Wendelstein 7-X Magnets: Experiences Gained During the First Years of Operation

Thomas Rummel, Konrad Riße, Michael Nagel, Thomas Mönnich, Matthias Schneider, Frank Füllenbach, Hans-Stephan Bosch, and the W7-X Team

Max-Planck-Institute for Plasma Physics, Greifswald, Germany

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Abstract — The Wendelstein 7-X (W7-X) experimental fusion device went into operation in 2015 after intensive commissioning. Meanwhile, the third plasma operation phase started and ran until October 2018. W7-X has three magnet systems. The superconducting magnet system creates the main magnetic field of W7-X. It consists of 70 superconducting coils, divided into seven individual circuits with ten coils each. Seven equal power supplies provide the electrical current to power the magnets. Seven magnet protection systems are also part of the system. A magnet protection system allows fast discharge of the magnets in case of severe failures, e.g., a quench that means a sudden transition from the superconducting to the normal conducting state. A special sensor system, the quench detection system, checks the status of the magnets continuously. During each of the operation phases, the superconducting magnet system is kept under cryogenic conditions at about 4 K. For that, a helium refrigerator with total power of 7 kW at 4.5 K runs steady state 24/7. The second magnet system is the trim coil system, a set of five copper coils, placed at the outer side of the machine cryostat. The coils are powered by five identical power supplies. The third magnet system is the control coil system, a set of ten copper coils, placed inside of the plasma vessel behind the divertor targets. Ten 4-quadrant power supplies power each coil separately. The power supplies can deliver bidirectional direct currents and, as per request by the experimental program, an alternating current with adjustable frequencies between 1 and 20 Hz. An operation phase of W7-X comprises about 20 weeks. During the phase, the magnet systems are normally operated 2 or 3 days per week. The superconducting magnet system is usually switched on in the morning, kept energized during the day, and ramped down in the evening. This paper analyzes the operation phases, reports on the issues during the operation, and names countermeasures and improvements performed during the breaks between the operation phases.

Keywords — Wendelstein 7-X, superconducting magnets, normal conducting magnets, power supplies.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

The experimental fusion device Wendelstein 7-X (W7-X) went into operation in 2015 after intensive commissioning. Meanwhile, the third plasma operation phase was started and ran until October 2018.

The W7-X device is a 725-ton “donut”-like machine with an outer diameter of 16 m, a height of about 4.5 m, and a nearly circular cross section of 4.5-m diameter. As a stellarator, W7-X has the intrinsic capability for steady-state operation since the vacuum magnetic field already provides plasma confinement. Consequently, the main magnet system is superconducting.

The mission of W7-X is to perform fundamental research on the magnetic confinement of high-temperature plasmas in magnetic fields and on methods for heating of...
plasmas, plasma diagnostics, magnetic field technology, data acquisition and processing, plasma control, plasma theory, materials research, and plasma-wall interaction.

The cryostat for the superconducting magnet system consists of the plasma vessel on the inner side, the cryostat vessel on the outer side, and 254 ports that connect the cryostat and the plasma vessel. All inner surfaces of the cryostat are covered with thermal insulation consisting of a thermal shield, operated at about 50 to 70 K, and multilayer insulation composed of up to 20 layers of polyimide foil and glass silk tapes. The cold mass is about 450 tons and comprises mainly the magnets and bus bars, their support structure, and the cryogenic pipes.

Wendelstein 7-X has several magnet systems. Figure 1 shows the arrangement of the coil systems.

The superconducting magnet system creates the main magnetic field of W7-X. It consists of 70 superconducting coils, divided into seven individual circuits with ten coils each. Five circuits contain five different types of three-dimensional coils (nonplanar coils), and the two other circuits contain two types of planar coils. The nonplanar coils have a weight of about 6 tons, dimensions of $3.5 \times 2.5 \times 1.5$ m. The five types differ slightly in shape and weight. The planar coils are nearly circular with a diameter of about 4 m and a weight of about 3 tons.

