Commissioning and first operating phases of the W7-X quench detection system

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Abstract. The quench detection system of the fusion experiment Wendelstein 7-X monitors the superconducting magnet system consisting of 50 non-planar and 20 planar coils, 14 current leads and bus bars. The commissioning phase contained the wiring check of the electrical contact between the 486 quench detection units and the superconducting magnet system, the verification of an unbroken and overlapping monitoring, the balance adjustment of the quench detection unit voltage measuring bridge and the parameterisation of the detection criteria: detection level and integration time. During the operation phases there were two unexpected fast discharges initiated through the trim-coils and a fast decay of the bootstrap current. As a result the interplay of the detection level and integration time was re-evaluated. The quench detection system worked stable over the first both operating phases of W7-X, performed from 2015 to 2018. There were no failures of the quench detection units or other parts of the quench detection system.

1. Introduction
The superconducting magnet system of W7-X is constructed of 50 non-planar, separated in 5 groups, and 20 planar coils, separated in 2 groups, 14 current leads and several hundred meters of bus bars [1]. It is monitored by the quench detection system [2] with 486 quench detection units [3]. The quench detection unit was developed in collaboration between the “Institute for Data Processing and Electronics” of the Karlsruhe Institute of Technology (KIT) and the “Max Planck Institute for Plasma Physics, Greifswald”. One quench detection unit (figure 1) monitors two adjacent coil double layers (DL) with a voltage measuring bridge (figure 2) or the current leads or bus bars with a simple voltage measurement. It is important to ensure an uninterrupted

![Figure 1. Quench Detection Unit.](image1)

![Figure 2. QD-Unit measuring bridge.](image2)
monitoring over the whole group of current leads, bus bars and coils. In the special case of joints, which provide the electrical and hydraulic connection between bus bars and coils and between different bus bar sections and between two double layers, an overlapping monitoring has to be guaranteed (figure 5).

![Figure 3. Original monitoring (planar coil).](image1)

![Figure 4. Backup monitoring (planar coil).](image2)

The quench detection system doesn’t use a one-to-one redundancy. It uses a reduced monitoring for the redundant system, called backup system (figure 3 and 4, exemplary for a planar coil with 3 double layers). The reduced redundancy of the backup system is only used for the coils, the current leads and all bus bar sections are monitored with a one-to-one redundancy.

For each quench detection unit monitoring two adjacent double layers, the voltage measuring bridge (figure 2) can be balanced (potentiometers P1&P2) to compensate for asymmetrical manufacturing variations between the inductance of both double layers. It is adjusted to compensate the difference of inductive voltages to $\Delta U \approx 0$ and measures the resistive voltage difference $\Delta U \neq 0$ between both double layers in case of a quench event. For the simple voltage measurement of current leads and bus bars the first path $U_1$ of the measuring bridge is used only: $\Delta U = U_1 - 0 = U_1$. The quench detection unit can monitor and measure with bipolar voltage levels. In summary, the quench event is detected with a voltage level $U_L$ and an integration time $t_i$ of an RC element (figure 2).

2. Commissioning

2.1. Wiring check

The aim of wiring check was to verify the correct connection paths between all quench detection units and the whole superconducting magnet system. Not only the electrical connections had to be checked, also the correct contact points of all wires (QD-wire) on the magnet system had to be verified. In particular, it was important to prove the correct contact points to ensure uninterrupted protection and overlapping surveillance (figure 5).

![Figure 5. Schematic diagram of a planar coil circuit. Current leads and bus bars are monitored with a voltage measurement and two adjacent double layers of a coil are monitored through the measuring bridge.](image3)

The wiring checks have been evaluated by voltage measurements (figure 6). These voltages were measured at room temperature with a current of 30 A for non-planar and 40 A for planar coil...
groups over each double layer of every planar coil (17mΩ/DL), every non-planar coil (22mΩ/DL), every joint (0.14 mΩ), each current lead (0.5-1 mΩ) and every bus bar section (0.15 mΩ/m). Prior to the measurements, the exact resistance values of each bus bar section were calculated considering the real installed length.

The defined current direction and the sign and value of measured voltages between every possible measurement points indicated the right or wrong connection of the wires. Overall, more than thousand individual measurements were executed and evaluated.

![Figure 6. Schematic diagram of the wire check. The voltage was measured between each connecting point of the wires. The correct connecting of each wire was determined with the sign and voltage drop.](image)

The wiring check was performed successfully. There were no interrupted monitoring parts and all wires were connected at the correct positions. Furthermore, there were no ascertainable anomalies during the balancing of the quench detection units (section 2.2), which is another indication for an error-free wiring.

