

Cryogenic commissioning, cool down and first magnet operation of Wendelstein 7-X

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Abstract. The construction of the stellarator fusion experiment Wendelstein 7-X (W7-X) was accomplished in 2014. Commissioning of cryogenic system, first cool down of W7-X cryostat and operation of the magnet system was achieved. First plasma operation was accomplished 10th of December 2015. W7-X consists of a magnet system with 70 superconducting coils inside a cryostat. The cold mass of 456 tons is cooled with a helium plant with an equivalent refrigeration power of 7 kW at 4.5 K. The paper presents the commissioning of the cryogenic system, the cool down of the cryostat and first steady state operation with currents up to 12.8 kA. Helium temperatures, mass flow rates and pressure drops inside W7-X cooling circuits are as expected allowing safe magnet operation. Heat loads on the thermal shield and on the superconducting coils are lower than specified for the cryostat design.

1. Introduction

The hot plasma of the stellarator fusion experiment W7-X is confined within a magnetic cage which is generated by a superconducting magnet system consisting of 50 Non Planar Coils (NPC) and 20 Planar Coils (PLC). The coils are wound from a cable in conduit conductor with 243 NbTi- copper strands enclosed by an aluminum jacket leaving a void fraction of 37 % for internal cooling. The coils and their support structures are cooled with supercritical helium at 3.9 K. The 70 coils are divided in 7 coil groups. Within a group the coils are electrically connected in series. 14 High Temperature Superconducting (HTS) Current Leads (CL) connect the ambient temperature power cables with the cold superconducting bus bars. Magnet system, cold bus bars and cold structures are located inside an evacuated cryostat. The warm surfaces inside the cryostat are covered with a thermal insulation to reduce the radiation loads on the cold components. 254 ports equipped with supply/return lines and plasma diagnostics connect the outside of the cryostat with the inside of the Plasma Vessel (PV). Figure 1 gives a schematic view of the magnet system. A schematic cross section of the cryostat is shown in figure 2 with Outer Vessel (OV), thermal shield, coils and PV.

The cooling of the cryostat requires three different temperature levels, 3.9 K for the coil and structure cooling, 50 K for the CL-cooling, and 50-70 K for the thermal shield. The cooling is provided with a helium refrigerator with an equivalent cooling power of 7 kW at 4.5 K.



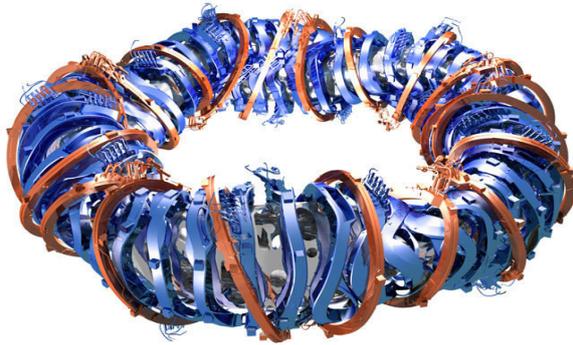


Figure 1. Schematic view of the superconducting magnets system with non-planar coils (blue) and planar coils (brown).

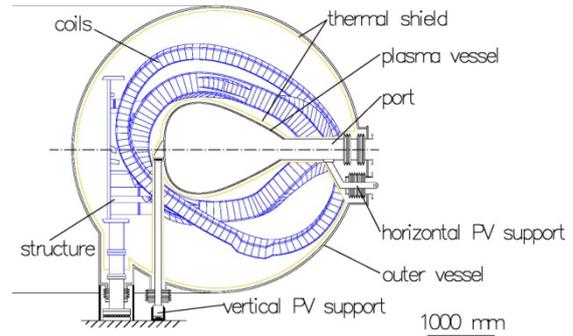


Figure 2. Schematic cross section of W7-X cryostat showing the outer vessel, the thermal shield, the coils and plasma vessel.

2. Refrigerator

The helium refrigerator was supplied by Linde Kryotechnik AG [1]. It consists of a two stage screw compressor station with oil removal system and a dryer unit. Two adsorbers operating at 80 K and one at 30 K remove nitrogen, hydrogen and neon impurities. The cold box contains 6 turbines expanding a partial flow of the high pressure flow from about 13 bars to around 3 bars to pre cool the main high pressure stream. A seventh turbine expands the pre cooled Joule Thomson (JT) -stream to 3.7 bars in the so called Standard Mode (SM). This mode applies when a magnetic configuration with 2.5 T on the plasma axis is operated. The Sub Cooler Box (SCB) contains a liquid helium bath at 1.1 bars and two sub cooler baths. The sub atmospheric pressure required to reach 3.9 K is generated with a cold compressor (see figure 3).

