Commissioning Results of the Superconducting Magnet System of Wendelstein 7-X

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***Abstract*—The superconducting fusion device Wendelstein 7-X (W7-X) went into operation in December 2015.**

One of the most important steps was the commissioning of the superconducting magnet system. It consists of 70 superconducting coils, 14 HTS current leads, and more than 100 superconducting bus bars. The system is divided into seven electrical circuits with ten coils, associated bus bars and two current leads each.

The commissioning of the magnet system was performed in two major steps: In a first step the seven coil circuits were separately energized and operated at several current levels in a range between 2 kA and 12.8 kA. In a second step all seven circuits were operated together. The adjustment of the quench detectors, the evaluation of the thermal and mechanical behavior, and the test of the magnet safety system were further work packages. Fast discharges were initiated to check the proper behavior of the magnet safety system. Steady-state operation of up to eight hours was performed to adjust the helium mass flows. The commissioning was successfully completed, the main goal of the magnet system is fully reached, which is also confirmed by magnetic flux measurements and the results of the first plasma operation.

***Index Terms*— commissioning, cryogenics, nuclear fusion device, Superconducting magnets, stellarator, Wendelstein 7-X.**

I. INTRODUCTION

THE WORLDWIDE ENERGY consumption is growing continuously. The search for new energy sources is one of the most important research activities now. Nuclear fusion is one candidate for a reliable, safe and carbon free energy production. Activities to improve the knowledge about the physical background as well as investigations about the best way to make nuclear fusion ready for usage are under way worldwide. Wendelstein 7-X (W7-X) is an experimental device which is intended to allow fundamental research on the confinement of high-temperature hydrogen plasmas in magnetic fields. The main objective of the project is to demonstrate the reactor potential of the optimized stellarator line. An intrinsic feature of stellarators is the steady-state operation capability, since the vacuum magnetic field already provides plasma confinement. Wendelstein 7-X combines a steady state magnetic field configuration with a steady-state divertor, a steady-state plasma heating at high power, a steady-state heat removal concept and a size which is sufficient to reach some reactor-relevant plasma parameters. Such a reactor relevant steady-state operation is a new feature for stellarators and therefore represents the major scientific goal of Wendelstein 7-X [1]. Consequently the main magnet system is superconducting.

The W7-X device is a 725 tons donut-like machine with an outer diameter of 16 m, a height of about 4.5 meters and a nearly circular cross section of 4.5 meter diameter. The cryostat system consists of the plasma vessel on the inner side, the cryostat vessel on the outer side and 254 ports which connect the cryostat and the plasma vessel (PV). All inner surfaces of the cryostat vessel as well as outer surfaces of the PV are covered with a thermal insulation consisting of a thermal shield, operated at about 50 K to 70 K and a multi-layer-insulation composed of 20 layers of polyimide foil and glass silk sheets. The cold mass is about 450 tons and comprises mainly the magnets and bus bars, the support structures, and the cryogenic pipes.

II. SUPERCONDUCTING MAGNET SYSTEM

A. Layout

The superconducting magnet system consists of 50 non planar coils, 20 planar coils, a superconducting bus system and 14 current leads. The ten coils of the same type are connected in series to form, together with bus bars and two current leads, an electrical circuit. Consequently there are five circuits consisting of non-planar coils and two circuits consisting of planar coils. Each of the seven circuits is fed by an independent power supply with maximum ratings of 30 V and 20 kA.

Coils and bus bars are using the same type of superconductor, a forced flow cable-in-conduit conductor using NbTi as superconducting material [2]. It is composed of the outer jacket, made of an aluminum alloy and the cable with 243 strands. The voids between the strands are used for cooling with supercritical helium of about 4 K. The void fraction is in the range from 35-39 %. The outer dimensions of the jacket are 16 mm x 16 mm. The main reason for choosing aluminum is to allow easier bending of three dimensional coils. The strands have a diameter of 0.57 mm and are made of 144 NbTi filaments each stabilized by copper with a copper to non-copper ratio of 2.6. The critical current of a

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superconductor is 35 kA at 4 K, in a background field of 6 Tesla. In total there are about 60 km of superconductor in the machine, made of about 15000 km of strands.

