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Updates on protection system for Wendelstein 7-X superconducting magnets

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The Wendelstein 7-X stellarator (W7-X), one of the largest stellarator fusion experiments, started the third plasma operation campaign in July 2018 at the Max Planck Institute for Plasma Physics in Greifswald, Germany. The W7-X experiment has a superconducting magnet system with 50 non-planar and 20 planar coils electrically connected in seven circuits. A quench detection system checks permanently the superconducting system regarding the onset of a quench. In case of a quench or a severe failure, the magnet protection system is activated and leads the current into discharge resistors. Based on new requirements and operation experiences, the discharge resistors of the non-planar coils were rearranged and improvements of several components were implemented in the last 12 month. The reconfigured discharge resistors slow down the discharge process, which increases the hot spot temperature in the conductor for about 18 K while the resulting peak voltage is reduced for about 30 %. The simulated data for voltages and currents during the discharge process are in good correlation with the measured data from July 2018.

Keywords: fusion, stellarator, superconducting magnets, magnetic field, quench detection, magnet protection system

1. Introduction

The stellarator fusion experiment Wendelstein 7-X (W7-X) started the third plasma operation phase in July 2018 [1]. The coming plasma experiments can be executed with increased Electron Cyclotron Resonance Heating (ECRH) power up to 10 MW and a plasma pulse length up to 60 s limited by a total energy input of 80 MJ. The superconducting magnet system is the core component of the W7-X stellarator. 50 non-planar coils (NPC) and 20 planar coils (PC) are electrically connected in seven circuits with 10 coils each [2]. Seven power supplies provide individual coil currents in the seven circuits. A quench detection system checks permanently the superconducting system with regard to the occurrence of a quench. In case of a quench, the magnet protection system is activated. The magnet protection system consists of a set of switches, breakers and a discharge resistor, made of pure nickel. Currently, the plasma operation is performed with a magnetic field of 2.5 T on the plasma axis, which requires currents of max. 15.3 kA in the non-planar coils, 10.2 kA in the planar coils respectively [3-5]. A redesign of the discharge resistors was implemented in 2017 to reduce the resulting voltages on the non-planar coils during a fast discharge. The redesign was one action for risk mitigation after the first plasma campaign where two non-planar coil groups failed the high voltage tests under partial vacuum conditions (Paschen test), whereas all coil groups passed the high voltage tests under operational conditions and under regular air pressure.

2. Components and functionality

The magnet protection system has been designed as highly reliable system for discharging the superconducting magnet circuits operating with DC currents up to 20 kA [6]. At this current level, a non-planar coil group stores app. 220 MJ and a planar coil group 80 MJ. In case of a quench the energy is led into a discharge resistor by a two-staged switching sequence. The inductances of the seven coil groups are linked to each other with a resulting inductance of app. 1.1 H for a non-planar coil group and 0.4 H for a planar coil group.

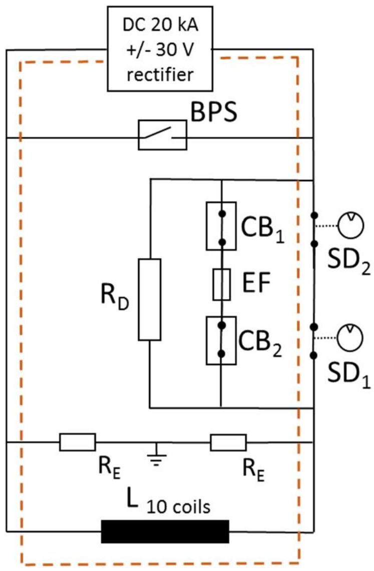

Fig. 1. Electrical scheme of magnet protection system. Dashed line present current during magnet operation.

Fig. 1 shows the electrical scheme of the realized magnet protection system for one electrical circuit with 10 coils in serial connection. The single components of system are the following:

- BPS – by pass switches,
- CB – DC circuit breaker,
- SD – switch disconnector,
- EF – explosion fuse,

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- R_D – discharge resistor,
- L – coil inductance,
- R_E – earth potential resistor.

The switch symbols of CB and SD in Fig. 1 show the closed position. The dashed line in Fig. 1 presents the electrical current during normal magnet operation. The component parameters, the functionality and the two staged switching sequence is well explained in [6,7].

To protect the superconductor from thermal overload the reaction time between the quench trigger and the start of discharge in all seven circuits was specified with 350 ms. The duration of the discharge process was 15 s with the original resistor design. A rearrangement of the discharge resistors in 2017, described in chapter 3, extended the discharge time. The maximum voltages across all 10 coils and between coils and earth potential were specified with 8 kV.