Two supercritical helium streams are circulated through the heat exchangers in the SCB via transfer lines and through a manifold inside the cryostat. The conductor cooling flow at 3.7 bars can be provided either with a cold circulator or by the JT-Flow. The structure cooling requires 300 g/s and is provided by a cold circulator. In a later operation phase the coils will be operated with a magnetic field of 3 T at the plasma axis. In that case the supply temperatures need to be lowered to 3.4 K using the second cold compressor unit. The refrigerator has already incorporated provisions to supply 10 Cryo Vacuum Pumps (CVP) with supercritical helium either at 3.9 or 3.4 K depending on the refrigerator mode. These cryo pumps will be mounted later inside the plasma vessel behind the divertor.

After the successful acceptance tests of the refrigerator in 2012 [2] the test boxes equipped with heaters were removed. Instead a transfer line was installed between the valve box in the torus hall and the W7-X supply terminal.

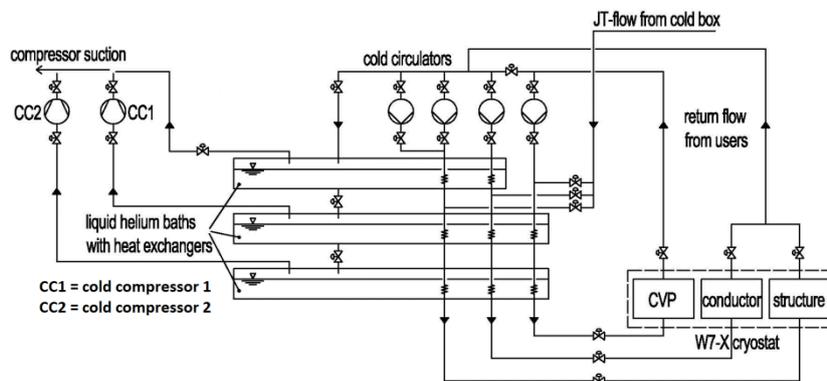


Figure 3: Schematic drawing of cooling of the W7-X cryostat. Cold circulators force a supercritical helium flow through the heat exchangers in the sub cooler box and then through the cooling circuits of the W7-X cryostat (coil conductor, structure, CVP).

3. Preparation of cryogenic system

The commissioning of the cryogenic system as part of the commissioning of W7-X was embedded in the central commissioning planning [3] to ensure correct sequence of connected activities. It comprises the preparation of the refrigerator, the supply lines to the cryostat, the piping inside the cryostat and the quench gas exhaust system and resulted in the following procedures:

- Verification that assembly of all involved systems had been finished and all required tests had been done successfully.
- Application of a flushing procedure: Filling individual pipe sectors with nitrogen gas up to 3 bars followed by rapid expansion into the surroundings. The expelled gas was filtered to check whether out coming gas carried dust or debris. Filling and expansion was repeated three times or more until no impurities could be observed. In case the pipe segments were long or had many bends inside the cryostat, the pressure was increased from 3 to 12 bars.
- Leak checking of screw connections which had to be opened for the flushing procedure.
- Evacuation and filling of the single cooling circuits: The pipes were evacuated to 30 mbar using a rotary vane pump and then filled to 1 bar with helium. This was repeated three times.
- Further cleaning of the helium circuits using the dryer and 80 K adsorber of the refrigerator: First the refrigerator itself was cleaned up to the valve box in the torus hall. Then the cooling circuits in the cryostats were connected separately one after another and then together in a second cleaning step. The nitrogen concentration in helium could not be measured in the return flow but only in the feed lines before and after the 80 K adsorber. So the impurity concentration before the adsorber was used as criteria for the cleaning (impurity less than 10 vpm for nitrogen). Four weeks time was used for cleaning with the cold adsorber.
- Measurement of the helium leak rate to the insulation vacuum: Parallel to the cleaning procedure the helium leak rates of all cooling circuits inside the cryostat were measured. The measured overall helium leak- rate was smaller than $3 \cdot 10^{-5}$ mbar l/s [4].

