Topic D

First experiences with the new W7-X like control system at the WEGA stellarator

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The new quality of the superconducting fusion device Wendelstein 7-X (W7-X) is its capability of steady state operation. Additionally the fusion device W7-X is a very complex technical system. The modular and strongly hierarchical control system has been designed to cope with these two requirements unique for fusion devices.

To minimize the risks before commissioning the control and data acquisition system at W7-X it will be thoroughly tested in a prototype installation at the WEGA stellarator. WEGA is a classical stellarator which allows steady state plasma pulses at a magnetic field of 0.5T. Despite its lesser complexity WEGA has the same main components, e.g. magnetic coil systems, ECRH, and diagnostics as W7-X and is therefore considered to be a suitable test-bed for the control system.

The installation of the new W7-X like control and data acquisition system has been finished in March this year. Individual components of the control system have already been commissioned during the installation phase. In April final commissioning and testing of the complete system took place. First discharges fully controlled by the prototype control system have been realized.

The contribution will focus on first discharges controlled by the new system. Furthermore it presents first experiences that will incorporate into the further development of the control system and the tools for planning, preparation, and realization of plasma discharges.

Keywords:
Wendelstein 7-X, WEGA, control, commissioning, prototype

Introduction

Wendelstein 7-X (W7-X) is a very complex fusion device with the capability of steady state operation. A modular and strongly hierarchical control system has been developed to cope with this [1]. The core element of the control system is the segment control, which allows operating experiments in real time. A discharge is divided into so-called project segments. Each project segment completely describes the operations of all components (one group segment for each component) of the fusion device during the concerning period. An experiment program consists of a chain of project segments. The segmentation is determined by the Central Segment Sequence Control Component (named Central in Figure 1). It has to switch its group segment every time one of the other components has to switch its group segment. A detailed description of the segment control concepts is given in [1]. Figure 1 shows a simplified survey of the structure of experiment programs.