B. Non Planar Coils

Fifty non planar coils are installed in W7-X. Due to the fivefold symmetry of the stellarator and the flip symmetric installations of two identical half modules five kinds of differently 3D-shaped coils are necessary. The dimensions are about 3.5x2.5x1.5 meters and the weight is approximately 5.5 tons each. But they are identical regarding their winding principles and cross section. All non planar coils consist of 108 turns, divided into six double layers, which are wound from one continuous length each. Electrically the six double layers are connected in series by so-called interlayer joints with a resistance of maximum one nano Ohm. Hydraulically the double layers are connected in parallel. All the non planar coils are designed for a nominal current of 17.6 kA. The coil insulation system is designed for a nominal voltage to ground of 6 kV dc and a related test voltage of 13 kV dc during the acceptance test at room temperature. It consists of glass fiber tapes with hot curing epoxy resin with a final thickness of 5 mm. Dimensional checks have shown that the three dimensional contour is reproducible with statistical deviations within 1.5 mm band only. Each winding pack is stiffened by a massive stainless steel case to withstand the electromagnetic forces [3]. The coils are equipped with an active cooling shield. Roughly 1100 small copper stripes are welded around the case and soldered to four cooling pipes for supercritical helium. Each coil is equipped with several sensors. Temperature sensors are located at the surface of the coil casing at three locations and at the helium inlet and outlet pipe of the conductor and coil casing cooling. Strain gauges are placed also at the surface of the coil casing at two locations per coil. Quench detection wires are the third instrumentation system. They are connected at seven points, at the two electrical terminals, and at the five inter layer joints.

C. Planar Coils

The planar coils in W7-X are used to change the magnetic configuration e.g. in terms of shear, iota and mirror. They also allow a shift of the plasma more in- or outwards. The planar coils are assembled over the non planar coils at an angle of around 20 degrees with respect to the main vertical axis (Fig. 1). The 20 planar coils are divided into two different types, type A and type B coils with 10 coils of each type. Each coil has a typical weight of around 3 tons and an outer diameter of approximately 4 meters. The coils are wound from the standard W7-X conductor. The nominal current of the planar coils is 16 kA. The coil insulation system is designed for a nominal voltage to ground of 4 kV dc and a related test voltage of 9 kV dc during the acceptance test at room temperature. The main components of the planar coils are the winding pack, the steel case, the case cooling system and the instrumentation. The winding pack is made from three double layers with 12 turns each, connected electrically in series by two interlayer joints. Hydraulically the double layers are connected in parallel with a similar schema than the non planar coils. The electrical insulation process (vacuum pressure impregnation) is similar to that of the non planar coils with the exception of using a primer before the application of the glass tape. The terminal area is insulated manually using cold cure resin and glass tapes.

