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First operational phase of the superconducting magnet system of Wendelstein 7-X

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HIGHLIGHTS

- The Wendelstein 7-X stellarator fusion experiment has a superconducting magnet system.
- The paper explains the commissioning steps of the superconducting magnet system performed between April and July 2015.
- The magnet system was operated during the first plasma operation phase as specified and with a high reliability.

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ABSTRACT

The Wendelstein 7-X stellarator (W7-X), one of the largest stellarator fusion experiments, has 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.

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, see Fig. 1 [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 elec-

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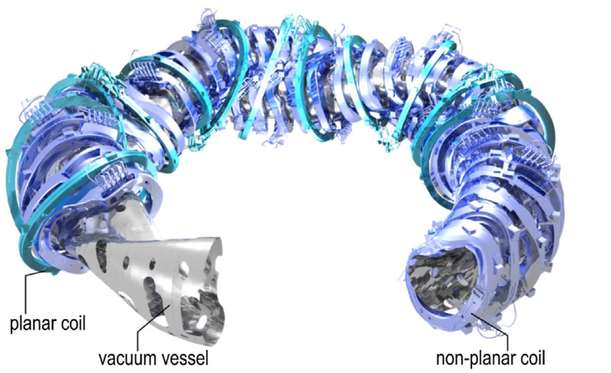

Fig. 1. Schematic view on the superconducting magnets system with non-planar coils, planar coils and vacuum vessel.

trically 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.

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 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 is connected to the power supply at the warm side of the CL and 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 are 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 activated 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 [4].

The commissioning strategy had to respond to the following challenges: the power supplies operated first time with full inductive load of 1H for non-planar coil circuits and 0.4H 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 [5]. 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.

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 of the system.

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.

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