EUROFUSION WPS1-CP(16) 15823

K. Risse et al.

First Operational Phase of the Superconducting Magnet System of Wendelstein 7-X

Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT
2016)

First Operational Phase of the Superconducting Magnet System of Wendelstein 7-X

Konrad Risse, Victor Bykov, Michael Nagel, Thomas Rummel, Hans-Stephan Bosch,
Andre Carls, Thomas Mönnich, Matthias Schneider, W7-X Team

Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

The Wendelstein 7-X stellarator (W7-X), one of the largest stellarator fusion experiments, has been accomplished successfully the first operational phase at the Max Planck Institute for Plasma Physics in Greifswald, Germany. To confine 30 m^3 plasma the W7-X machine has a superconducting magnet system with 50 non-planar and 20 planar coils. The magnet commissioning was successfully performed until mid of 2015 with tests of the complete magnet system functionality required for plasma operation, at a magnetic field of 2.5 T. The first operational phase started mid of December 2015 with He plasmas heated by the ECRH (Electron Cyclotron Resonance Heating) system followed by H_2 plasmas in February 2016. The magnet system operation was accompanied by an online monitoring of the mechanical sensors installed on the superconducting coils and their support structure to detect any deviations from the predicted behavior.

Keywords: Commissioning, Operation, Stellarator, Superconducting Magnet, Wendelstein 7-X

1. Introduction

The first operational phase of the Wendelstein 7-X (W7-X) stellarator has been accomplished successfully. W7-X is one of the largest stellarator fusion experiments operated at the Max Planck Institute for Plasma Physics in Greifswald, Germany [1]. The W7-X shall prove the reactor relevance of the optimized stellarator concept. W7-X has a superconducting magnet system with 50 non-planar and 20 planar coils grouped in five equal modules, electrically connected in seven circuits with 10 coils of each type. The magnet commissioning was successfully performed until mid of 2015 with tests of the complete magnet system functionality required for plasma operation, at a magnetic field of 2.5 T. The first operational phase started mid of December 2015 with He plasmas heated by the ECRH (Electron Cyclotron Resonance Heating) system followed by H_2 plasmas in February 2016. The superconducting coils and their support structure are equipped with a large set of mechanical sensors e.g. strain gauges, contact and distance measuring sensors. For these sensors an online monitoring has been established to detect any deviations from the predicted behavior.

2. Superconducting magnet system components

2.1 Superconducting coils

The superconducting coils and their interconnecting bus bar system use the same Cable in Conduit Conductor (CICC). The conductor comprises of a cable with 243 NbTi strands enveloped by an Aluminum (Al) jacket. Five different Non-Planar Coil (NPC) types with 10 coils each, provide the main magnetic stellarator field. The stellarator field can be modified by two different Planar Coil (PC) types with 10 coils each [2].

The NPC are made of 108 turns in 6 double layers and the PC have 36 turns in 3 double layers. The double layers are connected electrically in series and hydraulically in parallel. The electrical joints are specified with a resistance < 1 nOhm at 4 K level. The vacuum pressure impregnated winding packs are embedded into a heavy stainless steel cast casing.

The coils are screwed onto a central ring support structure and additionally interconnected by support elements in between the single coils. The coils and the support structure are equipped with an extensive set of sensors e.g. temperature measurements on the He–inlets and outlets on the winding pack as well as on the casing, strain gauges on loaded positions on the support structure and distance sensors to measure distance changes between coils.

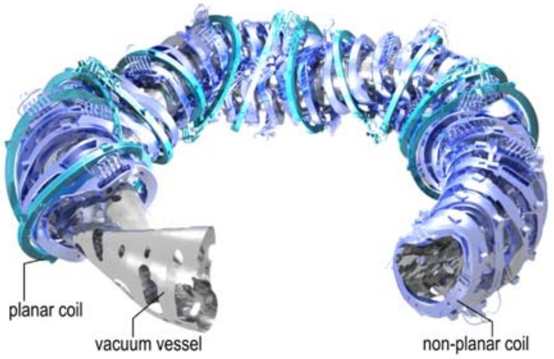

Fig. 1. Schematic view on the superconducting magnets system with non-planar coils, planar coils and vacuum vessel.

2.2 Current leads and superconducting bus

The 10 coils of the same coil type are connected in series by superconducting bus bars. In total 121 bus bars

---

author's email: konrad.risse@ipp.mpg.de

connect the coils in the seven circuits. The bus system uses the W7-X superconductor with slightly rounded jacket edges to allow bending in all directions.

Specially developed high temperature superconducting Current Leads (CL) feed the current into the cryostat by bridging the temperature gradient from room temperature down to the 4 K level. A copper cylinder with integrated tin plate heat exchanger takes over the current from the power supply at the warm side of the CL, leads the current through a high-temperature superconductor section and at the cold side through a copper bar with Nb3Sn rods to the connected bus bar. Fourteen CL operate in the seven coil circuits with the ability to carry steady state currents of 18.2 kA and designed to withstand a voltage strength up to 13 kV against ground potential in case of a fast discharge.