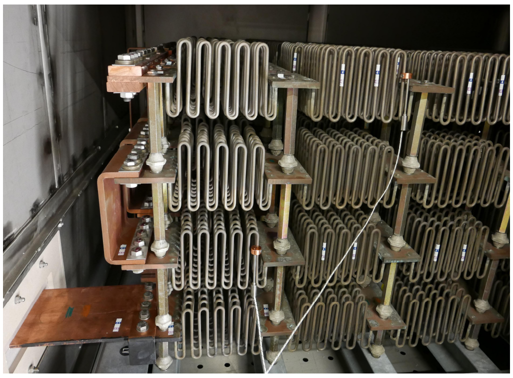

Fig. 2. Discharge resistor of NPC2 system with temporarily removed capsule wall.

3. Updates of components after first operation

3.1 Overview

The power supplies, the magnet protection system and the quench detection system worked well during the first plasma operation phase. Beside the regular maintenance of the components several improvements were implemented e.g. realization of a new data acquisition system including the recording of signals from the magnet protection system or additional switch position contacts easily accessible from outside for maintenance checks. The main change was the rearrangement of the discharge resistors of the non-planar coils.

3.2 Rearrangement of discharge resistors

The discharge resistors of the five non-planar coil circuits were rearranged in 2017 to reduce the resistance from 148 mΩ to 74 mΩ. The motivation for the re-arrangement of the discharge resistors was the aim to reduce the resulting discharge voltages for the non-planar coils against ground potential and to extend the discharge time for the coil system especially in case of a He leak inside the cryostat with resulting partial vacuum conditions. This becomes necessary for risk mitigation after the first plasma campaign when two non-planar coil groups failed the high voltage tests under partial vacuum conditions. The resistors for the planar coils have a value of 54 mOhm and were not changed.

The discharge resistor is made of pure nickel. Nickel has a non-linear specific heat capacity with a Curie temperature at 351 °C. This results in a slowdown of the resistor warming in the first seconds of the discharge process. The resistors of the non-planar coil circuits have a weight of 750 kg, respectively 270 kg for the planar coils. The temperature limit of the discharge resistors is 650 °C. The discharge resistors are placed in the 2nd basement for the torus hall and fully housed with a venting system, see Fig. 2.

A discharge resistor consists of six similar segments connected in series, see Fig.3. A reduction of the overall resistance can be achieved by a rearrangement either by parallel segments or by taking segments out of the circuit. Four different variants were analyzed and evaluated regarding following criteria: allowed temperature at the resistors, resulting peak voltage at the coils and hot spot temperature at the conductor in case of a quench. Following different analysis models were used for the evaluation of the resistor variants:

1. Simple modelling of discharge process in one circuit using PC tools used for first glance assessments. The model considers the inductance of the coil circuit and the non-linear behavior of the discharge resistor.
2. Modelling of the discharge process for all seven magnet circuits at ANSYS Simplorer. The inductances of the coils and the coupling inductances between the coils are implemented into the model, as well the non-linearity of the resistor.
3. Simple modelling of hot spot temperature at the location of a quench in the superconductor using PC tools. The model considers cryogenic data for material properties for the superconductor and uses isochoric and isobaric conditions at the quench location. The heat transfer into the electrical insulation is not considered.
4. The hot spot temperature at the conductor was analyzed for the final rearranged resistor for the Low shear configuration at 2.5 T and 3 T by SPC using the THEA program from Cryosoft [8].

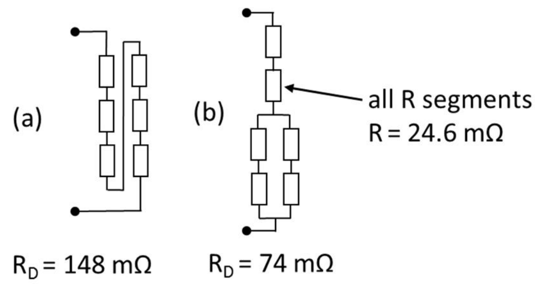

Fig. 3. Electrical scheme of NPC discharge resistor, (a) original arrangement (b) rearranged discharge resistor for non-planar coils.

The Fig. 3 shows the electrical scheme of an original discharge resistor (a), with six resistor segments. One resistor segment for the non-planar coil circuit has a resistance of 24.6 mΩ, which is 1/6 of the total R_D with 148 mΩ. With the rearrangement of the discharge resistors according Fig. 3(b) the resistance changes to 74 mΩ. These variant were chosen because of following main reasons: reduction of resulting discharge voltage for about one third on the NPC; keeping the limits for hot spot temperature <130 K and for the resistor temperature <600 °C (including 50 °C safety margin) and finally the rearrangement can be easily realized with short copper plate bridges.