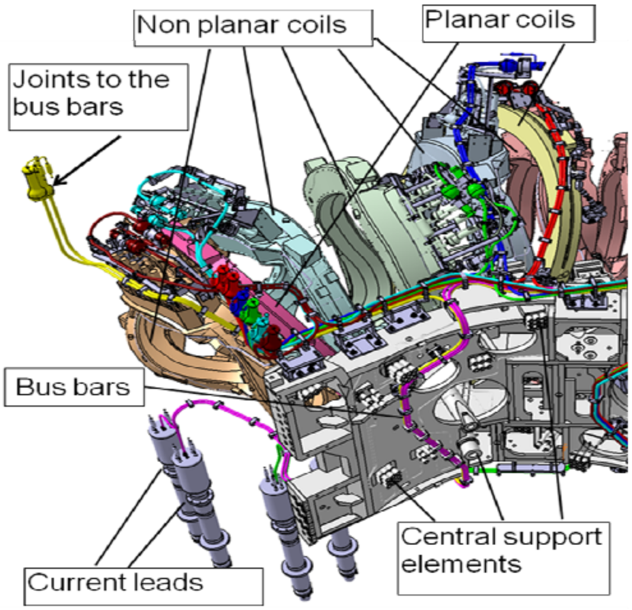

Fig. 1. One half module, consisting of five non planar coils and two planar coils Connection to the superconducting bus bars is made via the indicated joints. Connection of coils to the central support structure is made by the central support elements of the coils.

The achieved accuracy with respect to the CAD model was close to the limit of 5 mm, but the deviation between the winding packs of the same type are very small, and are in the range of one millimeter. To minimize the heat load from the cryostat walls all coils are equipped with a radiation shield made of copper plates which are tack welded to the coil case and soldered to a cooling tube. Ninety six segments of 100 mm width and 1 mm thickness were placed [4]. Like the non planar coils, also the planar coils are equipped with temperature sensors, strain gages and quench detection wires. In addition sensors which measure the mutual displacement between non planar and planar coils are installed.

D. Superconducting bus bars and joints

The superconducting bus bar system connects the coils to each other and provides the connection to the current leads inside the cryostat. In total 121 bus bar sections with lengths between 4.5 and 16 meters were manufactured. The connection of the bus bars and the coils was done by 184 joints (see Fig. 1) each with a maximum allowable resistance of five nano Ohm.

The bus bar system [5] is designed for operating currents of up to 18.2 kA, high mechanical load (up to 11 kN/m), differential thermal expansion, displacement of coils under load, pressure and leak tightness (17 MPa in case of a quench), high voltage capability (13 kV dc), low magnetic stray field generation (bifilar routing wherever possible). The joints had to be designed for low resistance, and for possible repair and replacement after assembly [6], [7]. In order to guarantee the high-voltage withstand capability even after a failure of an insulation layer the insulation concept involves two layers of Kapton foil being 50% overlapped each, embedded in epoxy resin impregnated glass fiber layers. Also the bus bars use the W7-X superconductor, but with slightly changed outer jacket dimension to allow better bending during the three dimensional routing. The square shaped cross section was machined to an almost round one (17 mm diameter).

E. Current Leads

The current leads (CL) provide the transfer of the electrical current from the room temperature bus bar system outside the cryostat to the superconducting parts inside the cryostat.

A special feature is the upside-down orientation of the current leads in W7-X. This orientation allows saving a lot of space in the vicinity of the machine, because no separate current lead cryostat is necessary. The current leads consist of a copper heat exchanger at the warm end side, a high temperature superconductor part (Bi-2223/AgAu tapes) and a copper bar with integrated Nb3Sn rods near the cold end side. A detailed description can be found in [8]. The cold contact consists of a semicircular copper bar with integrated Nb3Sn rods .The contact surface of 75 x 300 mm is polished and gold plated. The superconducting parts of the current leads are equipped with quench detection sensors. Voltage taps measure the voltage drop across the HTS module and the transition between CL and superconducting bus bar to the coils. In addition temperature sensors serve as input for the He mass flow and temperature control. These sensors are located at the warm and cold end sides of the HTS module, at the heat exchanger, and at the warm end of the CL. In low or idle current mode two electrical heaters of 500 W at the warm end side prevent the formation of ice on the warm end of the CL.

A current lead is 2500 mm long, has a diameter of 310 mm and a weight of about 180 kg.

III. COMMISSIONING

A. Strategy and Organization

The sequence of W7-X commissioning can be divided into six main phases, which can be treated separately [9], as they build up a sequence. Only some tasks in this sequence can be performed in parallel, but the main process has to follow a serial sequence:

(1) Vacuum tests of the cryostat.
(2) Cryogenic tests of the cryostat.
(3) Normal conducting coil systems tests.
(4) Vacuum tests of the plasma vessel.
(5) Superconducting magnet coil systems tests.
(6) Preparation for the first plasma.