2.3 Quench detection system

The Quench Detection System (QDS) monitors the superconducting components continuously regarding the development of voltages which indicates the loss of superconductivity. By comparison of two section voltages (one double layer is one section) in one quench detection unit, the QDS is able to eliminate electromagnetic interferences and to detect voltage differences between the two sections. The magnet protection system is triggered on two independent redundant interfaces in case of a quench.

2.4 Power supplies with coil protection system

Each of the seven coil circuits has its own power supply to provide individual currents. The construction of the power supplies with the integrated magnet protection system is similar for all seven circuits. Two transformers connected to the 20 kV grid in connection with a 12 pulse converter create a DC voltage up to 30 V. The magnet protection system is activated in case of a quench and the coil energy is dumped into nickel resistors with a non-linear resistance characteristic [3].

3. Commissioning of the magnet system

The commissioning of the superconducting magnet system was performed between April and July 2015 on 21 operational days. The first operation phase of W7-X required a magnetic field of 2.5 T on the plasma axis. To provide the magnetic field in the first operational phase the five NPC circuits were operated with 12.8 kA and the two PC circuits with 5 kA respectively.

The commissioning strategy had to respond to the following challenges: the power supplies operated first time with full inductive load of 1 H for non-planar coil circuits and 0.4 H for planar coil circuits respectively, the superconducting bus bars with the related joint connections carried for the first time an electrical current and the QDS needed a balancing process for the internal measurement bridge with current ramps.

The objective of the commissioning phase was:

- Stepwise commissioning of the magnet system components with full functionality for steady state operation by observing at least 1 K safety margin for superconducting components.
- Adjustment of cooling flow in the superconducting parts, especially the current leads.
- Continuous monitoring of the mechanical sensors, of the He flow and the component temperatures. Benchmarking of the data with the Finite Element (FE) models or with specified values.

The commissioning was structured into 3 main phases. The 1st phase was necessary to bring the QDS into operation by a balancing program with 500 A pulses in each single coil circuit. During this phase the QDS was not active. Analysis had shown that the superconducting parts e.g. coils or the bus system could carry the relative low current of 500 A even in normal conductive state.

The different discharge procedures, including a fast discharge by activation of the magnet protection system, were tested at different increased current levels. A 4 h plateau phase was introduced at the highest current level to adjust the cooling flow in the current leads. The temperature of the superconducting coils, the bus bar sections and the current leads were carefully monitored during the tests. Each current change of 1000 A or higher was accompanied by a so called in service high voltage test to check the insulation integrity.

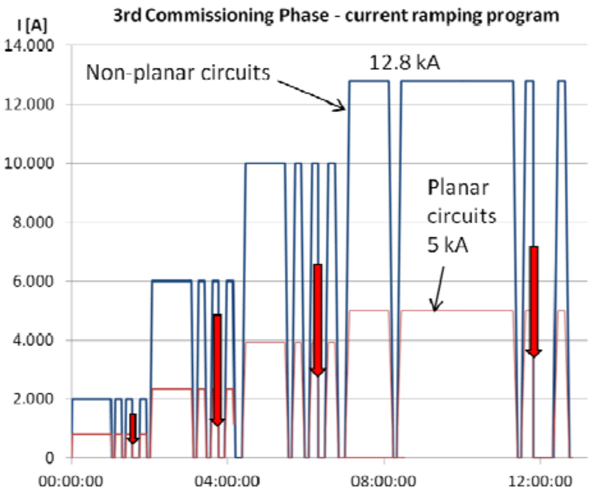

Fig. 2. Test program for third commissioning phase with all seven magnets operated in parallel, red arrow marks initiation of fast discharge.

In the 3rd commissioning phase the test sequence from the previous phase was repeated with all seven coil circuits in parallel operation, see Fig.2. The current was stepwise increased until 12.8 kA in the NPC circuits and 5 kA in the planar coil circuits. At each level a fast discharge was initiated, the stored energy in the magnets was 430 MJ at this current level. After each fast discharge a verification cycle has been performed to confirm structural integrity with MI sensors.

4. Operational phase 1.1

4.1 OP 1.1 magnet operation key dates

The first operational phase OP1.1 started 10th of December 2015 with He plasma heated up to 2 MJ energy by the ECRH. The energy was limited due to the limiter in the plasma vessel instead of 10 divertor units. The first H_2 plasma experiments were performed on 3rd February 2016. The OP1.1 period ended on 10th March 2016 after app. 900 plasma experiments finally heated up to 4 MJ energy and electron temperatures of 8 keV and discharge durations of 6 s.