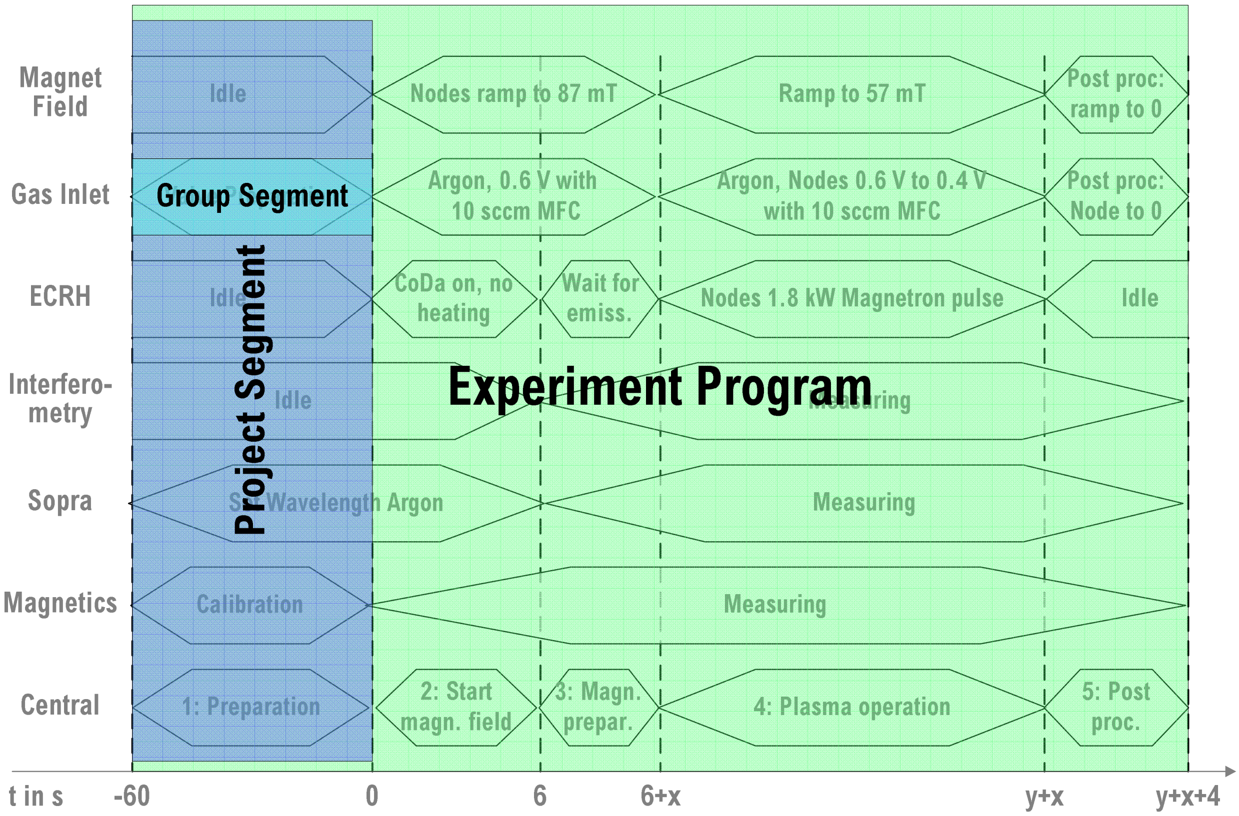

Figure 1 Definition of experiment program and segments

To minimize the risks before commissioning of the control and data acquisition system at W7-X it will be thoroughly tested in a prototype installation at the WEGA stellarator. WEGA is a classical stellarator which allows steady state plasma pulses at a magnetic field of 0.5T. Despite its lesser complexity WEGA has the same main components, e.g. magnetic coil systems, ECRH, and diagnostics as W7-X and is therefore considered to be a suitable test-bed for W7-X CoDaC (control, data acquisition and processing, and communication).

This paper describes the first experiments controlled by the W7-X like control system. It shows characteristic curves for the key control parameters of the major components. Taking additionally dependencies and constraints between and within components into account a segmented discharge for each experiment is presented as result.

Overview

In the first phase of the Wendelstein 7-X CoDaC prototype project the major WEGA components were adapted to the W7-X control and data acquisition standards.
These are gas inlet, magnet supplies, microwave heating and interferometry. Furthermore Magnetics and Sopra Echelle UHRS were included. Both are prototypes of W7-X diagnostics. Table 1 shows important control parameters and aspects for the segment control of all W7-X prototype components. An in-depth description of this phase is given in [2, 3].

Component	Important control parameters	Important aspects for segment control
Gas inlet	• Valve to open and close gas inlet • Gas type (usually Argon) • Gas flow	• Complex component with large amount of control parameters • Complex interaction with operational management
Magnet supplies (for helical, toroidal, vertical, magnetic fields)	• Coil currents	• Complex component with large amount of control parameters • Complex interaction with operational management
Microwave heating (e.g. ECRH: 6 kW Magnetron (M2), 20 kW Magnetron (M1))	• Power	• Complex component with large amount of control parameters • Complex interaction with operational management
Interferometry	• Plasma density	• Online determination of plasma density • High data volume
Magnetic pick-up coils / spectrometer		• W7-X diagnostic prototypes • Testing of data acquisition and analysis (high data volume)

Table 1 Important control parameters and aspects for segment control

Standard discharges

After commissioning the W7-X CoDaC group started with very well known discharges. They are usually used at WEGA to validate whether the device is working as expected. Experiment programs for discharges using one or all available Magnetrons have been prepared. Furthermore the restricted amount of start-up prototype components had to be taken into account for the selection of experiment objectives.
The intention of the discharge with only one Magnetron was to ignite a first plasma with the W7-X like control and data acquisition system. Later it should be reused to test the control system after modifications. Figure 1Figure 2 show the characteristic setpoint trajectories and the necessary switching operations during the discharge. The discharge can roughly be divided into the phases: preparation, Start of magnetic field, plasma operation, and post processing. This pattern is common to all discharges.