The commissioning of the superconducting magnets has the unique feature to run over several commissioning phases as listed above. It starts with the cool down as part of the cryogenic tests of the cryostat (2), but does not end before the preparation of the first plasma (6). Instead it runs also during the preparation and execution of the first plasma campaign and comprises also the warm-up of the cold components.

The integral commissioning of the superconducting magnet system started end of April in 2015. Two days per week were available for the tests, the remaining four days of the working week had to be reserved for the still running assembly work on plasma diagnostics, cable trays, water pipes and so on.

All superconducting magnets and all current leads were tested separately under cryogenic conditions up to the nominal current in the self field directly after fabrication [10]-[12]. Nevertheless the integral commissioning of one coil circuit comprises also additional components like the power supply, the room temperature bus bars, the flexible copper braids at the transition to the warm side of the two current leads, 11 superconducting bus bars which connect coils with each other and with the current leads. Superconducting bus bars and joints were never operated before under cryogenic conditions and with electrical current. The joints were assembled directly at the machine [13]. The power supplies were never operated before under such high inductive load of 1 Henry (non planar coil circuits) and 0.4 Henry (planar coil circuits). Therefore the commissioning had to show the proper superconducting behavior of all superconducting parts of the circuit, the low resistance of the resistive joints, and the proper operation of the power supplies and magnet safety systems under the final inductive load. Also here a stepwise commissioning approach was used [14]:

- Individual test of the seven coil groups one by one up to the required current for the first operation phase (OP1.1) or, if lower, up to the allowed current for individual operation,
- Combined test of the seven coil groups together up to the currents foreseen for OP1.1.

This strategy has the advantage of minimizing the consequences in case of a malfunction to one coil group and a failure location is easier to detect. On the other hand it represents a special situation which will not occur during plasma operation and it required additional sophisticated calculation and simulation especially of the mechanical behavior during the tests. As one consequence the maximum currents for individual operation for coil groups one and five had to be limited to 10 kA instead of the foreseen 12.8 kA operation current during OP1.1 [15].

The tests of the individual coil groups were done in the following order:

1. Adjustment of the quench detection system by increasing the current of up to 500 A (ramp rates from 5 A/s to 30 A/s);
2. Ramp-up to 2 kA, followed by a steady state phase of one hour, ramp-down to zero (ramp rates 30 A/s);
3. Ramp-up to 2 kA, followed by a steady state phase of ten minutes, ending with a slow discharge;
4. Ramp-up to 2 kA, followed by a steady state phase of ten minutes, ending with a fast discharge;
5. Ramp-up to 2 kA, followed by a steady state phase of ten minutes, ramp-down to zero (ramp rates 30 A/s) to check the proper behavior after the fast discharge;

6. Repetition of 2.-5. with currents of 5 kA (planar coils), and 6 kA (non planar coils) and 10 kA (non planar coils type 1 and 5) and 12.8 kA (non planar coils types 2, 3, and 4).
7. Ramp-up to the maximum current (see 6.), followed by a steady-state phase of minimum four hours to adjust the helium flow in the HTS-part of the current leads.

The combined tests of the seven coils circuits together followed the same sequence than the individual coil circuit tests. During all steps a check of the mechanical and thermo hydraulically behavior took place.