A nonplanar coil circuit represents an inductive load of about 1 H, whereas a planar coil circuit has an inductance of about 0.4 H. The magnetic coupling between the coil circuits depends on the location of the coils in the toroidal arrangement and its distance to the circuits containing other coil types. The maximum current in the nonplanar coil during plasma operation will be 18.2 kA. Each coil circuit is fed by one power supply with a maximum current of 20 kA and a maximum voltage of ±30 V. The ramp rate can be varied from 5 to 30 A/s. The power supply is supplied from the 20-kV grid. One of the essential aspects of operating superconducting magnets is protection against damage due to quenches. Therefore, the magnet protection system is an integral part of the system. In case of a quench or another severe failure, the stored energy in the magnets has to be removed from the coil very quickly (fast discharge). That means the protection system separates the power supply from the coil circuit and brings the coil current into a circuit containing a dump resistor. The total system consists of a combination of electronically and mechanically actuated switches and breakers; an explosive fuse; and the dump resistor, made of nickel. The protection system is able to de-energize the coil circuit within 25 s, whereas the rectifier would need 8 min. A special sensor system, the quench detection system, checks the status of the magnets continuously. During each of the operation phases, the superconducting magnet system is kept under cryogenic conditions at about 4 K. For that, a helium refrigerator with total power of 7 kW at 4.5 K runs steady state 24/7. The results of the commissioning and the initial operation of the superconducting magnet system are summarized in Refs. 2, 3, and 4.

The second magnet system is the trim coil system, a set of five copper coils, placed at the outer side of the machine cryostat, intended for enhanced experimental flexibility and error field corrections. It consists of five water-cooled copper coils of two different types A and B. Four coils (type A) are identical in size and shape. They have overall dimensions of $3.5 \times 3.3$ m with 48 turns and will be operated with currents of up to 1.8 kA. They represent a load of 19 mH and 51 mΩ. The trim coil type B is smaller ($2.8 \times 2.2$ m) than the type A coils but has more turns (72) and will be operated at higher currents (up to 1.95 kA). Its electrical parameters are 26 mH and 57 mΩ.

Despite the slightly different load conditions caused by the two coil types, five equal power supplies are being used. Each power supply is connected to the 400-V three-phase grid. The output parameters of each power supply are ±2200-A direct current and ±230 V (Refs. 5 and 6).

The third magnet system is the control coil system, a set of ten copper coils, placed inside of the plasma vessel, behind the divertor targets. One coil has dimensions of $2.0 \times 0.4$ m, a weight of about 70 kg, and an inductance of 188 µH. Each coil consists of eight turns of a rectangular copper profile with an integrated circular
cooled water channel. The complete system also contains ten power supplies, a supply distribution module, a cooling module, and a superordinated control unit. The output current of a power supply is a direct current of up to ±2500 A, which can be modulated by an alternating current of up to 625 A with frequencies between 1 and 20 Hz.

The control coil power supplies are installed in the experimental hall underneath the W7-X device. The consequences are similar to the situation of the superconducting coil power supplies. The space is very limited, and the power supplies including the local controls have to operate under the influence of the stray magnetic field; the search for failures requires the main magnetic field to be switched off.

II. OPERATION PHASES

The way toward full steady-state operation is staged. After the initial commissioning in 2014/2015, the operation phases and phase in which the machine is further completed are running alternating. Figure 2 shows the sequence of operation and completion phases until the full steady-state operation is reached.

In the first operation phase, called OP 1.1, a limiter configuration was used to take the device into operation for the first time. With five graphite limiters at the inner wall, only a few graphite tiles on the inner side [opposite of the electron cyclotron resonance heating (ECRH) launchers] were present; the energy to be delivered into the plasma was restricted to 4 MW. In this phase, from December 2015 until March 2016, first experiences with the device itself, the control systems, and the diagnostics were gained.

Afterward, in completion phase CP 1.2, an inertially cooled test divertor with ten modules (two in each of the five modules, one in the bottom, one in the top of the plasma vessel) and a fully C-covered wall were installed. Therefore, the energy during the second operation phase, OP 1.2a/b, executed in 2017/2018, was finally increased to 200 MJ. Only in the fourth operation phase, the so-called OP 2, will an actively water-cooled divertor, water-cooled panels and wall tiles, and cryopumps be established, aiming at steady-state operation with reactor-relevant plasmas, starting in 2021 (Ref. 7).