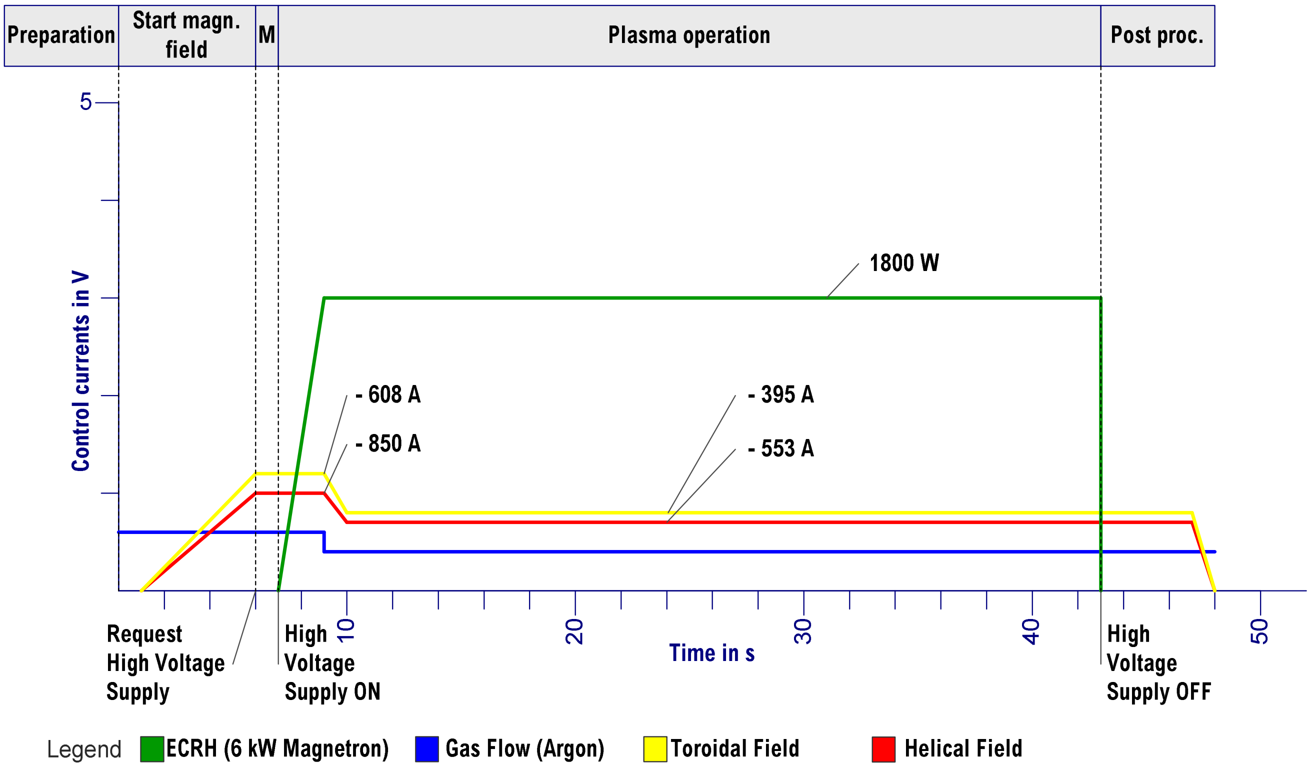

Figure 2 Discharge with 6 kW Magnetron

Because the segment control integrates arbitrary waveform generators, it is possible to generate almost any setpoint trajectory in one segment. A new segment is required when a request is made and the control system has to wait for an answer. Changing the monitoring rules ("software" interlocks) require a new segment too. The segmentation with as few segments as possible of the above described discharge is shown in Figure 3.