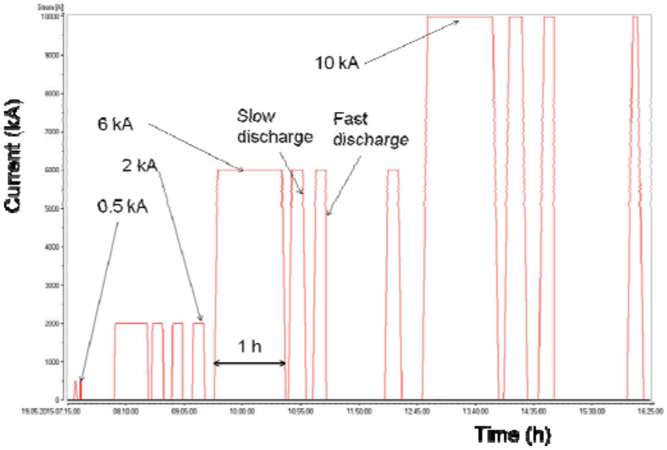

Fig. 2. Principle test sequence showing the steps 1 to 6 described above during the test of the non planar coil group 5.

After the successful completion of the tests of the coil circuits separately, the combined tests were started end of June 2015, reaching the operation current of 12.8 kA of the Wendelstein 7-X first plasma phase already on the 6th of July 2015 for the first time. Later in July 2015 the current was increased to 13.47 kA to have more flexibility with respect to the plasma operation program, and as a forecast to the upcoming operation phase OP1.2. Operation at the full current of up to 18.2 kA in the non planar coils and 12.3 kA in the planar coils is scheduled for the period after 2020 when the high power long pulse plasma operation of W7-X will be performed.

As discussed earlier, the execution of the plasma operation is also part of the commissioning of the superconducting system. Especially a possible temperature increase of the superconducting parts due to the plasma and during transient plasma phases like plasma start-up and plasma stop needed to be studied.

Three consecutive days per week were spent for the plasma operation over a period of nine weeks in 2016. During the regular plasma operation of W7-X the effort with respect to the superconducting magnet system was concentrated on securing a high availability. In general the magnets were ramped up in the morning and ramped down in the evening, after steady state operation of more than eight hours.

The operation current was around 12.5 kA in the non planar coils and between zero and 5 kA in the planar coils, which represents a stored energy of 420 MJ maximum. For comparison: the maximum stored energy at full current is calculated to 630 MJ.

After the end of the plasma operation the warm-up started in March 2016 and in April 2016 the magnet system reached room temperature which is considered as the completion of the commissioning cycle of the superconducting magnets.

In the following chapters the findings and results during the different phase of the commissioning will be presented.

B. Findings and Results: Electrical Behavior

Already at the beginning of the execution of step 1, the adjustment of the quench detection units, the process had to be modified, because immediately after start of the ramp up, the voltages measured by the QD-system exceeds the alarm level. It turned out that the planned pre-calculation of the expected voltage levels during ramp-up and consequently the pre-adjustment of the QD-units was not successfully done. Therefore the adjustment strategy had to be changed. Originally it was planned to start with pre calibrated QD-units. This would allow the start of the operation with current. Later the fine tuning should be performed. Now it was decided to block the alarm signal from the QD-System to the magnet safety system and the magnets were energized without active QD-system. For low currents of about 1000 A the superconductor can be operated even in normal conducting state for a certain time, because the superconductor is stabilized with copper and also with the aluminum jacket, which electrical conductivity at 4 K is by a factor of about 200 higher than at room temperature. All the adjustment, that means the balancing of the two half bridges inside of one QD-unit had to be performed during the ramp-up to the 500 A current level. Only after the adjustment the remaining test program was continued.

The later results were all positive; the several levels of the current were reached without problems, no quenches occurred neither during ramp-up, steady state or ramp-down, nor during slow or fast discharge. Also no wrong quench alarms were created anymore which was confirmed by the temperature and pressure sensors.

The power supplies have been working without major problems; the accuracy and the long term stability during pulses of up to 8 hours are well within the specification. The ramp rates are stable and linear, too. Slow and fast emergency discharges of the coils were performed in the expected manner. The maximum voltage during a fast discharge was about 2 kV, the current was ramped down to zero within 15 seconds. The time traces of voltage and current during a fast discharge are in very good agreement with the simulations.