4. Cool Down and first Operation

4.1. Cool down

The cool down of the thermal shield and the magnet system was done in parallel with the cool down of the refrigerator starting from room temperature. At the beginning the insulation vacuum was better than $2 \cdot 10^{-4}$ mbar [4]. The thermal shield was cooled in parallel with the cold structures down to the dedicated shield inlet temperature of 50 K. A maximum cool down rate of 1 K/h was defined for the first cool down. The temperature difference between helium inlet flow and the maximum of the cooled components was controlled to stay below 40 K. The mass flow distribution in different headers was adjusted daily to avoid non uniform cool down. Displacement signals were monitored caused by thermal shrinkage of mechanical supports of the magnet structure and of the current leads. The displacements were in line with the predicted values. Vacuum pressure and the helium leak rate were continuously monitored.

The cool down from room temperature to about 6 K was achieved within 24 days. The heavy steel structures and the temperature difference of 40 K limited the cool down rate which was much slower than 1 K/h at the beginning. The shield temperature followed the coil temperature down to about 120 K. Visual checks of the outside of the cryostat, pipes and wire feed-throughs, safety valves and transfer lines didn't show any ice or water condensation. There weren't any noticeable vibrations or noise by an instable helium flow. Measured displacements were within the predicted range [5]. The cryostat pressure inside the cryostat dropped down to 10^{-7} mbar [4] simultaneously with the cool down of the coils.

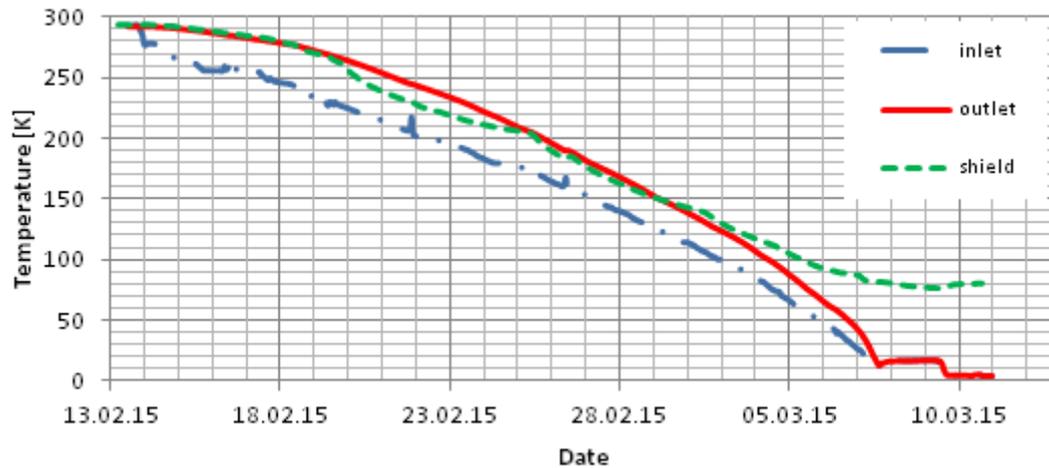


Figure 4. Cool down of W7-X cryostat. Helium inlet (blue), coil outlet (red) and thermal shield outlet (green) are shown.

4.2. Testing of Operation Modes

4.2.1. Short Standby Mode (SSM)

The SSM mode is characterized by return temperatures for the structure and conductor cooling below 10 K, while the thermal shield and current leads are supplied at 50 K. It turned out that the return temperature from the coils and structures could be kept at about 6 K by using the JT-flow only without using a cold circulator. This mode is used to keep the cryostat cold over weekends or holidays.

4.2.2. Standard Mode (SM)

After the test of the SSM the refrigerator operation was changed to the SM cooling stabilizing the magnet system at 3.9 K. Two cold circulators and a cold compressor were put in operation. Several control parameters of the refrigerator were adjusted. Flow distributions between parallel cooling circuits were checked and adjusted.

Table 1. Heat loads, mass flow rates and pressure drop in the circuits for SM and SSM.