The first operation phase of W7-X required a magnetic field of 2.5 T at the area where the ECRH waves should be absorbed from the plasma. To provide the magnetic field, the magnet system was operated with the magnetic field configuration "OP1.1 Limiter" which was defined with 12.8 kA in the five NPC circuits and 5 kA in the two PC circuits respectively. To shift the ECRH resonance into the plasma center, the coil currents were fine tuned in small steps. Finally the configuration with 12.37 kA in the NPC circuits and 4.82 kA in the PC circuits was found to be the optimum regarding the absorption of the ECRH waves.

The superconducting magnets were energized during OP1.1 for about 183 hours spread over 31 operation days. The magnet system was energized 35 times up to 2.5 T level during OP1.1. The availability of the magnet system was approximately 94%, see Table 1.

Table 1. Key dates of OP1.1 phase.

	Key dates
Magnet operation days	31
Magnet charge number	35 for 2.5 T
Magnet operation	183 h for 2.5T
Stored energy in magnets	430 MJ at 2.5T
Availability	94%
Fast discharges	1 (no quench)
No. of plasma experiments	900
ECRH heating	up to 4 MJ

4.2 Superconducting magnet system in operation

The superconducting magnet system was energized each operational day according to the needs of the plasma physics program planned for the day. The superconducting coils are cooled by supercritical He with a temperature of 3.9 K on the coil inlets. The correct cooling of the superconducting components was monitored by an operation crew and additionally by a supervisor in the W7-X control room. The automatic evaluation of the conductor inlet and outlet temperatures with the implemented function to reduce the coil current for keeping the 1 K temperature margin was not realized for OP1.1.

During a fast discharge starting at the 2.5 T level a high voltage up to 2.1 kV against ground potential occurs in the non-planar coil circuits, respectively 600 V in the planar coil circuits. A so called in-service high voltage test (IS test) measures leak currents generated by high voltage up to 2.5 kV during operation every time after the coils are stressed due to a significant change in the current [4].

The Fig. 3 presents the current operation of the superconducting magnets on one typical operation day on the 16th of February 2016. Parallel to the superconducting coils a set of 5 normal conducting trim coils was operated at this day. The trim coils allow a fine tuning of the main magnetic field and work as a tool to influence field errors disturbing the toroidal periodicity [5]. The ramp up and down rate of the trim coil currents is up to 2000 A/s. The diagram contains also the plasma heating shots from the ECRH system with a total heating power up to 4.4 MW. 34 plasma experiments were performed this day.

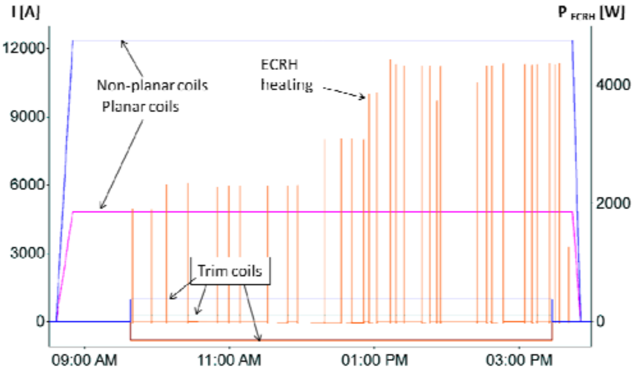

Fig. 3. Experimental day 16th February 2016 with currents in superconducting coils and trim coils, ECRH heating power shots as small bars.

4.3 Discussion of special issues

The magnet operation was only rarely hampered by defects on the power supplies e.g. problems with relays contacts or minor failure in controller boards. Such defects were immediately repaired by using spare parts. Systematic failures occurred on the current measurement systems with similar effects. After implementation of a snubber diode and replacement of an overloaded resistor the systems worked reliable over the whole OP1.1 period.

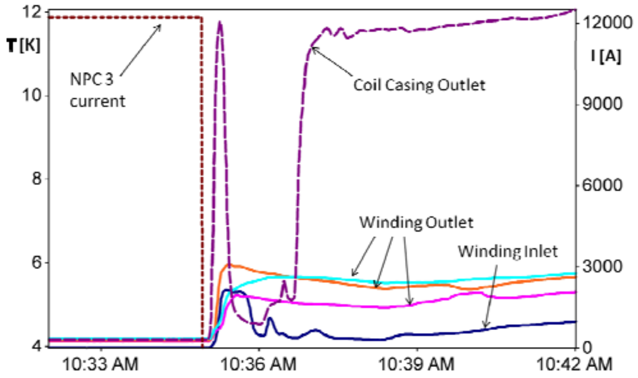

Fig. 4. Thermal behavior of one NPC 3 coil (AAB28) during fast discharge on 25th February 2016, NPC 3 current use the right axis.