Table 1. Comparison of non-planar coil discharge process parameters for original discharge resistor and rearranged resistor.

Requirement	Original resistor	Rearranged resistor
DC current	max. 20 kA	max. 15.3 kA
Energy in discharge resistor per circuit	220 MJ	107 MJ
R_D	148 mΩ	74 mΩ
τ (*)	3s	5-7s
Voltage $_{peak}$ (*)	2635 V	1865 V
T $_{max.}$ resistor (*)	270 °C	590 °C
T $_{Hot\ spot}$ coil (*)	102 K	120 K 116 K (**)

(*) values for 2.5 T discharge process for Low shear config.
(**) value taken from SPC analysis [8]

The rearrangement of the resistors changes the main parameter of the discharging process according the values presented in Table 1. To allow a comparison of the performance criteria the values for the time constant τ, voltage peak, maximum temperature on the resistors and hot spot temperature on the conductor were calculated for the 2.5 T magnetic field configuration Low shear.

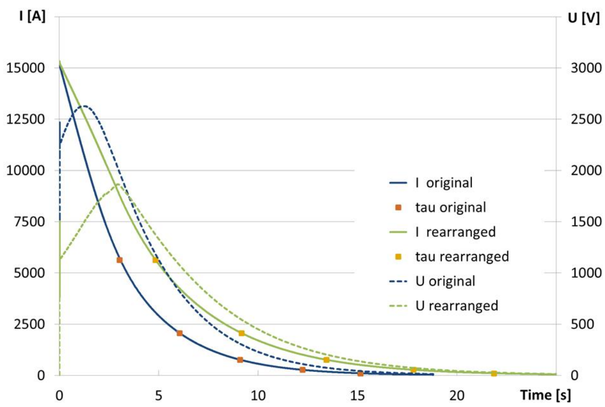

Fig. 4. Comparison of discharge process in NPC 1 at 2.5 T Low shear configuration with two variants: original resistor configuration and rearranged resistors, marks for τ implemented.

With the rearranged discharge resistors of the non-planar coils all 10 magnetic field reference configurations can be discharged up to the 2.5 T level. The operation with 2.5 T at the plasma axis is foreseen for the next W7-X operation phases. For an eventual 3 T operation the discharge resistors needs to be reassembled back into the original configuration accompanying with an updated risk assessment regarding the weakness on the electrical insulation in partial vacuum conditions or a new discharge resistor design has to be developed.

The diagram in Fig. 4 presents the ANSYS Simplorer simulation results for voltage and current during a fast discharge from 2.5 T Low shear configuration as comparison of two variants: original resistor configuration and rearranged resistors.

The resulting discharge voltage is reduced for about 30% for the rearranged resistors. Because of the middle grounding by R_E (earth potential resistors) the voltage against earth is reduced to 932 V. The discharge process is extended by 7 s, 45% respectively. This time extension has a major influence on the hot spot temperature in the superconductor in case of a quench. With the extension of the discharge time the hot spot temperature increases to 116 K [8], which is well below the limit of 130 K.

4. Operation of magnet protection system with rearranged discharge resistors

After rearrangement of the discharge resistors the system has been thoroughly tested before the 2nd operation phase has started. The last fast discharge was triggered during the commissioning tests in preparation of the third experimental campaign on the 27th June 2018. It occurred during operation in standard configuration due to a defect on one current measurement system. The 2.5 T standard configuration has a uniform current of 13.47 kA in all non-planar coil circuits and zero current in the planar coils.

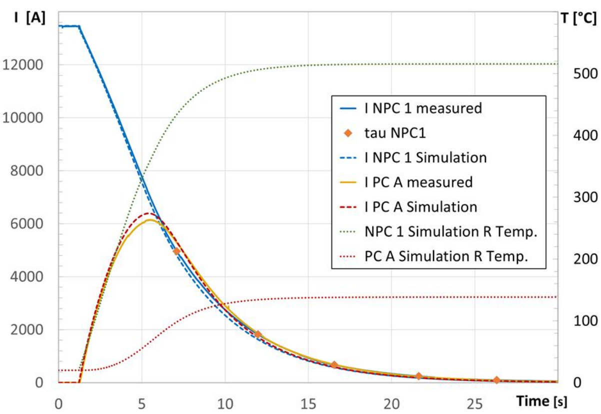

Fig. 5. NPC 1, PC A currents during fast discharge of 2.5 T standard configuration 2018-06-27 compared with simulation results, added simulated resistor temperatures.