Apart from the problem with the tuning of the QD-units at the very beginning, the following unexpected events occurred:

The current measurement devices of the power supplies showed several defects during the first days of the commissioning. During the test of the fast discharge sequence at low current several switches and breakers indicated internal failures, but the power switches and breakers behaved as expected. It turned out that relay contacts which should simply transmit status information had no proper switching behavior anymore, most likely due to their age of more than ten years.

Once, the public grid was lost for a period of 300 ms. It was detected by the magnet power supplies which lost their reference for creating the ignition signals for the thyristors (zero crossing of the sinusoidal grid voltage). As a consequence a fast discharge of the magnet system was initiated. At the same time the water cooling circuit of the helium refrigerator also stopped as a level sensor of the cooling water system didn't work due to the loss of the grid. This led to a switch off of the compressors of the helium plant. Another fast discharge of the magnets was initiated by the normal conducting coils. In addition to the superconducting coils also 15 sets of normal conducting coils are present in W7-X. The power supply of one of them detected wrongly a grid under voltage and initiated a fast switch off of the trim coils. The field change in the trim coils induced a field change and then a voltage in the superconducting coil nearby, the quench detection system interpreted it as a quench and triggered a fast discharge of the superconducting magnets. It turned out that here there is a systematic weakness, which will be solved by a design change in the trim coil power supply.

Nevertheless the fast discharge process itself, artificially induced or triggered due to faults described above, ran always very stably and reliably. The measured current and voltages fit to the simulations. Fig. 3 shows the time traces of the currents during a fast discharge from 12.5 kA in the non planar coils and 5 kA in the planar coils, respectively.

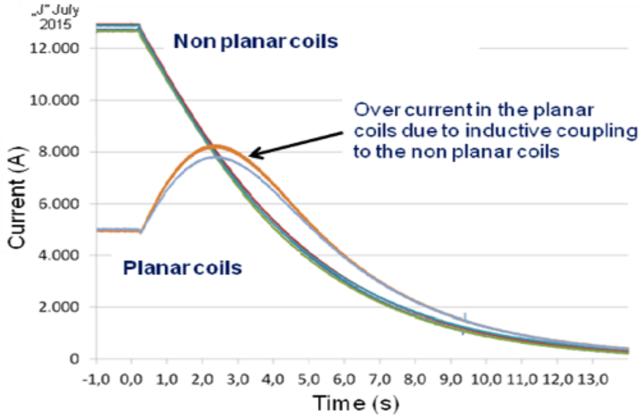

Fig. 3. Currents after a fast discharge from about 12.5 kA and 5 kA in the five non planar coil circuits in the two planar coil circuits, respectively.

Also the effect of the inductive coupling of the magnet circuits is clearly visible. Part of the current from the non planar coils is taken over by the planar coils.

C. Findings and Results: Thermo-Hydraulic Behavior

Starting from ambient condition the cool down of the magnet system was done in parallel with the cool down of the refrigerator. At the beginning the insulation vacuum was better than $2{*}10^{-4}$ mbar. A maximum cool down rate of 1 K/h was defined for the first cool down. In practice the cool down took 4 weeks down to 6 K. During that period the temperature difference between helium inlet flow and the maximum temperature of the cooled components was controlled to stay below 40 K. In conclusion the cool down ran smoothly and without major problems.

The average helium outlet temperature of the conductor cooling was 4.2 K without charged magnets. The temperature increases by 0.05 K only when all non planar coil groups are operated with constant current of 12.8 kA (limiter configuration). This low increase of the outlet temperature is a result of low ohmic heating in the normal conducting joints and confirms the good joint quality.

Transient coil currents have a more pronounced impact on the coil temperature. A current ramp with 30 A/s from zero to 12.8 kA results in a temperature increase of 0.2 K caused by the induced eddy currents in the coil casing and in the winding. The impact is much more pronounced during a fast discharge of the coils.