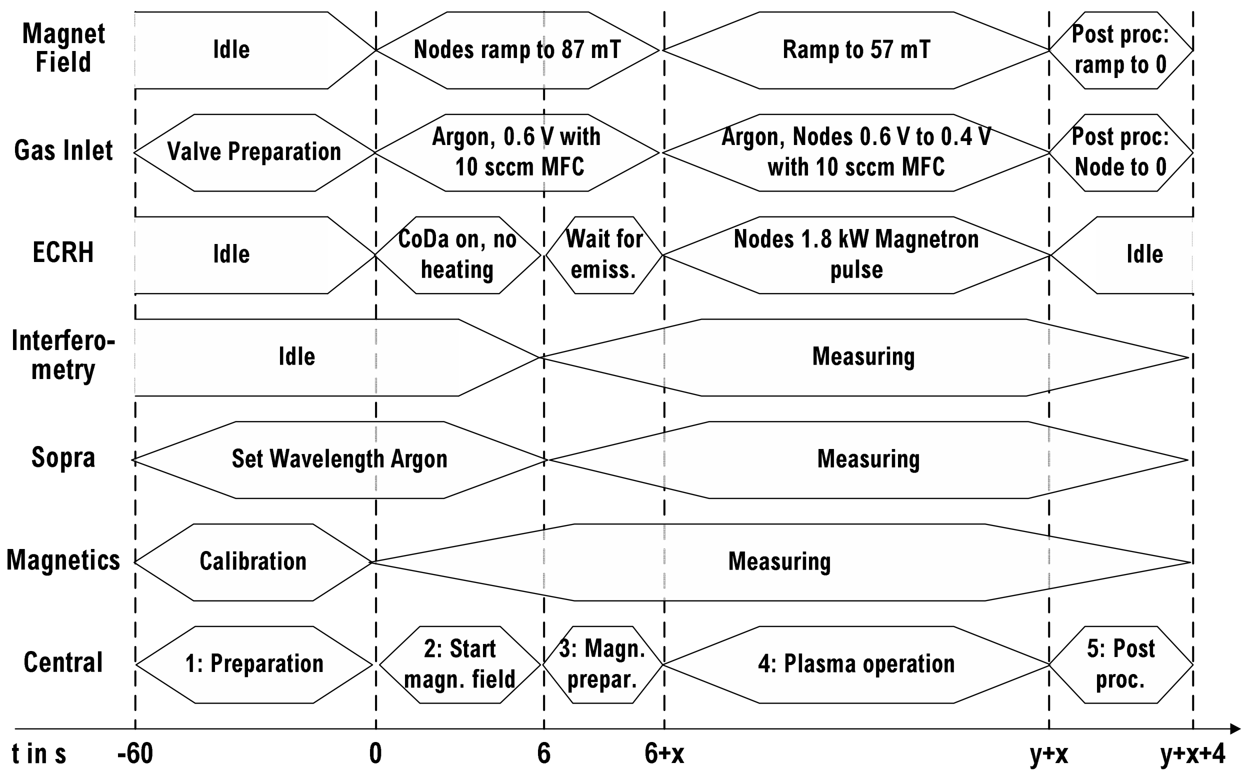

Figure 3 Segmentation of discharge with one Magnetron

In the 1st segment (1: preparation) the diagnostic systems (magnetic pick up coils and spectrometer) are prepared for measurement; the valve of the gas inlet is opened. Then the magnetic field is ramped up and the torus is filled with gas (2: start magnetic field). Next (3: Magnetron preparation) Magnetron emission is requested. As soon as Magnetron emission is available the segment control will switch to the next (4th) segment.. If the request is not successful within a given time the segment control system will switch to the 5th segment. During the 4th segment the plasma ignites and burns, physics measurements take place (4: plasma operation). In order to achieve a burning plasma, the Magnetron power is ramped up, the magnetic field is lowered, and the gas flow is reduced.. Usually the plasma operation segment runs a predefined time (here: 35 seconds). In case of a failure of the microwave heating or of an unsuccessful plasma ignition the segment will be aborted. In the last segment (5: post processing) coil currents of the magnetic fields are ramped to 0. The Magnetron is shut down and the valve of the gas inlet is closed. At the end of the segment all measuring activities are stopped. By switching to the idle segment the discharge ends.