Mode	SM (3.9 K)		SSM (<10 K)	
	Coil housing and structure	Conductor cooling	Shield cooling	Coil conductor, housing and structure
Feed temperature [K]	3.9	3.9	50	5.2
Flow rate [g/s]	300	200	110	160
Heat Load [W]	426	256	5600	566
Design value for heat load [W]	1800	800*	9000	1800
Pressure drop [mbar]	140	360	1180	140-290

* design value for refrigerator performance

4.2.3. Results of the mode tests

The specified mass flow rates in the SSM and SM were achieved for the conductor and structure cooling circuits. The results are presented in table 1. The pressure drop for the circuits was within the expected range. The heat loads on the thermal shield and on the cold structures were well within the conservative assumptions for the cryostat design. The overall load on the cold structures was 680 W in

the SM while the specification considered a conservative design value of 1800 W assuming a heat load of 1.5 W/m² on 4-5 K cold surfaces.

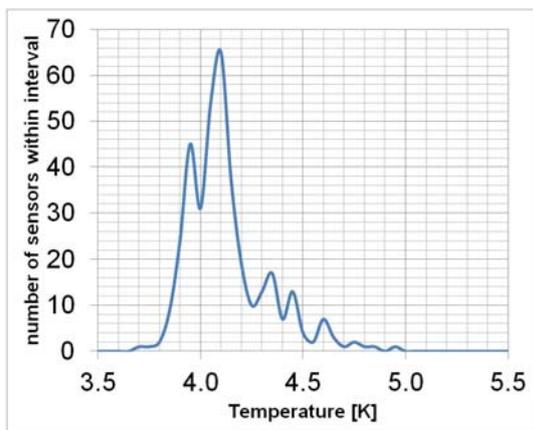


Figure 5. Helium temperature distribution for conductor and housing cooling of all NPC (inlet, outlet, at housing).

The helium outlet temperatures of different sensors at the coils vary between 4.0 K up to 4.7 K when operating in the SM. The accuracy of the temperature sensor is ± 50 mK. But as the helium temperatures were not measured inside but at the surface of the pipes these temperature values are affected by the surroundings and are therefore less precise. Figure 5 shows the helium inlet, outlet and coil housing temperature distribution within temperature intervals of 50 mK for all NPC for conductor and coil housing cooling. The first maximum in figure 5 shows the helium inlet temperature, the second maximum indicates the most frequent outlet temperature of 4.10 K. For comparison, the helium return temperature shows 4.18 K measured in the flow of the return line in the valve box.

4.2.4. Performance of the thermal shield

The thermal shield covers the OV (about 500 m²), the ports (700 m²) and the PV (200 m²). The shield cooling is realized with 10 parallel loops, cooling first a half module of the OV and then the corresponding half module of the PV shield in series. The port shield is cooled indirectly only by heat conduction. The supply temperature for the thermal shield is around 50 K. The mass flow is adjusted so that the temperature increase is about 10 K.

The overall heat load on the shield is 5.6 kW leading to an average heat load of 4 W/m². That is lower than the design value of 6 W/m². The measured value is nevertheless high compared to an ideal Multi Layer Insulation (MLI) blanket with 1 W/m². The conservative design value was chosen because of the complex shield geometry intersecting with 254 ports, which penetrate the OV, pass the vacuum space and give access to the PV. The lack of space inside the cryostat made the assembly of the port shield insulation and the overlap of the MLI between neighboring sectors difficult. It was analyzed that 67 % of the heat is absorbed by the OV-shield cooling and 33 % by the PV-shield cooling. The OV-shield and port shield temperatures vary between 65 K in undisturbed areas and 115 K close or at big port shields. The PV-shields show temperatures between 65 K and 85 K.

5. Operation with Current

5.1. Coil Commissioning procedure

Commissioning of the magnet system with current was structured into 3 main phases [5]. First it was necessary to bring the quench detection system into operation by balancing the voltages from the quench detectors with 500 A pulses in each coil circuit. Second, the functionality of the single coil circuits was tested. The current levels were stepwise increased applying a ramp of 30 A/s until the set point for the current was achieved. Then the current was kept constant for 10 min up to 1 hour followed by ramp down to zero current. Next a fast discharge was performed at each current level, finally with 12.8 kA in the NPC and 5kA in the PLC. In the 3rd commissioning phase the test sequence was repeated but with all seven coil circuits in operation. Finally the current in the PLC was varied between 0 kA and 5 kA while the NPC coil stayed at 12.8 kA.