Fig. 4 shows the coil current and helium inlet and outlet temperatures during several current ramps from 0 to 12.8 kA. The results are shown on the left side of the diagram when only coil group 4 is in operation. As an example the helium inlet and two outlet temperatures for coil AAB27 are plotted. In case of a fast shut down, the outlet temperatures rise to 5.5 K. In that configuration the helium pressure rises temporarily by 0.6 bars.

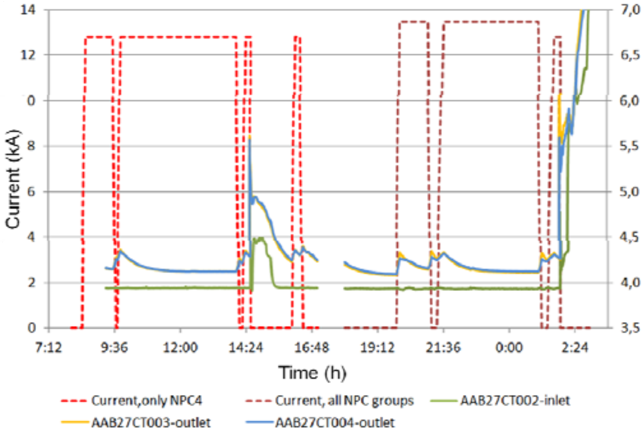

Fig. 4. Inlet and outlet temperatures of the helium flow for the coil cooling AAB27 during coil tests. The current in the coil is plotted as well. The left side shows the results when non planar coil group 4 is charged. The right side gives the results when all NPC-groups are operated.

When all non planar coil circuits are operated in the limiter configuration a fast shut has a more severe impact. The outlet temperatures rise to 6 K immediately and finally go above 7 K. Helium expulsions from 50 coils results in a pressure increase from 3.7 bars to 8.6 bars. The sudden temperature increase and the pressure wave cause trips of the cold compressors and cold pumps of the refrigerator. These disturbances cause finally a trip of the cryo plant compressor system. After such an event it takes one day to bring the cryogenic system back to the required operation conditions.

The warm up of the cryostat started on 17th of March 2016 and took 5 weeks. A maximum warm up rate of 1 K/h was defined equivalent to the cool down rate. The same criterion of 40 K was defined for maximum allowed temperature difference between helium inlet flow and the minimum temperature of the cold components. This criterion was the reason for the practically achieved average warm up rate of 0.6 K/h. So the heat conduction within the massive steel structures limited the warm up rate.

D. *Findings and Results: Mechanical Behavior*

The sophisticated W7-X superconducting magnet system with its non-linear support system is instrumented with an extensive set of mechanical and temperature sensors.

Nearly 500 strain gauges measure the strain on coils but also on the coil support structure, 70 distance sensors monitor coil displacements between planar and non planar coils and 88 contact sensors check collisions between the coils and the cryostat system, mainly the thermal shield.

Each superconducting coil is fastened to the central support structure (CSS) by two central support elements (CSE). The CSE is a bolted connection allowing possible opening of the flange. The narrow support elements (NSE) and the lateral support elements (LSE) connect adjacent NPC casings on the high field and on the low field sides of the machine, respectively. The NSEs are sliding contacts, while LSEs are welded connections with the exception of the inter-module ones which are bolted. The planar support elements (PSE) connect the two types of planar coils to non-planar coils type 2 and type 5. Detailed information about design and manufacturing of the coil support structure elements can be found in [15], and in [17]-[19].

All phases of the commissioning were continuously monitored with respect to the mechanical behavior [16]. Measurements were compared with the prediction of the finite element (FE) models. Special attention was given to the movement of the cryolegs during cool down and warm-up, to the load on the PSEs and LSEs, and to the displacements, too.

