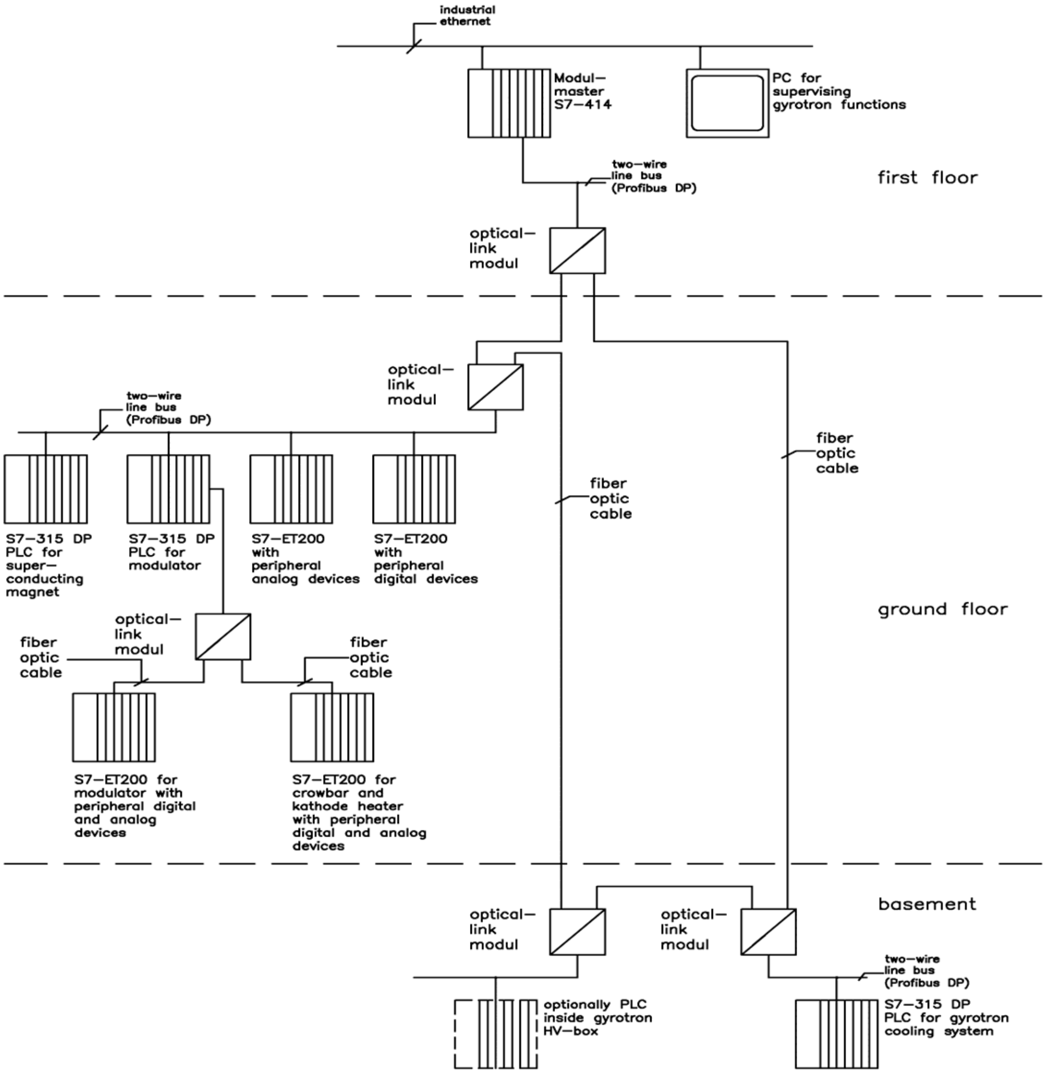

Fig. 7: Arrangement of PLCs for one gyrotron

8. Experiences during CW – operation of the CPI gyrotron

The CPI gyrotron was successfully tested at IPP-Greifswald at about 900 kW RF power (cathode voltage -61 kV, body voltage +21 kV, beam current 44 A) for 30 minutes pulse duration, which is the target value for W7-X.

The interplay of two types of power supply technologies, semiconductor based in the main supply and vacuum-tube based in the body supply, produced a very stable RF output power during the long pulse operation. The gyrotron relevant noise, which is generated by the main power supply (typical 500 V peak peak) is compensated by the fast feed back control loop and a high amplification of the body power supply. The suppression of the voltage noise of the main high-power supply is verifiable at the RF-output power of the gyrotron. The HV servo-amplifier in vacuum-tube technology does not generate additional noise of practical relevance. It would be much more complicated to compensate the PSM noise, with a body power supply based on the PSM principle, too.

9. Summary and conclusions

All power supplies and supporting devices have demonstrated safe and reliable continuous operation with the first 1 MW class gyrotron for W7-X. Some minor improvements are presently under development, particularly the measurement device of the real part of the body current.

The interlock system has detected all dangerous states and has switched the high voltage supplies off by shut down pulses. Typical delay time, until the gyrotron is on zero potential, is five microseconds. An excellent interaction of all devices controlling the ECRH plant was achieved with the installed hierarchy set of PLCs and computers.

The development results and the experiences from the ECRH plant for W7-X have a high relevance for ITER; in particular, the plant is qualified to operate an ITER-gyrotron in CW mode without modification.

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