5.2. Temperature limits

The maximum allowed conductor temperature was calculated to 5.16 K as outlet temperature of the coils. This calculation was based on the following simplified assumptions:

- Calculation of the maximum field at the coils for the limiter configuration (12.8 kA for all NPC and 5 kA for all PLC, see [6]).
- The maximum flux density (B) is used for all coils ($B_{\max} = 5.05$ T, simplified procedure).
- Calculation of the critical temperature using a scaling law with parameters fitted to measurements of the strands of W7-X conductor [7] and to the quench tests for the W7-X coils [8].
- Applying 1 K safety margin against quench.

5.3. Required cryogenic parameters

Before ramping up the current, the supply and return temperature, as well as the mass flow rates were checked and surveyed. The 50 K helium cooling of the current leads was adjusted to the applied currents [9] while keeping that maximum temperature of a HTS section of a CL below 60 K (see table 2). This was done for each CL and repeated for different current values. These data were put in a table and allowed the operators to define the correct set points for the control of the individual CLs. As the CLs did have a big thermal inertia, several hours of stable operations were required to get reliable data.

Table 2. Average helium mass flow rate for a current lead cooling with 50 K inlet temperature.

Current in kA	0	5	6	10	12.8
Flow rate in g/s	0.42	0.50	0.51	0.8	0.94

5.4. Operation with current

A typical result for current operation is shown for a test case when only NPC type 4 is in operation (figure 4). The conductor inlet temperatures were 3.91 K. The outlet temperatures varied between 4.0 to 4.5 K without current. The temperature values are below the limit of 5.16 K. Ramping up the current with 30 A/s to 12.8 kA resulted in a temperature increase at the coil outlet of 0.25 K caused by induced currents in the conductor and in the coil housing. After an operation time of more than 2 h the outlet temperature of the coils is about 50 mK higher than without current. This temperature increase is due to ohmic heating at joints. The emergency function in case of a quench was investigated during a sharp ramp down of the current with a time constant of 5 s. The conductor outlet temperatures increased temporarily up to 5.8 K. During such an event the overall heat load on the phase separator and sub cooler of the refrigerator was so big that the cold compressor tripped. When the full magnet system is in operation, the induced current and resulting heat loads are even more pronounced. Conductor outlet temperatures rise up to 6.5 K and the pressure in the ring manifold increased from 3.6 up to 8.7 bars (see figure 6). The maximum pressure was well below the set pressure for the safety valves of the manifolds in the cryostat (18 bars). Cold compressor and both cold circulators tripped under this condition.

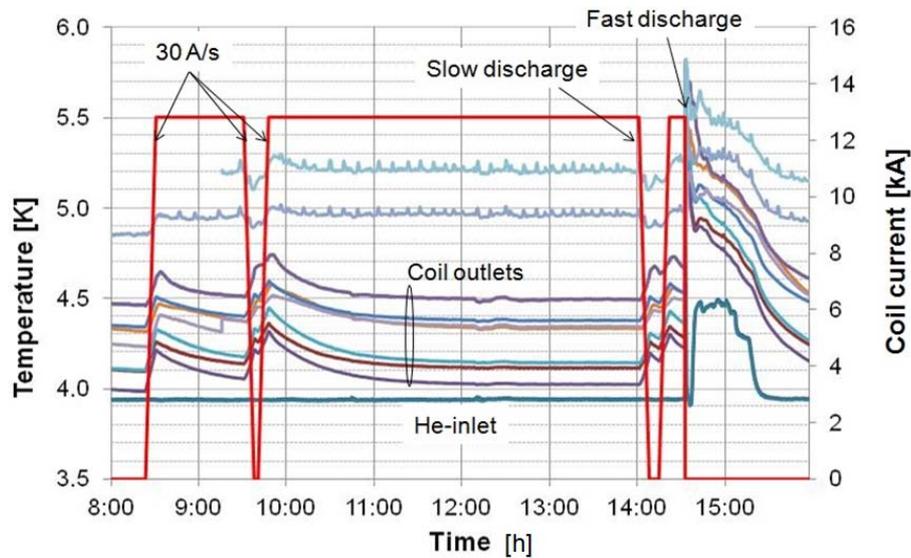


Figure 5. Applied current (red, right axis) and resulting helium inlet and outlet temperatures (in blue, left axis) for NPC coil group 4 during the coil commissioning. 3 current pulses are applied with a fast discharge at the end.