There are 2 dependencies in this discharge that are reflected in the variable end times of the segments 3 and 4. It takes an unknown amount of time x to request Magnetron emission and get the reply that it has been switched on. Therefore segment 3 waits several seconds for the availability of high voltage supply. The segment control will switch to segment 5 if it is not available and a timeout is reached.

The feasibility of segment 4 depends on the flawless operation of gas inlet, magnetic fields, ECRH and interferometry. If one of these components discovers a problem that is critical for plasma operation the segment control will switch to the next feasible segment (segment 5 in this case) to shut down the discharge. Thus the end time y of segment 4 is unknown in advance.

Other dependencies are of a simpler nature, e.g. the calibration of the magnetic pick up coils must have been finished before it is ready to measure during the rest of the experiment. The time for the calibration is well known.

Another realised discharge combines the use of the both Magnetrons. Figure 4 shows the typical trajectories of the discharge.

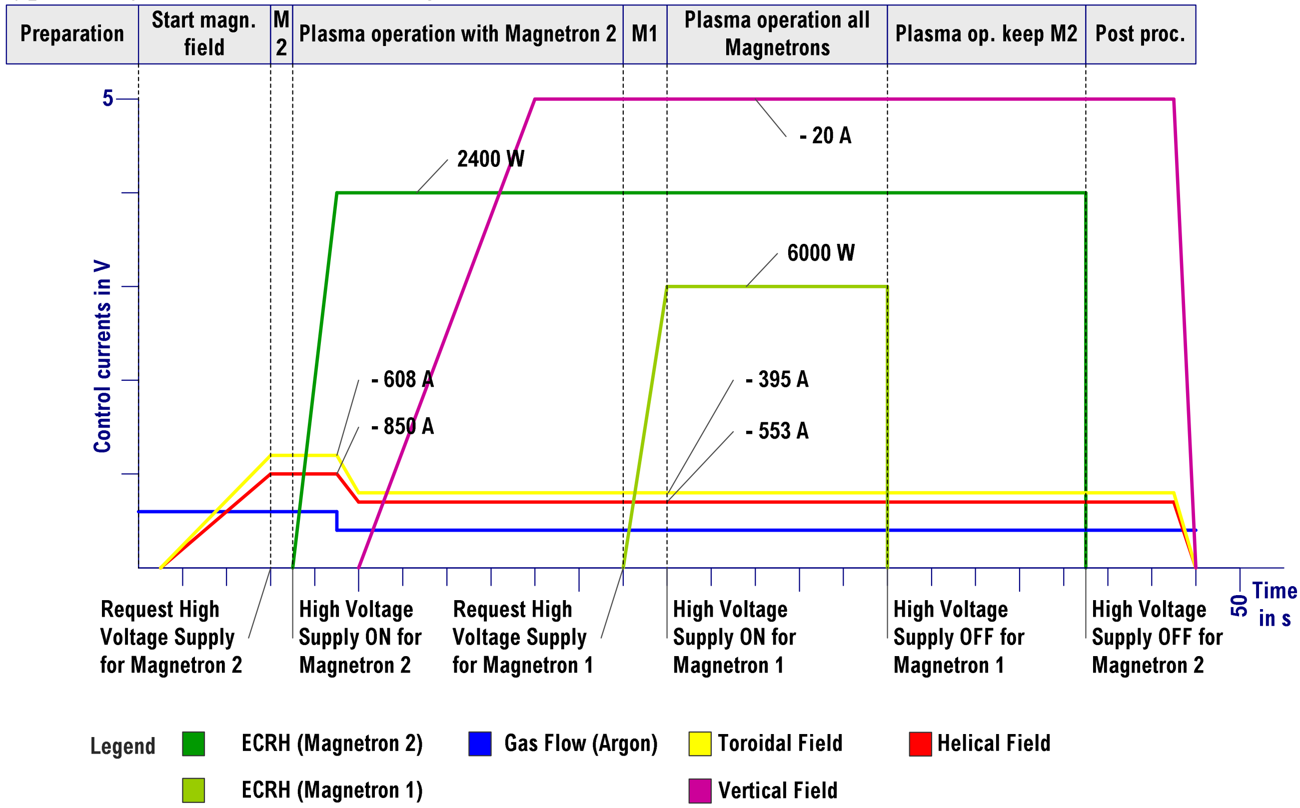

Figure 4 Discharge with two Magnetrons

At first glance one can see that each Magnetron needs to request emission conditions separately and has to wait until ready to emit into the torus. To handle these dependencies a more complex segmentation is needed. Furthermore a vertical field is introduced. But due to the use of node waveforms to describe its setpoint trajectories this has no impact on the segmentation. The description of the discharge by segments is shown in Figure 5.

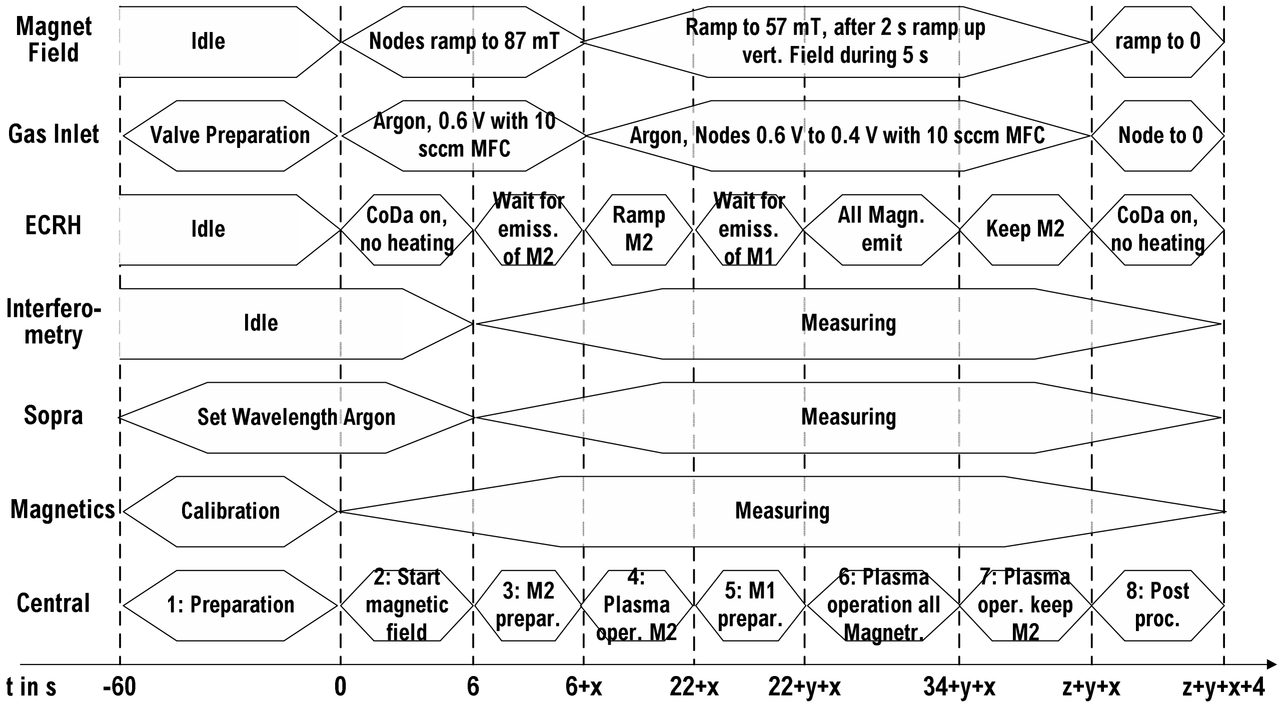

Figure 5 Segmentation of discharge with two Magnetrons

Again we have dependencies reflected in the end time of some of the segments. Whereas x and y mark the availability of high voltage supply for Magnetron 2 (x) and the Magnetron 1 (y), z marks the unknown end of the plasma operation in case of the occurrence of a problem.