At the end of the operational phase 1.1 a defect in the trim coil system led to a rapid discharge of the five trim coils. The trim coil discharge went with a speed of 22 kA/ s. This fast current change in the trim coil circuits activated the quench detection system due to the inductive coupling between both systems. To solve this issue the control system of the trim coils will be reengineered until beginning of OP1.2 to reduce the probability of the rapid discharge activation path. Fig. 4 shows the thermal behavior of one NPC type 3 coil during this particular fast discharge of the complete superconducting magnet system. The outlet temperatures of the winding jumps by app. 2 K due to AC losses in the conductor and the casing outlet jumps for app. 8 K because of eddy currents in the stainless steel casing of the coil. Such a temperature increase in the He return lines leads to a trip off of the cryogenic supply system with a recovery time of about 24h.

During the OP 1.1 phase the current ramp up speed for the superconducting magnets was reduced from 30 A/s down to 15 A/s due to control problems in the cryogenic supply systems.

4.4 Evaluation of mechanical sensor data

The superconducting magnet system is equipped with a large set of mechanical sensors. About 510 strain gauges measure the strain on magnet system components, 58 distance sensors monitor coil displacements and 88 contact sensors check collisions between the coils and the cryostat system.

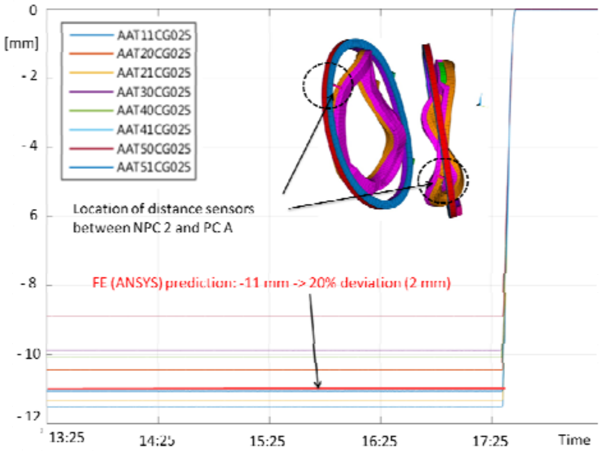

Fig. 5. Measured relative displacements between NPC 2 and PC A during current operation. Locations of sensors are marked on fragment of ANSYS model.

The mechanical sensor data were permanently evaluated during magnet operation to guarantee a structural reliability of the W7-X machine [6]. The areas of most attention on the magnets are: displacements between coils, mechanical loads on the coil support elements recalculated from strain gauge signals and collisions of components in the cryostat. The magnetic field accuracy depends on the coil deformations. For this reason the fitting between measured displacement data and calculated values from the FE models is very important.

The Fig. 5 shows the maximum measured relative displacements between NPC type 2 and PC type A coils for 8 sensors during current operation. At 17:25 o'clock the current was ramped down to zero. The location of the distance sensors is also shown in Fig. 5 in a fragment of the ANSYS FE model. The measured values from the 8 sensors differ between 9 and 11.5 mm. After ramp down the distance sensors signals go back to the origin with no residual displacements. The predicted values from FE calculations with ANSYS models amount to 11mm. The difference between the measured and calculated values is less than 2mm. The present quality of the FE-predictions is within a range of 20 % for the displacements, as expected.

4. Summary

The W7-X superconducting magnet system was operated during the first plasma operation phase with a high reliability according to the requirements of the plasma physics program. Smaller problems on the power supplies could be fixed immediately and didn't hamper the operation. One fast discharge of the superconducting magnets was triggered due to the activation of the QD system by a rapid discharge of the normal conducting trim coil system. The monitoring of the mechanical sensors confirmed the FE modelling and the integrity of the mechanical support structure of the magnet system.

Acknowledgments

Sincere thanks to all colleagues from the W7-X operations division, the magnet system group members and the complete W7-X team for their support. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] H. S. Bosch, Transition from Construction to Operation Phase of the Wendelstein 7-X Stellarator, IEEE Trans. on Plasma Science, Vol. 42, 432 (2014).

[2] T. Rummel, The superconducting magnet system of the stellarator Wendelstein 7-X, IEEE Trans. on Plasma Science 40 (3), March 2012.

[3] T. Rummel, "Power Supplies for the Wendelstein 7-X stellarator", Fusion Engineering and Design, 66-68 (2003), pp. 1115-1118.

[4] F. Füllenbach et al., Design and Prototype of the High Voltage In-Service-Tests on the Superconducting Magnet System of Wendelstein 7-X, IEEE Transactions on Applied Superconductivity 24 (3), June 2014

[5] K. Risse, Wendelstein 7-X trim coils – component safety aspects and commissioning strategy, IEEE Trans. on Plasma Science, Vol. 42, (2014)

[6] V. Bykov, Structural Analysis at the Transition from W7-X Construction to Operation, IEEE Trans. on Plasma Science, in press