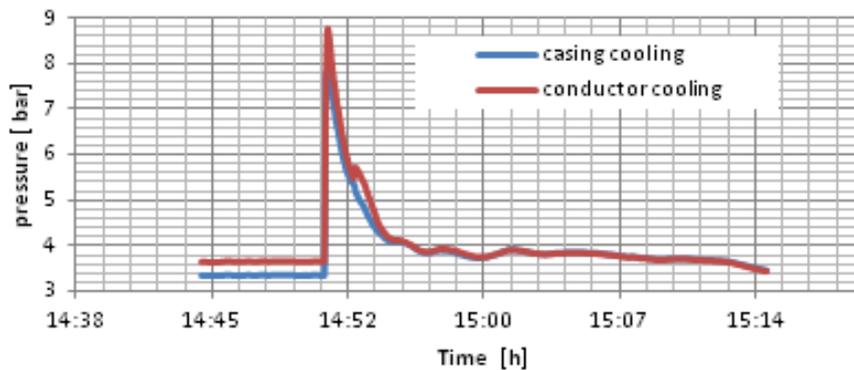


Figure 6. Pressure increase in manifold for coil casing and coil conductor cooling during a fast discharge.

Figure 7 shows the temperature increase $\Delta T = T_{\text{start}} - T(t)$ for the conductor outlet temperatures verses time when ramping the current up of all 50 NPC from 0 kA to 12.8 kA with 15 A/s. Then the current is kept constant over hours. The temperature rise at the beginning is caused by eddy currents again. The temperature difference after hours is a result of the ohmic heating at joints. The average increase for the conductor cooling is about 50 mK and 10 mK in the coil housing cooling. The coil housing is affected because of heat transfer between conductor and coil housing cooling. The moderate temperature rise confirms the good quality of the joints.

5.5. Plasma Operation

After commissioning, the first plasma was produced on 10th of December 2015 starting the experimental campaign. During a typical experimental day the coil current was ramped up in the morning with only slight variations over the day. In the evening, the current was ramped down. Stable operation conditions with charged magnet system were achieved over the whole experimental day. No impact of the plasma operation on the cryogenic systems has been observed so far.

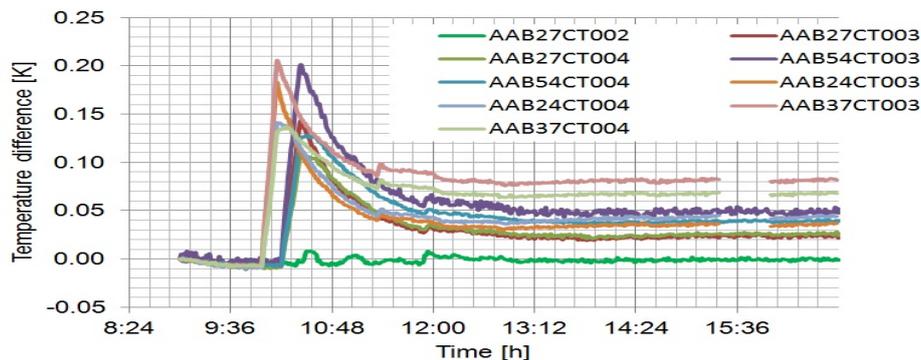


Figure 7. Temperature increase $\Delta T = T_{\text{start}} - T(t)$ of conductor outlet temperatures (CT003, CT004) over time during current operation in the limiter configuration. CT002 is the inlet temperature. AAB24/27/37/54 are names of coils.

6. Conclusion

The cryogenic commissioning of the Wendelstein 7-X cryostat started in the second half of 2014. A flushing and purging procedure was carried out for transfer lines and manifolds inside the cryostat. The purifier and dryer of the refrigerator were used for further cleaning. The maximum allowed cool down rate was 1 K/h, the maximum temperature difference between helium inlet and the cooled structure was set to 40 K. The cool down from room temperature to 6 K was performed within four weeks. The SSM and the SM were successfully tested showing stable cooling conditions. The heat loads on the cold structures and on the thermal shield were well below the design values. The superconducting coils were operated up to a current of 12.8 kA for the NPC and 5 kA for the PLC achieving a magnetic field of 2.5 T on the plasma axis. With first plasma operation in December 2015 commissioning of W7-X was finished and the experimental campaign has been started.

Acknowledgement

This work was supported in part by the EUROfusion Consortium and by the Euratom research and training program 2014-2018 under Grant 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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