Long-term discharges

A major aspect of the W7-X segment control system is its capability to handle steady state and long-term operation. The first step on the way of the evaluation of the control and data acquisition system was the adaptation of the first discharge to a plasma operation of 30 respectively 60 minutes. Therefore only the segment (4^{th} segment in standard discharge with one Magnetron), responsible for plasma operation, had to be exchanged with segments of the desired durations. Here the modular and strongly hierarchical concept of reusing identical control objects for identical tasks pays off. The preparation of the experiment program for these discharges took only a couple of minutes as only the objects that determine the duration of the plasma operation segment had to be exchanged. The edited segments are simply saved as copies of the original segment and included in the long-term experiment programs.

The longest discharge ever run at the WEGA stellarator device using the old control system lasted 30 minutes. With the W7-X like control system this was easily reached. Thus the precondition for running multiple experiments in one long-term discharge was fulfilled.

Multiple experiments in one discharge

To have several experiments in a single discharge will be the focus of quite a number of tests at the W7-X CoDaC prototype in the next time. In a steady state and long-term operating device this will be the standard operation mode as there is no need to shut down the plasma between experiments. On the other hand a failure of a component during a long discharge cannot be ruled out. The segment control systems allows for developing plasma recovery strategies. First attempts in this direction have been made, but they are limited to segment control issues at the moment. The complexity of such experiment programs is way greater than of those described above. Hence this paper can only give an outline of one example.

The scope of the following example is to test the behaviour of the segment control system on simulated failures in one component. The experiment program will consist of 4 scenarios. A scenario is a chain of segments, which usually perform a specific task within the experiment. Some of these segments are marked as entry segments. If a segment is interrupted the segment control finds the next feasible entry segment. All segments between the interrupted and the next feasible entry segment will be skipped. The (simplified) scenarios in the test are: (1) plasma start up with both Magnetrons, (2) heating only with the Magnetron 2, (3) heating only with the Magnetron 1, and (4) post processing.
There are 2 possible test cases: (A) Magnetron 1 fails and (B) Magnetron 2 fails after the plasma start up (scenario 1).

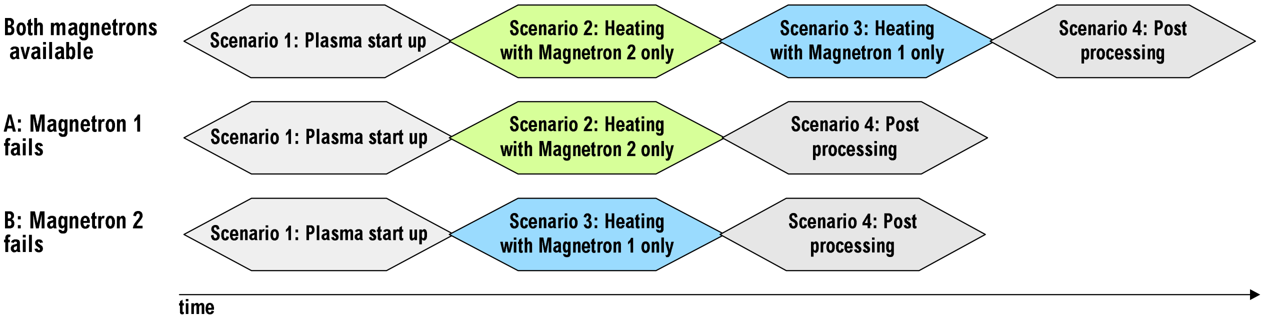

Figure 6 Possible discharges if one of the Magnetrons fails

In Figure 2Figure 6 the sequence of scenarios of the resulting discharges are shown. To add even more complexity to this, 2 further scenarios were added. In case the plasma density is too small prior to scenario 2 or 3 re-ignition scenarios were added for both.