Fig. 5 presents the current ramp of the non-planar coil group 1 (NPC 1) and the planar coil group A (PC A) during a fast discharge process. The continuous line present the measured values for the currents while the dashed line presents the results from the ANSYS Simplorer model. The discharge process starts at 1.2 s. The ANSYS Simplorer model contains the seven coil circuits with the related inductance matrix and the non-linear discharge resistors. Due to the inductive coupling the current in the planar coil group increase from zero up to 6 kA.

The results from the simulations are in very good accordance with the measured values. Additionally the diagram contains the temperature development in the discharge resistors using the results from the model.

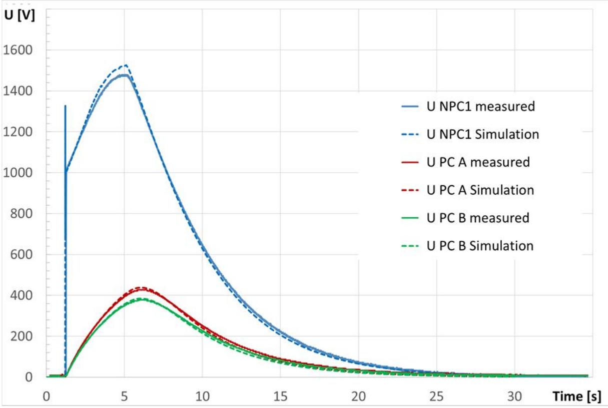

Fig. 6. Voltages in non-planar coil group 1 (NPC 1) and planar coil group A (PC A) during fast discharge of 2.5 T standard configuration 2018-06-27 compared with model calculation results.

The temperature raises up to 515 °C for the non-planar coil resistor and 138 °C for the planar coils respectively. Fig. 4 contains also the time constant for the discharge process which is defined as tau = L / R_D. Due to the non-linear behavior of the discharge resistor, the time constant decrease slightly from 7 s at the beginning to 5 s at the end.

Fig. 6 shows the resulting discharge voltages for the NPC 1 circuit and for the two planar coil circuits. The voltage raise in the NPC 1 circuit up to 1478 V and 427 V in the planar coils respectively.

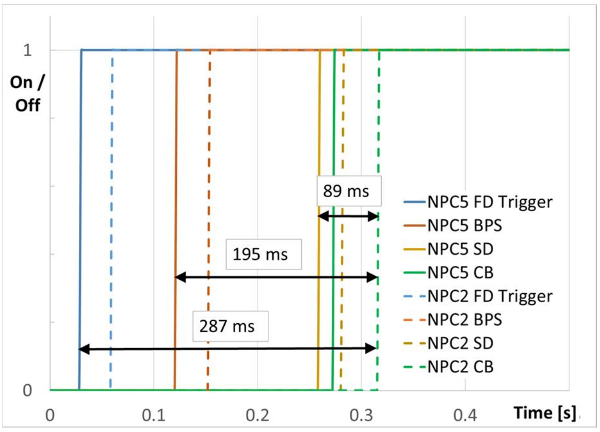

Fig. 7. Measured signals for switching sequence of first and last magnet protection system of fast discharge on 2018-06-27.

During the fast discharge, all seven magnet protection systems work simultaneously. Fig. 7 presents the recorded switching signals of the fastest (NPC 5) and the slowest (NPC 2) protection system broken down to the single components as explained in Fig. 1. The signals are the feedback signals for successful switching which means for BPS - closed, SD – opened and CB – opened. The right order of the switching sequence: Trigger – BPS – SD - CB becomes visible. The time difference between the first switch (BPS of NPC5) and the last switch (CB of NPC2) is 195 ms, while the time difference in the final switching step is 89 ms. The time difference between the first Trigger signal (NPC1) and the last switch (NPC2 CB) is with 287 ms well below the required value of 350 ms.

5. Summary

The protection system discharge the seven circuits of the superconducting magnet system in a controlled way in case of a quench, failure or safety interlock. The electrical energy is discharged into non-linear discharge resistors made of pure nickel material. The rearrangement of the discharge resistors for the non-planar coil circuits in 2017 reduced the discharge voltages for about 30 % down to 930 V against earth potential and extended the discharge duration for about 45 % up to 26 s. The hot spot temperature inside the superconductor in case of a quench is with 116 K well below the limit of 130 K. The maximum temperature of the discharge resistors is below 600°C, still keeping a 50 °C margin. The superconducting magnet system can be operated with the rearranged resistors in all 2.5 T magnetic field configurations, for an eventual 3 T operation the resistors needs to be redesigned. The magnet protection system works well with the rearranged discharge resistors. The form for measured voltages and currents are in very good accordance with the results from ANSYS Simplorer analysis.

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