### 2.2. Balancing of the quench detection units

The single double layers of a coil differ slightly from one another in their manufacturing characteristics. In particular, the inductance of double layers varies around a value of 3 mH/DL for planar and 8 mH/DL for non-planar coils. Without a balancing of the voltage measuring bridge unnecessary misinterpreted quench events could be the consequence. During the up-and-down ramping of the current with a maximum change of ±40 A/s, the configured detection levels can be possibly exceeded.

The quench detection units were adjusted under the following conditions: a superconducting magnet system, an active current ramp of ±30 A/s and a permitted maximal current of 500 A. The magnet system can carry a current of 500 A even for the case of loss of the superconductivity, for example in case of a quench event. Therefore, the quench detection system was deactivated during the phase of balancing. The balancing of the quench detection units is a critical process because there is no way to detect a quench event when the quench detection system is deactivated. In short sequences of a cycle of positive and negative ramps from 0 to 500 A and back to 0 A, the quench detection units were automatically balanced to reach a different voltage level $\Delta U \approx 0$ through changing both potentiometers P1 and P2.

The ability of the quench detection units to compensate asymmetries enables the possibility to compare not only one double layer with another but also to compare two or three double layers with one double layer. The balance settings can be set between an equipartition of both measuring branches of the bridge, $R_{P1} \approx R_{P2}$, and to gate one of the branches ($R_{P1} = 0$ or $R_{P2} = 0$). Thus, wide asymmetries can be compensated. This fact is used for the redundant monitoring through the backup system.
2.3. Parameterisation of detection criteria

The final commissioning step was to parametrise the detection criteria. A quench event is detected by a defined difference voltage level $\Delta U \geq U_L$ and an integration time $t_i \geq 0$ s of an RC element (figure 2). If both criteria are fulfilled, a quench event is detected and the power supply of the superconducting magnet system is triggered to shutdown whereby a fast discharge of the superconducting magnetic system is initiated.

The start detection criteria were defined based on existing experiences of various tests of the superconductor [4]. All coils and current leads were tested under cryogenic conditions and nominal current after fabrication. Table 1 shows the various start detection criteria for the different superconducting components to be monitored.

| Component       | System     | $U_L$    | $t_i$  |
|-----------------|------------|----------|--------|
| non-planar coil | original   | ± 150 mV | 50 ms  |
|                 | backup     | ± 300 mV | 50 ms  |
| planar coil     | original   | ± 100 mV | 50 ms  |
|                 | backup     | ± 200 mV | 50 ms  |
| bus bar         | original   | ± 20 mV  | 50 ms  |
|                 | backup     | ± 40 mV  | 50 ms  |
| current lead    | original   | ± 20 mV  | 50 ms  |
|                 | backup     | ± 30 mV  | 50 ms  |

Table 1. Start detection criteria.

The detection levels $U_L$ were verified with balanced quench detection units. During a positive or negative current ramp a voltage is induced ($u(t) = L \frac{di(t)}{dt}$) in the coils. Bus bars and current leads are not concerned. Even non-completely balanced quench detection units for monitoring two adjacent coil double layers measure a partial difference of the induced voltage $\Delta U_p$ (figure 7). The detection levels $U_L$ have to fulfil two requirements: high enough to compensate the partial difference voltages and small enough to detect a quench event at an early stage. The time delay through the integration time $t_i$ between the occurrence of a quench event and the initiation of the shutdown of the power supply of the superconducting magnet system must not exceed the specified limit of 250 ms [5]. This corresponds to the maximum allowed detection time for a quench in order to avoid damage to the superconductor due to overheating. The parameterisation was completed with accepting all start criteria for all monitored superconducting components.

3. The first both operating phases

The first operation phase lasted from December 2015 to March 2016 and second operation phase from August 2017 to October 2018 with a break of 6 months.

The quench detection system worked stable over the entire first both operating phases of Wendelstein 7-X. There were no failures in any of the quench detection units or other parts of the quench detection system but there were two unexpected triggers of the quench detection system, once through a safety shutdown of the trim-coils [6] and secondly due to a plasma collapse during the increase of bootstrap current to 19 kA. In both cases two fast discharges of the superconducting magnetic system were initiated. In the case of the plasma collapse, the quench was triggered by a misconfigured quench detection unit. As a result all configurations of the quench detection units were checked and the interplay of detection level $U_L$ und integration time $t_i$ was re-evaluated. Actually no changes of the parameters were made or are planned.
The figures 8 and 9 displays the limits for detection level $U_L$ and integration time $t_i$. All combinations with a detection time $t_q$ less then the design specified limit of $t_q^* \leq 250$ ms [5] can be used for the parametrisation of the quench detection units for a secure quench detection without negative effects for the superconductor. The detection time $t_q$ of all investigated combinations of detection level $U_L$ and integration time $t_i$ was determined with a quench detection unit and a real measured voltage curve of a temperature-initiated quench event in a superconducting coil.

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