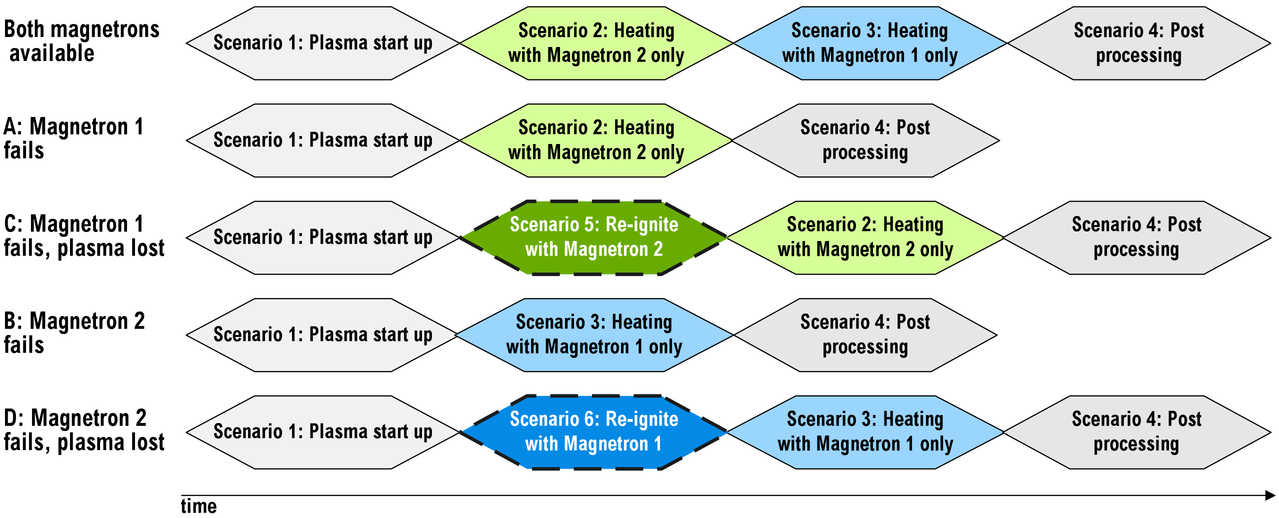

Figure 7 Possible discharges if the plasma is lost in addition

In Figure 7 one can see the sequence of scenarios of the resulting discharges if a re-ignition of the plasma is needed. These simple examples demonstrate that the complexity of a discharge of a steady state and long-term operating fusion device is growing rapidly the more dependencies and constraints are taken into account in experiment programs.

Conclusion and outlook

After a few months of operation of WEGA with the W7-X like control and data acquisition system one has to denote that no major problems occurred and all parts of the system worked as expected. The W7-X CoDaC group is now has the opportunity to evaluate all parts of the system on a W7-X like device. Except for missing complexity and amount of components all aspects of the control system can undergo an in-depth review. Refinements with regard to a later productive use can be made.

This paper showed the development from a first ignition of the plasma towards complex discharges which consider complex dependencies and constraints. At the moment experiment planning is a challenging and time-consuming task. By abstracting technical and temporal aspects of segments to a higher level this could be simplified. First steps towards this direction are described in [4].

It is planned to include further diagnostics in the W7-X like control and data acquisition system at WEGA to be more attractive to physicists. The collaboration of physicists and members of the W7-X CoDaC group in future experiments is the major goal for the second phase of the project. First realistic experiment programs are expected here. Thus W7-X CoDaC aims at a refinement and evaluation of concepts and tools.

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