An operation phase of W7-X comprises on average about 20 weeks. During the phase, the magnet systems are normally operated 2 or 3 days per week. The superconducting magnet system is usually switched on in the morning, is kept energized during the day, and is ramped down in the evening. In contradiction, the two other systems, the trim coil system and the control coil system, are normally powered only during the plasma discharges. As a result of this operation regime, so far the superconducting magnet system has experienced not more than 100 load cycles, whereas the trim coil system and the control coil system have several hundred load cycles. Nevertheless, it is expected that all the systems run with high reliability and availability during the operation phases.

As this paper will focus on the technical results, the scientific results of the operation phases are reported in Ref. 8.

III. MAGNETIC CONFIGURATIONS

The standard magnetic configuration of W7-X is formed by 50 nonplanar superconducting coils operated at the same current in all coils. The 20 additional planar superconducting coils, together with different currents in the nonplanar coil circuits, allow the modification of plasma confinement parameters like shear, mirror, or the rotational transformation iota. In addition, it will allow the plasma to shift farther inward or outward to position it properly with respect to the plasma-facing components. This flexibility is a key element of the W7-X experimental device. But, it results in more demanding requirements for the supply systems. Instead of one common power supply for the standard magnetic field, now seven independently adjustable power supplies are necessary. In general, ten basic magnetic configurations are predefined in W7-X, but intermediate configurations during the transition between the two basic configurations are also possible.

Table I gives an overview of the number of basic magnetic configurations, the maximum currents, and the polarities in the three plasma operation phases.

The number of magnetic configurations has increased from phase to phase. As a consequence, the current amplitude and/or complexity have been increased, too.

| 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
|------|------|------|------|------|------|------|
| Commissioning | OP 1.1 | CP 1.2a | OP 1.2a | CP 1.2b | OP 1.2b | CP 2 | Comm. | OP 2 |

Fig. 2. Schematic view of operation phases (OPnn) and completion phases (CPnn) of W7-X.
Also, a change of the polarity of one or two planar coil groups took place. Polarity change means that the current in the planar coils flows in the opposite direction than in the nonplanar coils. A polarity change in the planar coil leads is therefore more challenging for the power supply controller and for the sensors of the quench detection system. The controller of the planar coils has to counteract the controller of the nonplanar coils because of the rule of the flux constancy among magnetically coupled magnet circuits. Another consequence is the completely different energy exchange between the (magnetically coupled) coil systems during current ramps and, more severe, during fast discharges. Total field reversal means that the current direction in all coils was the opposite that in the standard case.

Figure 3 shows a typical plasma operation day in OP 1.2b. Until 8:30 the current in all systems was at an intermediate level of 8.5 kA in the nonplanar coils and 6.5 kA in the planar coils, respectively. Later, the full 2.5-T field was required, but with a small variation of the planar coil currents. From 11:00 onward, the magnetic configurations were changed by changing the planar coil

| Operation Phase | OP 1.1 2015/2016 | OP 1.2a 2017 | OP 1.2b 2018 |
|-----------------|------------------|-------------|-------------|
| Number of magnetic field configurations | 2                | 6           | 7           |
| Maximum current in the nonplanar coils (kA) | 12.8             | 14.88       | 14.88       |
| Maximum current in the planar coils (kA) | +5               | −10.2       | +9.2        |
| Polarity of planar coils A and B with respect to the main field direction | +/+               | +/-         | +/-         |
| Total field reversal | No               | Yes         | Yes         |

Fig. 3. Currents in the magnet systems during a typical operation day in OP 1.2b. The ECRH pulses indicate the plasma discharges.
 currents, changing the rotational transformation of the plasma. This was also the part of the day when the trim coils were more intensively used to influence the plasma boundaries. Control coils, which have the strongest influence on the impact of heat to the divertor, were used mainly in short pulses. The ECRH pulses shown give an indication about the number of plasma discharges.