It was found and accepted that reliable results are at the level of above 20 MPa and 1 mm for strain gauges and mutual displacements between coils, respectively.

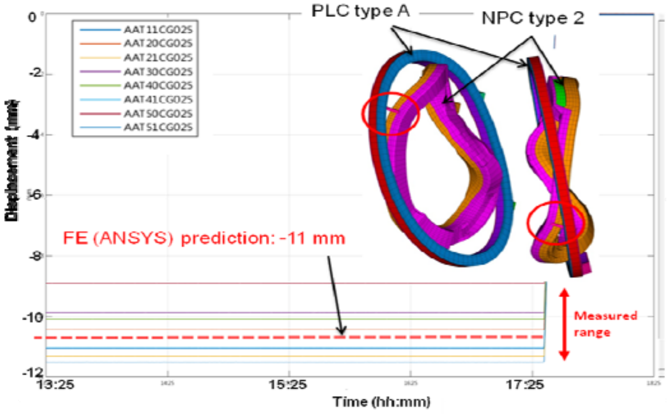

Fig. 5. Maximum measured relative displacement between non planar coil (NPC) type 2 and planar coil (PLC) type A during the plasma operation on 08 March 2016 and comparison between FE model and measured values (AATxyCG025 = sensor tags).

70% of open NSEs and 60% of PSEs respectively have been closed at the 2.5 T operation. The maximum compression force transmitted through NSE is about 0.75 MN (67% of the value at the 3 T operation), while PSE forces are still below 21% of maximum expected 3 T values. Just very local plastic deformations of the NSE pads are to take place during OP1.1.

The most critical central supports have been loaded during OP1.1 by force well above 1 MN. The critical support for coil type 1 is under 0.7 MN tension with a possible flange opening up to 0.2 mm. Lateral supports are also considerable stressed: three types of them transmitted forces above 1 MN (also about 67% of 3T expected values). In any case, all the measured stress values are far below any critical one.

The maximum measured mutual displacements are between planar coil type A and non-planar coil type 2 and are in the range between 8.8 mm and 11.7 mm. Fig 5 shows the displacement measurement between a non planar and a planar coil during the plasma operation with 12.5 kA in the non planar and 5 kA in the planar coils, respectively. Measurement results showed that the magnet system behavior is in good correspondence with original predictions from numerical models. 95% of the mechanical sensors are fine and deliver usable data.

IV. CONCLUSIONS AND OUTLOOK

The commissioning of the superconducting magnet was successfully completed, the main goal of the magnet system is fully reached, which is also confirmed by magnetic flux measurements and the results of the first plasma operation.

The adopted strategy to test first the individual coil groups and afterwards all coil groups together, was successful and minimized the risk. 79 current pulses between 2 kA and 12.8 kA were performed for the individual commissioning of the non planar coil groups. The commissioning of the planar coil groups took 17 pulses between 2 kA and 5 kA. During the combined magnet tests 28 current pulses between 2 kA and 13.47 kA were performed. It took 21 test days only before the system was declared to be ready for the first plasma operation.

The behavior of the superconducting magnet system meets in general all the expectations. It was possible to run the system stable up to eight hours at 13.47 kA which represents 74 % of the finally expected highest current. The superconducting magnets were energized 35 times on 30 operation days for about 183 hours to secure the first plasma operation phase. The high availability of 94% of the superconducting magnet system, which includes cryogenic and power supply, as well as quench detection system during the plasma operation is another important result. Only two out of the planned 32 operation days had to be skipped due to the unavailability of the magnet system. No quenches occurred, the electrical, the thermal as well as the mechanical behavior are a good basis for the operation at higher currents and other, more demanding magnetic configurations.

Main challenges during the next operation phases will be the reversed current direction in up to two of the seven circuits, the higher current, and, as a consequence, the higher stored energy. Also the influence from the plasma operation is expected to be increased e.g. by the significantly increased plasma heating power and the longer plasma pulses.

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