IV. FINDINGS DURING THE OPERATION OF THE MAGNET SYSTEM

For the evaluation of findings and experiences, it is important to take the step from the individual components (e.g., coils) to the total magnetic circuit. One circuit consists of the power supply, room temperature bus bars, flexible copper breeches at the transition to two high-temperature-superconductor current leads, and 11 superconducting bus bars that connect the coils to each other and to the current leads by means of special low ohmic joints. There are also the required boundary conditions, like sufficient vacuum in the cryostat and appropriate cooling to the liquid helium temperature of the cold components. The sensors, especially the quench detection sensors, play an important role when analyzing the behavior of the magnets during operation.

After the third plasma operation phase, the main findings and results of the operation of the superconducting magnets and their associated systems like the vacuum system and the cryogenic system are as follows.

The vacuum in the cryostat can be achieved without problems. To start the cooldown, a pressure of less than $1 \times 10^{-4}$ mbars is required, which is usually reached after 3 days of pumping. An important parameter for the quality of the cryostat sealing is the presence or development of air and helium leaks. In W7-X the leak rates are stable. The helium background did not increase over the years. This indicates that there is no increasing helium leak. This is of high importance because helium leaks are difficult to localize and much more difficult to repair because of space restrictions. The cooldown runs smoothly. The helium mass flow and its distribution were successfully adjusted during the commissioning in 2015 and did not need to be corrected. The thermal insulation of the cryostat is working well. Temperature measurements at the shield panels did not show thermal degradation.

The adjustment of the quench detection system had to be checked and partially adjusted before each operation phase. One reason is the increased number of components connected to the basic machine and the associated increase of the level of electromagnetic noise. The system itself is working stable.

The requested levels of the coil current were reached and operated without problems. No quenches occurred, and the temperature increase during steady state compared to idle current mode has not changed over the years. The reproducibility of all the components of the cryostat during pulses of up to 8 h as well as the reproducibility are well within the specification. That means that the current can be controlled with a maximum measured deviation of $\pm 2$ A with respect to the reference value.

Slow and fast discharges of the coil circuits were performed in the expected manner, with planned as well as unplanned fast discharges. There was no visible change in the important parameters over the years (ramp rate, synchronization, and dump resistor temperature). The cryoplant is able to manage the amount of helium gas after a fast discharge. The necessary time to recover the cryosystem could be reduced from 1 day to 4 h. Nevertheless, a fast discharge still has a severe influence on the operation of the cryoplant.

The displacements and the stresses in the coils and support elements turned out to be an important item and needed to be carefully monitored and evaluated. So far, some changes in the pre-tension of the bolts, which fixes the coils to the central support ring, have been observed, but far away from critical values.

There are no signs of too-high ohmic resistances of the joints, neither in the joints that connect two bus bar sections with each other nor in the joints that connect the bus bars with the cold end of the current leads.

No thermal influence from the plasma and the plasma heating systems became visible after plasma shots of 8-MW power nor after plasma shots of 100-s duration. Finally, also, the warm-up ran smoothly and without severe disturbances.

The availability and the reliability of the superconducting magnet systems, although not specified, are greater than 90%. The definitions of the reliability and the availability presented here are different from the definitions otherwise used. In scientific machines, which do not run steady state and 24/7, the following definitions seem to be more appropriate. An availability of 100% means that all planned plasma operation days could be started as planned. A reliability of 100% means that a started plasma operation day is performed without unexpected stops or interruptions.

Table II shows the respective numbers for the three plasma operation phases.
In OP 1.1, there were 33 planned operation days, but only 31 of them could be started. Two days were lost due to the unavailability of current measurement devices of the magnet power supplies. Three systems showed a systematic failure on the printed board. Only one system was available as a spare part, and it took 2 days to repair the printed boards in the electronic workshop. Meanwhile, this systematic weakness was repaired in all systems.

From Table II, it can be seen that 2 operation days had to be aborted. One stop was caused by an external event: A short (200 ms) loss of the public grid voltage led to a fast discharge of the magnet system and to a stop of the main compressor of the helium plant. The first action was as planned, but the second action was not a planned event. Detailed investigations afterward showed that the compressor stop was initiated by a loss of cooling water, and this was initiated by a trip of a temperature sensor in the water-cooling system. The tripped sensor did not restart automatically after the grid was available again. Meanwhile, automatic restart of the sensor was implemented.

A second operation day had to be aborted due to an unexpected fast discharge of the superconducting magnet system. The reason was interference between the trim coil power supply and the quench detection system. The trim coil power supply detected a grid failure and performed a fast discharge of the trim coils. The change of the magnetic flux in the trim coil induced a voltage in the superconducting coils. This voltage was interpreted from the quench detection system as a quench and led finally to the fast discharge.

TABLE II
Availability and Reliability During the Three Operation Phases

| Plasma Operation Phase | OP 1.1 2015/2016 | OP 1.2a 2017 | OP 1.2b 2018 |
|------------------------|------------------|-------------|-------------|
| Planned operation days | 33               | 40          | 44          |
| Executed operation days| 31               | 40          | 44          |
| Operation days that had to be aborted | 2 | 0 | 2 |

Regarding number 1, temperature sensors of coils and support structures showed wrong values or became out of order during the operation. But, nearby sensors were still okay, and the operators decided to proceed with
the operation. Temperature values from the cold box of the helium plant were lost. As long as the values from the valve box are available, the cryoplant can run in manual mode. Water leaks in cooling water fittings of the power supplies were detected during operation but were small enough to be repaired after the planned end of the operation day. Communication errors between control units during the switching ON sequence, which indicated a failure message, were overcome by a simple repetition of the sequence. The same applies to the erroneous failure messages from breakers during the switching ON sequence.

Number 2 above includes the following issues: loss of communication between control units, general computer failures (blue screen), failures in relays of breakers and switches, broken sensor plugs, loose contacts of signal wires, broken screws in breakers, unexpected or wrong reaction of the control system during changes between operation states, and wrong current measurement in one of the three current measurement systems. Most of the failures for number 2 were detected during tests between the operation days or had already been detected during the switch-off process at the end of an operation day. Thanks to the experienced and trained technicians and engineers, and because of the availability of spare parts, all the issues were analyzed and fixed on short notice.

There were 10/11/10 (OP 1.1/OP 1.2a/OP 1.2b) issues during each of the three operation phases. They are mainly from electronic components but are also from mechanical components that have to move regularly (mechanical contact elements like relays). It is interesting and somehow unexpected that the number of issues did not decrease significantly. But, a closer view turned out that the number of systematic failures went down (e.g., relay contact failures), mainly due to replacement of all components under suspicion by another type. At the same time the number of single failures increased. The assumption is that two converse effects were acting at the same time. On one hand, there was the aging effect because the oldest parts were installed in 2002, and on the other hand, there was installation of additional new components (new data acquisition system) or new functions in the control systems (implementation of safety functions) in the completion phases between the operation phases.

It is important to note that no severe failure in the function of the main magnet system components like coils, bus bars, and current leads disturbed the operation. Also, the magnet protection main functions did not show any failures or deviations from the specified values.

V. SUMMARY

During the first three plasma operation phases of W7-X, the superconducting magnet system was energized more than 100 times for about 900 h up to 80% of the maximum current. The requested currents were achieved with the required accuracy. The long-term stability, although not specified, is better than ±2 A over an operation day. No severe failure in the function of the main magnet circuit components like coils, bus bars, current leads, and power supplies disturbed the operation. The magnet protection main functions worked properly during planned fast discharges as well as during unplanned fast discharges. There were only a few issues that disturbed the plasma operation. Several minor issues occurred but could be analyzed and fixed on short notice thanks to the experienced and trained technicians and engineers. A proper set of spare parts has to be kept up to date and updated with respect to the accelerated aging of the power supply components, especially the control system.

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ORCID

Thomas Rummel http://orcid.org/0000-0002-6968-8750

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